

Study on thermal mixing enhancement of
liquid metal film-flow under magnetic fields
by using submerged vortex generators

Department of Nuclear Engineering

Kyoto University

Koji Kusumi

Table of Contents

Chapter 1 Introduction	5
1.1 Fusion reactor.....	5
1.1-1 Reactor concept	6
1.1-2 Plasma-facing-component	8
1.2 Divertor concept	9
1.2-1 Solid divertor	10
1.2-2 Gaseous divertor	11
1.2-3 Liquid divertor	11
1.3 MHD effect of the liquid metal flow	14
1.3-1 Governing equation	15
1.3-2 Dimensionless parameter	15
1.3-3 Effect of Lorenz force	18
1.3-4 MHD vortex damping	19
1.4 Thermal mixing enhancement	23
1.4-1 Cube	24
1.4-2 Hemisphere	27
1.4-3 Delta-wing	28
1.5 Objective of this study	30
1.5-1 Numerical simulations	30
1.5-2 Experiments	31
 Chapter 2 Numerical Simulations	 32
2.1 Introduction	32
2.2 Governing equations	33

2.2 Governing equations	33
2.3 Uniform transverse magnetic field	35
2.3-1 Numerical model	35
2.3-2 Boudanry conditions	40
2.3-3 Flow under non-magnetic field	41
2.3-4 Effect of a single obstacle	45
2.3-5 Effect of inline hemisphere arrangements	54
2.4 Vertical parabolic magnetic field	64
2.4-1 Numerical model	64
2.4-2 Reference case	67
2.4-3 Effect of a single obstacle	70
2.4-4 Effects of inline and staggered arrangement	72
2.4-4-1 Numerical model	72
2.4-4-2 Results and discussions	73
2.5 Summary	80
2.5-1 Reference case	80
2.5-2 Uniform transverse magnetic field	81
2.5-2 Vertical parabolic magnetic field	82
 Chapter 3 Liquid metal experiment	 84
3.1 Introduction	84
3.2 Uniform transverse magnetic field experiment	85
3.2-1 LMX	86
3.2-2 Diagnostics	90
3.2-3 Flow under the non-magnetic field	91

3.2-3-1 Experimental apparatus and conditions	91
3.2-3-2 Temperature rise at the bottom-wall	93
3.2-3-3 Heat flux at the bottom-wall	97
3.2-3-4 Comparisons	99
3.2-3-5 Discussions	100
3.2-4 A single delta-wing experiment	101
3.2-4-1 Experimental apparatus and conditions	101
3.2-4-2 Temperature rise at the bottom-wall	102
3.2-4-3 Heat transport performance	106
3.2-4-4 Thermal fluctuations	108
3.2-4-5 Comparisons	109
3.2-4-6 Discussions	110
3.2-5 An inline hemisphere arrangement	112
3.2-5-1 Experimental apparatus and conditions	112
3.2-5-2 Temperature rise at the bottom-wall	115
3.2-5-3 Heat flux at the bottom-wall	121
3.2-5-4 The efficiency of heat transport	123
3.2-5-5 Comparisons	126
3.2-5-6 Discussions	127
3.3 Vertical parabolic magnetic field experiment	129
3.3-1 LMFREX.....	129
3.3-2 Diagnostics	136
3.3-3 Reference case	138
3.3-3-1 Experimental apparatus and conditions	138

3.3-3-2 Temperature characteritic	140
3.3-3-3 Heat transport performance	147
3.3-3-4 MHD effect to the velocity field	150
3.3-3-5 Comparisons	152
3.3-3-5 Discussions	152
3.3-4 Effect of a single obstacle	154
3.3-4-1 Experimental apparatus and conditions	154
3.3-4-2 Effect of obstacle height.....	156
3.3-4-3 Temperature characteritic	157
3.3-4-4 Heat transport performance	160
3.3-4-5 Comparisons	167
3.3-4-6 Discussions	167
3.3-5 Effect of inline and staggered arrangement.....	169
3.3-5-1 Experimental apparatus and conditions	169
3.3-5-2 Temperature characteritic	170
3.3-5-3 Heat transport performance	173
3.3-5-4 Comparisons	177
3.3-5-5 Discussions	177
Chapter 4 Discussions	180
Chapter 5 Implementation	184
Chapter 6 Conclusions.....	187
Appendix	190
Reference	195
Acknowledgements	200

Chapter 1 Introduction

This study was conducted by the experimental and numerical investigations of the effect of various magnetic fields on thermal mixing characteristics and flow structures of liquid metal film-flow with using various shapes vortex generators. The objective of this thesis is to understand physical phenomenon and find an optimum heat removal technique of liquid divertor utilizing high electrical conductivity fluids for nuclear fusion reactor.

1.1 Fusion Reactor

Development of a nuclear fission reactor has been proactively conducted as an energy source to replace fossil fuels because of free greenhouse gas emission. However, nuclear fission power emits long-lived high-level radioactive wastes in the reprocessing process. For the treatment of these wastes, a geological disposal is necessary that is an enormous cost and longtime management are required. In addition, nuclear fission reactor has a possibility to cause catastrophic nuclear and radiation accidents by the thermonuclear runaway. On the other hand, the renewable energy cannot be generating electricity as a constant due to the dependence of natural weather, therefore it is necessary to a high performance of adjustable capabilities such as fossil fuel energy or nuclear energy. Based on these backgrounds, the development of fusion reactors is being conducted internationally as an energy source that can be a clean and renewable energy source.

In a fusion reactor, the energy is generated by collision of relatively light atoms as a fusion reaction. To enhance the reaction, it requires keeping high temperature plasma for the collision by some plasma confinement. However, this keeping necessary the high magnetic field. Due to this, the reaction can be stopped by lowing magnetic field suddenly and do not runaway and, the safety measures are relatively easy compared to nuclear fission.

The fuels considered for fusion power have all been light elements like the deuterium, and tritium in reactors. The deuterium and tritium reaction is $D + T \rightarrow He(3.5MeV) + n(14.1MeV)$ generates the neutron energy of 14.1MeV. The kinetic energy of the neutron produced by this reaction is converted into thermal energy and generate nuclear transmutation energy in divertor and blanket, and it is cooled by some coolants to keep integrity and safety of the equipment and finally convert thermal energy into electrical energy. Although the massive heat is retained by the fusion reaction place a load on divertor at the bottom of Tokamak fusion reactor by the divertor magnetic configuration as described in the following sections.

1.1-1 Reactor concepts

There are two concepts for plasma confinement to obtain a fusion reaction, those are an inertia confinement and a magnetic confinement for a thermonuclear plasma described below:

• Inertial confinement

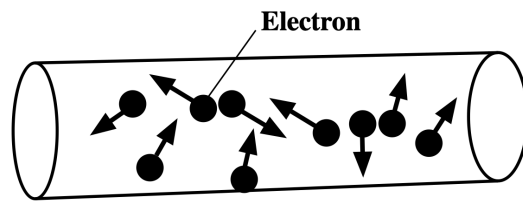
In an inertial confinement reactor, a tiny fuel pellet (typically 1 to 10 mm in diameter) as a solid sphere contained deuterium-tritium (D-T) would be compressed to tremendous density and temperature with focusing many lasers or charged particle beams (Hydrogen, Helium ,and particles from walls) [1], so that the fusion power is produced in the few nanoseconds before the pellet blows apart from a focus of lasers or beams. For efficient thermonuclear reaction, the time allotted for the pellet to react must be less than the disassembly time. This means that, in the compressed state, the product of the pellet mass density and the pellet radius must exceed about $3.00gcm^{-3}$ [2]. A high mass density will hasten the reaction, and a large radius will slow the disassembly time. The ratio of fusion energy produced in the pellet explosion to the driver energy is called a “pellet gain.” High pellet gains of 100 or more are required for an inertial confinement fusion reactor [3].

- **Magnetic confinement**

The most developed approach for plasma control is a magnetic confinement reactor. The plasma interacts with magnetic and electric field, so charged particles tend to spiral motion on a magnetic line (Larmor motion) as illustrated in Fig. 1-1. It is necessary that these particle trajectories do not intersect the bounding wall, that is the plasma-facing-components (PFCs). The thermal energy of all the particles exerts an expansive pressure on the plasma. For the plasma to be in equilibrium, the magnetic force acting on electrical current within the plasma must be balanced the pressure at every point in the plasma.

To confine the plasma by the magnetic field, there are two approaches have been devised and testes over the years: (1) Increasing magnetic field directed at the edge of linear system, because of the conservation of particle energy some plasma particles are forced to invert the particle motion at the time reached on the device. This is so called as “Mirror-phenomena” and the devices using as the plasma confinement are named as “Mirror-machines.” However, this confinement technique has a lack of the particle confinement performance [4]. Hence, another approach (2) has been proposed that the plasma is confined by the magnetic field like an around the torus. This is called as a “toroidal confinement” [4]. The toroidal magnetic field induces a toroidal electrical current. In this configuration, particles are transported as the combination of Larmor motion and a transverse drift motion due to the magnetic gradient [5]. This behavior makes the many collisions to the wall. To overcome this problem, it is required a poloidal magnetic field that makes the twist the magnetic field lines [6]. This confinement technique is used in Tokamak. The schematic illustration of the magnetic field and current field inside fusion reactor as illustrated in Fig. 1-2.

(a) No-magnetic field



(b) Magnetic field

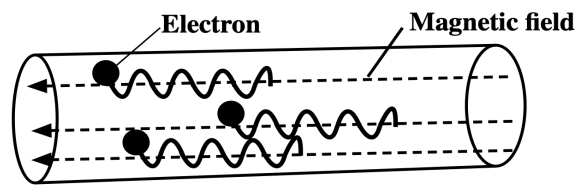


Fig. 1-1. Schematic illustration of charged particle behavior.

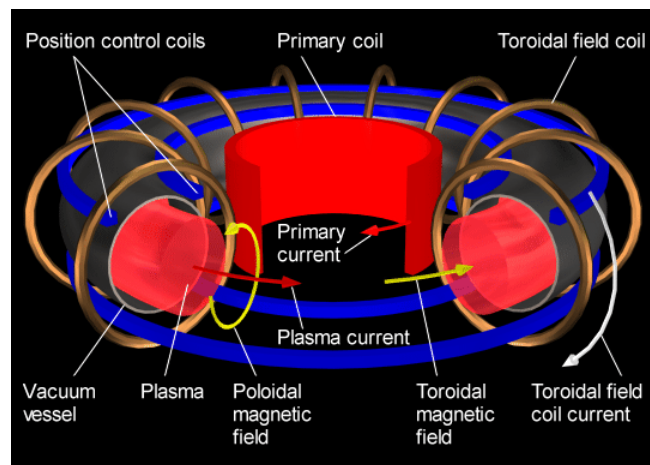


Fig. 1-2. Schematic illustration of magnetic/current fields in Tokamak [7].

1.1-2 Plasma-facing-components

The PFCs expose in a very harsh environment by high heat load and charged particle flux. An ideal characteristic of PFCs must be able to remove deposited energy efficiently and no-effect to the plasma. Mainly three devices are proposed:

- **Limiter:** This is one of the structures for inducing plasma-material-interaction in order to protect coils and some diagnostics in the magnetic confinement reactor. Plasma is bounded by a material limiter inside the vessel, so the high energy particles from the hot plasma along the magnetic field impinge directly on the limiter. However, the limiter configuration has become less important because the divertor configuration as described below has proved to be more favorable for good plasma confinement [6].
- **Divertor:** The outer poloidal magnetic lines are open and directed towards toroidal direction symmetric regions named “divertor target plates.” This device performs better than the limiter. Particularly, it makes possible to be a high confinement plasma regime so-called as “H-mode.” [6] The divertor system must withstand against the extremely high heat loads and particle fluxes in the tokamak, and for these reasons, it’s design/the choice of materials are fundamental for guaranteeing the operation of tokamak properly. The detail description of divertor is on Section 1.2.
- **First wall:** The first wall of the blanket is facing to a plasma and to protect the magnet coil structures and the vacuum vessel. In addition, the blanket is an energy conversion device that is responsible for heat exchange by thermonuclear reaction energy to the electric power generation.

The highest heat loading plasma facing devices is divertor, therefore, it needs to develop an efficient heat removal technique. This study is focused on the fundamental cooling method for the liquid divertor concept and to improve the cooling performance.

1.2 Divertor concepts

In fusion reactors, the core plasma must be high purity for keeping high temperature due to the enhancement of thermonuclear reaction [6, 8]. The engineering solution for this problem is a divertor magnetic configuration [6, 9, 10] and makes it possible to have

high confinement of plasma regime. Although the amount of impurities can be reduced by this configuration, the impurities are generated by the interaction with walls including limiters introduced on above, so-called as "plasma-wall-interactions." [11, 12, 13]. In addition, helium ash and electrically charged un-reacted fuel particles generates in the fusion reactions [14], are transported by magnetic field. Finally, they deposit to the divertor surface. Therefore, the function of divertor requires a particle control for keeping high purity of plasma by directing the charged particles along the lines of the magnetic force to the exhaust port by a crossing magnetic field configuration, so-called a "Separatrix" in Fig. 1-1. [6, 15].

Regarding the function of divertor, the charged particles on the divertor surface lose their charge when they deposit on the divertor surface and generate neutral gas [6, 10]. This charge exchange induces the energy conversion from the kinetic energy of the particles to the heat [16, 17]. In this conversion, the massive heat load is generated in the case of neutron irradiation [17]. For example, steady-state heat loads on most stressed PFCs of divertor in ITER (International Thermonuclear Experimental Reactor) will be on the order of 20.0MWm^{-2} , and for the transient edge localized modes unsteady state heat load could generate beyond 1.0GWm^{-2} in about 0.50ms. Under such extremely high heat loads, the surface temperature may over the melting or vaporizing temperature point. Detail descriptions for the characteristic of divertor types are described in following sections.

1.2-1 Solid divertor

The solid divertor concept uses a solid material withstanding the extremely high heat load as a divertor wall described in section 1.2. The power-handling and lifetime constraints compete against one another in solid material PFCs candidates such as graphite or tungsten. The thickness of the solid PFCs must be thin because of the conductive thermal impedance to the underlying coolant channels. In addition, the effect of particle and neutron flux, PFCs decreases the lifetime due to the erosion and a plasma

disruption that the plasma rapidly quenches and deposits large amounts of energy in a very short time. For handling PFCs for appropriate operation, tungsten PFCs have been studied to degrade over the time-scale of seconds to hours in fusion environments, resulting in ‘fuzz-growth’ or ‘blistering’ [16, 18, 19]. The concern is that this ‘fuzz’ can easily become detached from the PFCs and become a contaminant to the fusion plasma, where it could disrupt the core plasma. In contrast, studies for graphite as PFC show the transport of carbon to the core of plasma due to the sputtering effect [16]. To solve these problems, many studies are being conducted.

1.2-2 Gaseous divertor

The gaseous divertor design was first proposed in Princeton Reference Reactor design in 1974 [20]. The principle of this divertor design is based on the interaction of the plasma at the separatrix and a high density cold natural gas. In other words, plasma particles, momentum, and energy are dissipated by injecting the inert neutral gas such as Ar or Ne before touching the wall. Due to this interaction, the heat flux can be redistributed over a large surface area by plasma-neutral collisions [20, 21].

1.2-3 Liquid divertor

The liquid divertor has been considered that the heat removal technique improves based on heat transfer by using liquid film-flow rather than heat conduction in solid (so-called as "Inertia cooling"). The schematic concept of the liquid divertor is shown in Fig.1-3. Due to high heat load/radiation and high particle flux, the free-surface of liquid divertor is exposed to such harsh environment, but this concept using liquid covering the divertor surface is useful to protect the walls (so-called as “Self-healing feature”) besides of the high heat removal.

The thermal performance of the film-flow depends on the flow velocity. There are two options for the liquid divertor: (1) the high temperature fluid transports to the downstream reservoir with high velocity and is cooled there by other cooling system. This

system is called as “fast-flow divertor”, and (2) the high temperature fluid transports to the downstream reservoir with slow velocity, eventually the divertor wall must be additionally cooled by some other method. This system is called as “slow-flow divertor”.

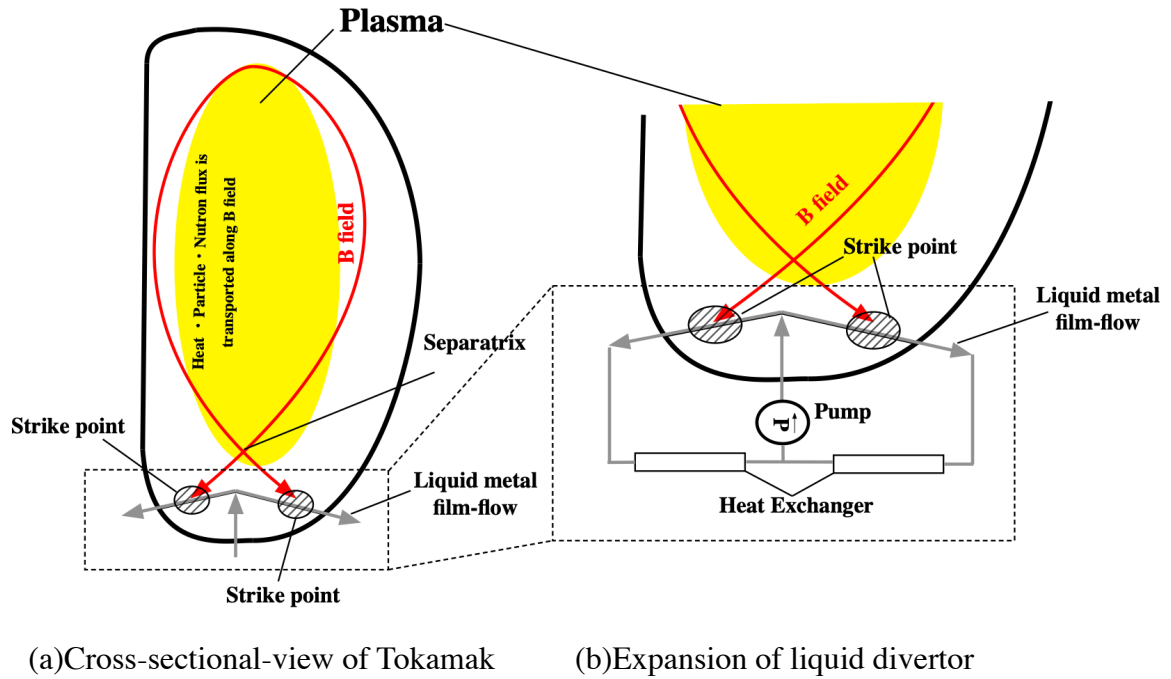


Fig.1-3. Double plate liquid divertor concept for Toakamak.

In case of the fast-flow divertor system, it requires a high-power pump producing high flow rate and high pressure because of the heavy coolant such as liquid metal, so it raises an economical problem for sustainable operation. In addition, there is concerned for the energy balance that the generating energy and the input energy for the circulation. Therefore, the slow-flow divertor system such as the film-flow cooling is suitable for the liquid divertor. However, there are still several problems. First, the liquid metal interacts with the presence of strong magnetic field in the reactor. This is called “Magnet-Hydro-Dynamic (MHD) effect.” One of the major characteristics of MHD flow is the flow velocity suppression by Lorentz force which is the result of interaction between the induced electrical current and the magnetic field. The velocity suppression leads a

laminarization of turbulent flow and the resulting heat transfer deterioration. The detail descriptions of the fundamental phenomenon of MHD effect on the liquid metal flow is described in Section 1.3. Second, the evaporation of the liquid film-surface is a problem when the high heat load is localized on the free-surface. The heat load on the free-surface causes the temperature stratification inside the liquid metal film-flow, thus it makes temperature rise of the fluid near the free-surface gives rise to the evaporation. To reduce the surface temperature of the liquid divertor of PFCs, “thermal mixing enhancement” in the film-flow must be required.

From mentioned above, desirable features of the working liquid for PFCs on liquid divertor are listed below, and also tabulated in Table 1-1:

- 1 . Low melting temperature
- 2 . high evaporation temperature
- 3 . Low density for less pump power
- 4 . High heat removal characteristics
- 5 . Minimal chemical reactions to the wall materials
- 6 . Minimize MHD effect
- 7 . Low cost for materials and operation

To minimize the MHD effect, the candidate material should be chosen the low electrical conductivity. However, it can be considered that MHD effect has a possibility to use effectively for thermal mixing enhancement described in section 1.4.

Table 1-1. Characteristics of liquid PFCs candidates [22, 23, 24].

	Lithium(Li) at 320°C	Lithium-lead(Li-Pb) at 320°C	Tin(Sn) at 280°C	Gallium (Ga) at 60.0°C
Melting point [°C]	180.9	273	231.9	29.8
Evaporation temperature [°C]	1342	2602	2602	2403
Density [kg m ⁻³]	530.0	9450	6990	5980
Chemical reaction with water	Generate H ₂	Oxidation	No	Oxidation
Chemical reaction with solid	No	Dissolution of Ag	No	No
Thermal conductivity[Wm ⁻¹ K ⁻¹]	47.6	22.6	66.8	40.6
Electrical conductivity [Sm ⁻¹]	3.20× 10 ⁶	3.87× 10 ⁶	7.10× 10 ⁵	9.10× 10 ⁶
Kinetic viscosity [m ² s ⁻¹]	8.64× 10 ⁻⁷	2.10× 10 ⁻⁷	1.15× 10 ⁻⁶	1.53× 10 ⁻⁷
Cost	Expensive	Normal	Cheap	Expensive

To minimize the MHD effect, the candidate material should be chosen the low electrical conductivity. However, it can be considered that MHD effect has a possibility to use effectively for thermal mixing enhancement described in section 1.4.

1.3 MHD effect of the liquid metal flow

The behavior of an electrical conducted fluid flow under the magnetic field has been studied for many years. For the cooling, heat exchange and fuel breeding for the fusion reactor, the liquid metal is the most appropriate candidate. The concept is widely developing to the blanket, divertor, and first-wall. However, the liquid metal is strongly affected by the magnetic field as MHD effect due to the high electrical conductivity of fluids. Here, the basic behavior of liquid metal flow under the magnetic field is described.

1.3-1 Governing equations

In following contents includes analytical methods of MHD to derive physical parameter for experiments and numerical simulations. Magnet-hydro-dynamics condition is defined by a magnetic Reynolds number $Re_m = \sigma \mu_m u_0 L \ll 1$ in which σ is electrical conductivity of the working fluid, μ_m is magnetic permittivity, u_0 is flow velocity as an absolute value of the flow velocity vector $\mathbf{u}$ and L is a characteristic length. The definition of the magnetic Reynolds number describes on Subsection 1.3-2 dimensionless parameters. For all experiment in this study, $Re_m \ll 0.01$. Suppose governing equations of liquid metal flow under the magnetic field, Navier-Stokes equation, Ohm's law, Maxwell equation can be expressed as

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{j} \times \mathbf{B} \quad (1.1)$$

$$\mathbf{j} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \quad (1.2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1.3)$$

$$\nabla \times \mathbf{B} = -\mu_m \mathbf{J} \quad (1.4)$$

$$\nabla \cdot \mathbf{B} = 0, \quad \nabla \cdot \mathbf{u} = 0 \quad (1.5)$$

where, ρ is a density of the fluid, p is a pressure, μ is a viscosity, $\mathbf{j}$ is a current density, $\mathbf{B}$ is a magnetic field and $\mathbf{E}$ is an electrical field. The magnetic field includes an external magnetic field $\mathbf{B}_0$ and an induced magnetic field $\mathbf{B}_{in}$ by the induction theory as linearly $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_{in}$. However, an induced magnetic field is less than an external magnetic field in this study. Thus $\mathbf{B}_{in}$ was neglected.

1.3-2 Dimensionless parameters

The dimensionless parameters in the fluid dynamics are possible to evaluate as the specific results of experimental scaling to understand generally. To derive dimensionless

parameters for evaluating the results in this study, terms of governing Equations can be used. To suppose following transformations,

$$u \rightarrow u_0 \mathbf{u}^*, t \rightarrow \frac{L}{u_0} t^*, p \rightarrow \rho u_0^2 p^*,$$

$$\mathbf{E} \rightarrow u_0 B_0 \mathbf{E}^*, B_0 \rightarrow B_0 \mathbf{B}^*, j \rightarrow \sigma u_0 B_0 \mathbf{j}^*$$

$$\nabla \rightarrow \frac{1}{L} \nabla^*, \frac{\partial}{\partial t} \rightarrow \frac{u_0}{L} \frac{\partial}{\partial t^*}$$

in which, u_0 is an averaged flow velocity, L is a characteristic length, and asterisk means dimensionless variable. Eq. (1.1) can be deformed by using above transformations,

$$\frac{\partial \mathbf{u}^*}{\partial t^*} + (\mathbf{u}^* \cdot \nabla^*) \mathbf{u}^* = -\nabla^* p^* + \frac{1}{\text{Re}} \nabla^{*2} \mathbf{u}^* + N \mathbf{j}^* \quad (1.6)$$

where $\nu = \mu/\rho$ is a kinetic viscosity. The physical meaning of Reynolds number is a ratio of internal and viscous term, $\text{Re} = u_0 L/\nu$. Reynold number is the most important dimensionless parameter for distinguishing the flow conditions as turbulent or laminar. At high Reynolds number, the non-linear term domestics the dynamics of the flow, leading to turbulent motion. On the other hand, the viscous term dominates on the flow dynamics as laminar, smooth fluid motion. In the MHD condition, there are a few parameters for evaluating the electrically conducted fluid flow. Interaction parameter is one of them, it means the ratio of the electromagnetic force term to the inertial force term, $N = \sigma L B_0^2 / \rho u_0$. This ratio is also called ‘‘Stuart number.’’ As the interaction parameter increases in proportional to the square of the strength of the magnetic field which means the induced Lorentz force increases. This Lorentz force directs towards the anti-flow direction works as the suppression to the flow circulation. To against this prevent force, it should be increased the inertial force as increasing Reynolds number to enhance

turbulent. The interaction parameter for liquid divertor and the blanket concept of ITER and DEMO could be in the range of 10^3 to 10^5 by the presence of the magnetic field over 5.0T [25, 26]. Another MHD dimensionless parameter is Hartmann number. The Hartmann number is defined as the ratio of the electromagnetic force term and the viscous force term,

$$\text{Ha}^2 = \frac{\sigma B^2 L^2}{\mu u_0} = \text{N} \cdot \text{Re} \quad (1.7).$$

At divertor magnetic configuration, Hartmann number would be extremely large as 4.00×10^3 . Let us consider the effect of an induced magnetic field inside the liquid metal flow under the imposed external magnetic field. From Eqs. (1.2), (1.3) and (1.4), the time derivative of the magnetic field can be formed as,

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{\sigma \mu_m} \nabla^2 \mathbf{B} \quad (1.8)$$

which is called the magnetic diffusion equation. Eq. (1.8) deforms the dimensionless equation similar to the Eq. (1.6),

$$\frac{\partial \mathbf{B}^*}{\partial t^*} = \nabla^* \times (\mathbf{u}^* \times \mathbf{B}^*) + \frac{1}{\text{Re}_m} \nabla^{*2} \mathbf{B} \quad (1.9)$$

where $\text{Re}_m = \sigma \mu_m u_0 L$ is a magnetic Reynolds number due to the similarity of Reynolds number. This is the ratio of magnetic diffusivity term to advection term. If the advection term smaller than the diffusivity term ($\text{Re}_m \gg 1$), the diffusion of the magnetic field is negligible and similar to the vorticity Eq. of complete fluid. Conversely, at the low magnetic Reynolds number ($\text{Re}_m \ll 1$), the magnetic diffusivity is the dominant situation.

The magnetic field permeates the fluid on timescales much shorter than those associated with the flow dynamics, suggesting that the induced fields caused by the motion of the fluid are weak compared to the background field. In case of the liquid metal $Re_m \approx 0.01$.

1.3-3 Effect of Lorentz force

One of the general behaviors of MHD liquid metal flow is a velocity suppression by induced Lorentz force inside the bulk. In this subsection, the mechanism of the velocity suppression is introduced.

To suppose an electrically conducting wall duct channel and the wall insulation duct. The main difference for MHD liquid metal behavior of two ducts is the induced electrical current density inside the wall. This induced current makes the Lorentz force $\mathbf{j} \times \mathbf{B}$, thus the relationship between $\mathbf{j}$ and $\mathbf{B}$ decides the strength of the force. In the case of the current parallel to the magnetic field is ineffective. In contrast, the vertical relation generates the maximum $\mathbf{j} \times \mathbf{B}$. Additionally, the behavior is depending on the electrical properties of the wall material. At the conducting wall, the current difference generates near the walls. This could affect to the spanwise velocity distribution as changing from the parabolic distribution to the M-shape [27, 28, 29]. On the other hand, a trapezoidal shape distribution is made due to the constant current density in case of insulation duct [28, 29, 30]. From these behaviors, the current density affects the heat transport performance. In this study, all experiments and numerical simulations are insulation walls and the top wall as the free-surface because that there is no side-wall in liquid divertor.

Regarding to the boundary layers of the flow inside the circular and the duct flow, the Hartmann number is important for evaluating the thickness of boundary layers. As discussed in any fluid dynamics text, fluids passing over a solid surface will develop a layer where the fluid velocity transitions from the free-stream velocity to the no-slip boundary condition at the surface [31]. In hydrodynamic flows, the thicknesses of these boundary layers are typically a function of the Reynolds number such as Blasius solution

$\delta \approx \sqrt{\text{Re}}$ for laminar, $\delta \approx L/\sqrt{\text{Re}}$ for turbulent. As increases Reynolds number, the thickness of the boundary layer decreases because of the inertial force can overcome the viscous drag on the wall efficiently. In case of MHD duct flow which is similar like in this study, the wall perpendicular to the external magnetic field called as Hartmann wall have a thickness of boundary layer different from the ordinary flow condition. It is proportional to the Hartmann number like $\delta_H \approx 1/\text{Ha}$. In contrast, the wall parallel to the field has a boundary layer thickness $\delta_s \approx 1/\sqrt{\text{Ha}}$ called as the side-layer.

1.3-4 MHD vortex damping

In turbulent flow, the flow fluctuations are induced by near the shear on the boundaries and create tiny eddies. These eddies play essentially important role to increase the heat transfer. In general, the eddy size decrease with increasing Reynold number, forming an energy cascade process. The injected energy from the driving scale to the viscous scale dissipated to the heat in this process. However, an external injected magnetic field induces the electrical current inside the liquid metal, this phenomenon enhances the changing the form of eddies as an inverse cascade process. The detail descriptions below.

Before introducing the vortex behavior under the magnetic field, Joule dissipation should be introduced because that the injected energy has been removed as the mechanism of an inverse cascade. For simplicity, neglect the viscous forces and take the imposed magnetic field to be uniform. The liquid metal moved through under the magnetic field lines induces a current. By this current leads not only Lorenz force but also leading to Joule dissipation and the resulting rise in thermal energy is accompanied by a corresponding fall in kinetic energy. This is called Joule heating. Firstly, the scalar product the momentum Eq. by $\mathbf{u}$, that is

$$\mathbf{u} \cdot \left[\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) \right] = -\nabla p \cdot \mathbf{u} + (\mathbf{j} \times \mathbf{B}) \cdot \mathbf{u} \quad (1.10)$$

$$\frac{D}{Dt} \left(\frac{1}{2} \rho u^2 \right) = -\nabla p \cdot \mathbf{u} + (\mathbf{j} \times \mathbf{B}) \cdot \mathbf{u} \quad (1.11)$$

where $D/Dt \equiv \partial/\partial t + (\mathbf{u} \cdot \nabla)$. The last term of Eq. (1.10) can be given with using Ohm's law Eq. (1.2) as

$$(\mathbf{j} \times \mathbf{B}) \cdot \mathbf{u} = -\mathbf{j} \cdot (\mathbf{u} \times \mathbf{B}) = -\mathbf{j} \cdot \left(\frac{\mathbf{j}}{\sigma} + \nabla \phi \right) = -\frac{j^2}{\sigma} + \nabla(\phi \mathbf{j}) \quad (1.12)$$

using the relation between the electrical field and electrical potential ϕ as $\mathbf{E} = -\nabla \phi$, and used the divergence of current density $\nabla \cdot \mathbf{j} = 0$. To derive the relation to the Joule dissipation, we use Eq. (1.12) and integrate by the volume,

$$\frac{d}{dt} \int \frac{1}{2} \rho u^2 dV = -\frac{1}{\sigma} \int j^2 dV \quad (1.13)$$

Therefore, the joule dissipation leads the kinetic energy, E_k . This relation can be used for investigation of the vortex behavior under the presence of the magnetic field as describes below.

To bring out the tendency of eddy under the magnetic field, let us consider an angular momentum $\mathbf{\Gamma}(\mathbf{r}, \mathbf{z})$ inside a spherical vortex as illustrated in Fig. 1-4. Note that this derivation follows Chapter 5 of P.A. Davidson's book [28]. Axial gradients in $\mathbf{\Gamma}(\mathbf{r}, \mathbf{z})$ induce the poloidal motion by a centrifugal force. This motion makes the behavior as complex to the results. Here, the velocity field is defined as $\mathbf{u} = (0, \Gamma/r, 0)$ in the cylindrical coordination (r, θ, z) and the external magnetic field lies to the z direction. Due to the induced electrical current and the external magnetic field, the induced Lorentz force $\mathbf{j} \times \mathbf{B}$ was generated. The Lorentz force is equivalent to specifying that the magnetic damping time τ , it is much less than the inertial time scale

δ/u_0 . Since poloidal motion grows on a time scale of δ/u_θ , can be neglected up for times of order τ .

To the beginning from induced electrical current, Ohm's law Eq. (1.2) gives rise to the radial component of the current density, j_r . As based on this current, the electrical potential field $\phi(r, z)$ was established on the (r, z) surface. This allows the electrical current density $\mathbf{j}$ to form closed current paths to the (r, z) surface as illustrated in Fig. 1-4. Since $\mathbf{j}$ is solenoidal, and given as

$$\mathbf{j} = \nabla \times \left[\frac{\psi}{r} \mathbf{e}_\theta \right] = \left[-\frac{1}{r} \frac{\partial \psi}{\partial z}, 0, \frac{1}{r} \frac{\partial \psi}{\partial r} \right] \quad (1.14)$$

where, ψ is a stream function of the current and $\mathbf{e}_\theta$ is a unit vector of θ component. The Lorentz force can be given as

$$\mathbf{F} = \mathbf{j} \times \mathbf{B} = -\frac{j_r B}{\rho} \mathbf{e}_\theta = F_\theta \mathbf{e}_\theta \quad (1.15)$$

where, F_θ is the θ component of Lorentz force. In terms of the angular momentum $\mathbf{\Gamma}$, it can be used by Eq. (1.15) and $\mathbf{\Gamma}$ is

$$\mathbf{\Gamma} = \mathbf{r} \times \mathbf{F} = r F_\theta \quad (1.16)$$

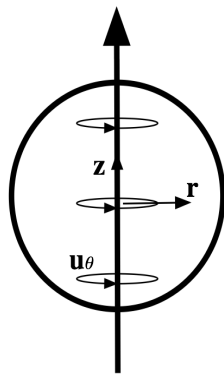
From Eq. (1.15), the magnitude of Lorentz force is negative in the core of the vortex, decelerating the fluid, and is positive above and below the vortex, inducing motion in previously quiescent regions. Finally, the angular momentum spreads to the magnetic field lines.

From Eq. (1.13), the time scale for dissipation can be estimated based on the curl of Ohm's law $\nabla \times \mathbf{j} = \sigma \nabla \times (\mathbf{u} \times \mathbf{B})$, firstly the current can be approximated as $j \approx \delta_c \sigma u B_0 / l_z$ in which δ_c is a characteristic length of the current, l_z is characteristic axial length based on the velocity gradient. From the energy relation Eq. (1.12), to derive dissipation time scale by

$$\frac{dE_k}{dt} = -\frac{1}{\sigma \rho} \int j^2 dV \approx -\frac{2\sigma \delta_c^2 B_0^2}{\rho l_z^2} E_k = -\frac{2E_k}{\tau} \left(\frac{\delta_c}{l_z}\right)^2 \quad (1.17)$$

where τ is defined as magnetic damping time as $\tau \equiv \rho / \sigma B_0^2$. This shows the energy exponentially dissipate with $\tau/2$. This Eq. can be deformed for derive the characteristics axial length as $l_z \approx \delta_c \sqrt{t/\tau}$. This suggests that the kinetic energy of the vortex declines as $\sqrt{t/\tau}$ and the shape of vortex like elongated to axial direction as illustrated in Fig. 1-5. Therefore, the vortex behavior under the magnetic field behaves as a vortex elongation on the magnetic field line and the rotational axis of the vortex allies with the magnetic field.

(a) No-MHD spherical vortex



(b) MHD spherical vortex

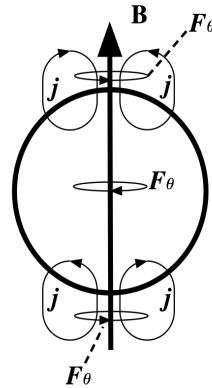


Fig.1-4. Schematic of behavior of the induced electrical current and Lorentz force inside the spherical vortex (F_θ is Lorentz force of θ direction component).

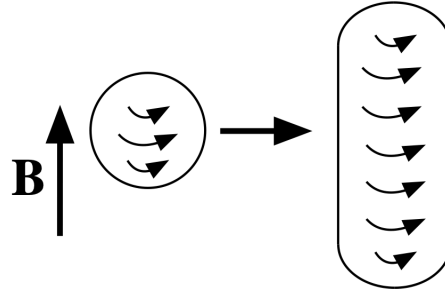


Fig.1-5. The vortex evolution direct toward to the magnetic field lines.

1.4 Thermal mixing enhancement

One of the thermal mixing enhancement methods is to install “obstacle as a vortex generator” on or near the heat transfer surface (free-surface and wall). The obstacle in the flow generates various characteristic vortices at the wake of various obstacles. Generally, the vortex enhances the flow fluctuation and induce the turbulent [32, 33]. This behavior can be utilized for thermal mixing enhancement in engineering equipment which is required the fluid mixing and thermal mixing [34].

The characteristic of the low Prandtl number fluids such as liquid metal forms the thick thermal boundary-layer near the heating position, it is generally known that the locally heated on the free-surface of liquid metal film-flow forms a temperature stratification structure. Thereupon, I conceived the obstacle to prevent the temperature rise in the liquid metal film-flow.

Based on these characteristics and experienced so far, it has a possibility to enhance thermal mixing by using optimum vortex generators for heat transport of the liquid divertor efficiently. Therefore, thermal mixing enhancement of liquid metal film-flow under the magnetic field required optimized shape/arrangement of obstacles. The diagram of the thermal mixing enhancement process on the liquid divertor which targeting this study is shown in Fig. 1-6. Next subsection, the vortex characteristic from three types of obstacles used in this study are introduced.

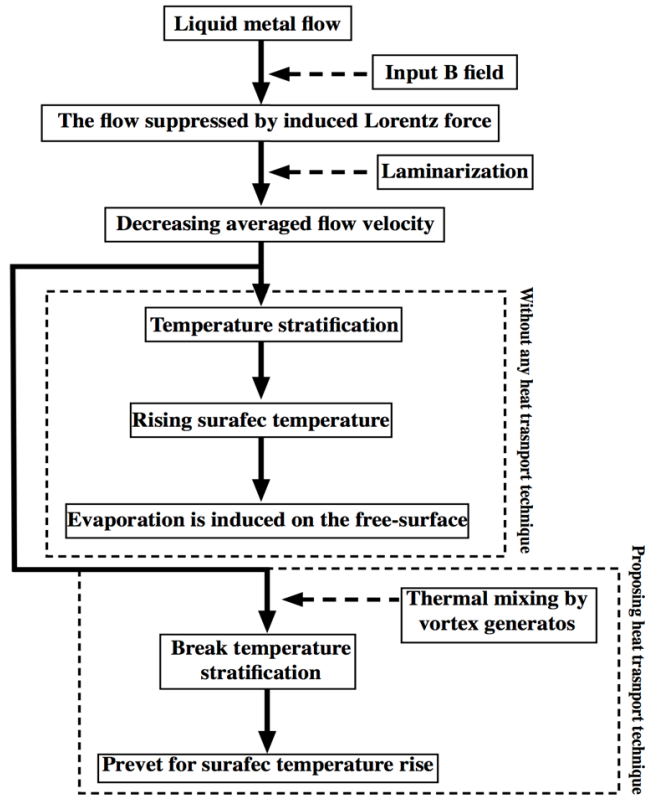


Fig. 1-6. Strategy for thermal mixing liquid metal film-flow for the heat removal technique of liquid divertor.

1.4-1 Cube

Generally, the vortex generated from the cube such as a Karman vortex, a horseshoe vortex, and an arch vortex [31, 35]. Schematic of vortexes around the cube as illustrated in Fig. 1-7 [35]. In case of Localized heated free-surface liquid metal film-flow, the heat transfer surface is located on the bottom-wall and the free-surface. Hence, the cube can be installed on the bottom-wall. However, the rotational direction of the Karman vortex is perpendicular to the free-surface and the wall and fluid mixing is enhanced in the spanwise direction. As I shall see later, the cube generates the horseshoe vortex and the arch vortex, it can be expected that the combination of these three types of vortexes enhances thermal mixing performance.

Apart from Karman vortex, the horseshoe vortex and the arch vortex are the candidate for thermal mixing enhancement for vertical heat transfer. The horseshoe vortex is generated near the bottom-wall and, the rotational direction towards the bottom-wall such as the suction flow, this flow structure likely to transport the fluid near the center of the bulk to the bottom-wall and enhance vertical thermal mixing. Moreover, the arch vortex is generated on the behind the cube. This vortex rotates on the plane of the streamwise/vertical direction as makes suction flow from the free-surface to the center of the bulk. If the horseshoe vortex still available even on the location of the arch vortex, there is likely to enhance heat transport from the free-surface to the bottom-wall by using these two types vortexes. In addition, the recirculation generates on the wake of the cube as illustrated in Fig. 1-7. This flow structure also transports the fluid from the free-surface to the bottom-wall. Therefore, these vortex structures can be enhanced heat transport liquid metal film-flow.

In the case of MHD, the rotational axis of the vortex is the key factor for thermal mixing enhancement. From the analytical section 1.3-4, the rotational axis parallel to the magnetic field enhances an angular momentum and increasing the size of the vortex. As regard to the vortex from the cube for the vertical heat transfer, the rotational axis of the arch vortex has the parallel relation under the transverse magnetic field, thence vortex size might be increased with increasing the strength of the transverse magnetic field. For the horse-shoe vortex, the rotational axis under the transverse or vertical magnetic field is perpendicular to the magnetic field direction. Generally, it can be considered that the rotation of the vortex decrease in this case by the vortex damping behavior. However, the following two cases of vortex behavior are estimated in this study based on previous studies.

- (1) The rotational axis of vortex which is perpendicular to the magnetic field damped with increasing the strength of the magnetic field as according to the theory. The damping scale of this study is 0.40s at the minimum. For example, the vortex survives

0.04m on the wake at the flow velocity 0.10ms^{-1} under 0.38T.

- (2) In the hypothesis, the vortex behavior in case of the vertical relation between the magnetic field direction and the rotational axis of the vortex, the axis is bent to the direction which is parallel to the magnetic field direction caused by conservation of the angular momentum [28]. The behavior of the vortex bending is illustrated in Fig. 1-8. The reason of this vortex bending is depending on a vorticity. To suppose, the rotational axis of vortex parallels to the flow direction constitutes the vorticity of streamwise direction and the vorticity of the vertical direction. Mück [36] investigated the vorticity behavior of Karman vortex on the wake of the cylinder under the vertical magnetic field numerically, he reported that the vorticity of vertical direction survives and the spanwise direction component is diminished under the vertical magnetic field. However, the rotational surface of the vortex is not completely perpendicular to the magnetic field direction due to the fluctuation or some physical influence in the real condition. This is to say; the vorticity may have all vorticity direction components. For example, even the relatively tiny spanwise direction vorticity is likely to be developed or survived under the transverse magnetic field by inverse cascade process. In contrast, the tiny vorticity of the vertical direction may be developed under the vertical magnetic field. The descriptions on here are illustrated in Fig. 1-8. In the process of vortex developing, vortex damping would be inducing simultaneously. Therefore, there is a possibility to induce vortex bending that is enhanced in case of the vorticity which has the rotational axis parallel to the magnetic field.

Both cases can be applied for the vortex from other obstacles not only the hemisphere. In case of (1), there are less thermal mixing performance than the case (2).

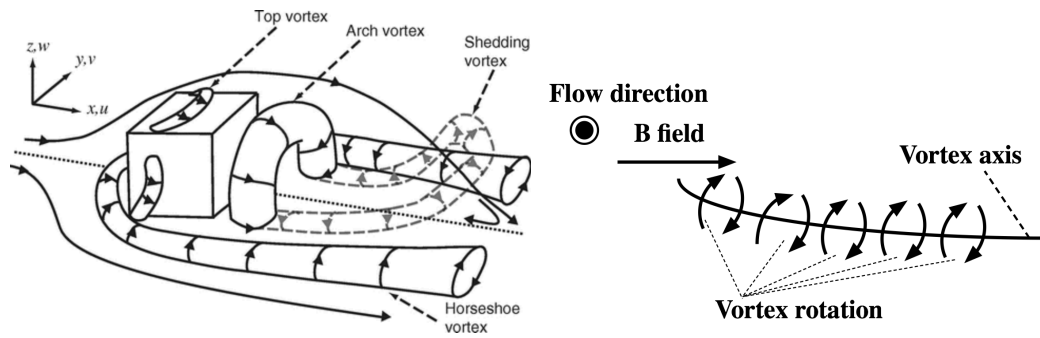


Fig. 1-7. The vortex surround the cube [35]. Fig. 1-8. The vortex bending behavior.

1.4-2 Hemisphere

The vortex generated from a hemisphere is similar to the vortex generated from the cube, and it forms the Karman vortex, the horseshoe vortex and the arch type vortex [37, 38]. Illustrated a vortex generated around the hemisphere in Fig. 1-9. In addition, hemispheres can be easily installed on the heat transfer surface and the effect of the drag force is lower than that of the cube and the delta-wing [39]. It is a highly realizable obstacle that can be installed on a liquid divertor. The drag force is acting opposite to the relative motion of any object moving with respect to a surrounding fluid. Note that the drag coefficient is a dimensionless quantity that is used to quantify the drag or resistance of an obstacle in a fluid. It is used in the drag equation in which a lower drag coefficient indicates the object will have less hydrodynamic drag. The drag coefficient of the hemisphere is 0.38, the cube is 0.80 in case of laminar. Therefore, the hemisphere is the highest possibility to appropriate technique for installing as a vortex generator.

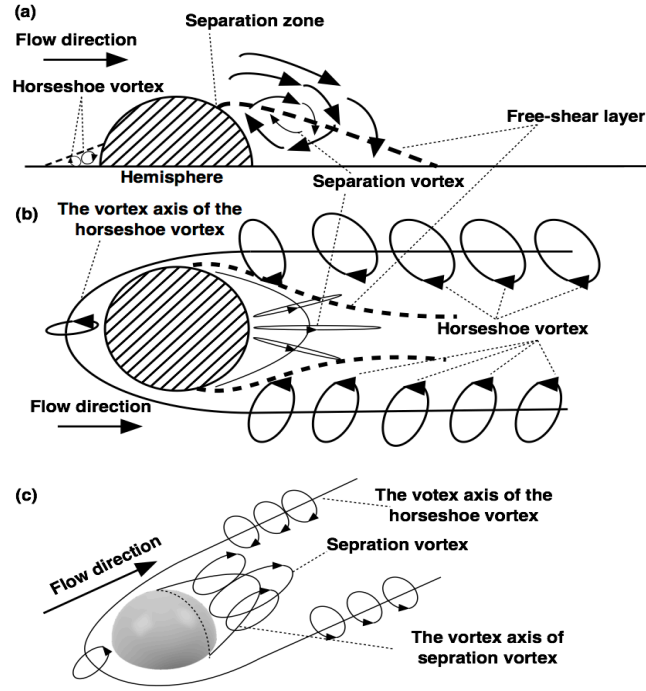


Fig. 1-9. The vortex around a hemisphere:(a) Cross-sectional view, (b)Top-view, (c) Whole-view.

1.4-3 Delta-wing

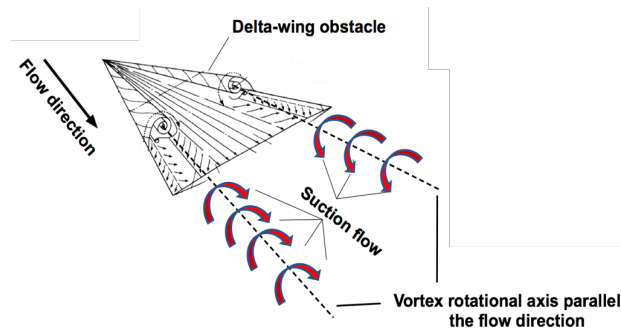
Thermal engineering has some studies aimed to improve heat transfer performance by installing delta-wings in the air flow [32, 33, 34]. However, the flow behavior of parallel relation of the rotational axis of a vortex and the flow direction in MHD case has not been investigated so far. In this study, I focused to understand the behavior of a pair of vortices from the delta-wing at the liquid metal film-flow under the magnetic field.

The vortex generated from the delta-wing are generated from the side edges of wings as shown in Fig. 1-10, it forms a pair of vortices having the rotational axis parallel to the flow direction on the wake. The rotational direction of this vortex enhances heat transport in a downward direction to the bottom-wall, forming a relatively strong suction flow compared to the vortex structure generated from the cube, and the hemisphere. The behavior of this vortex in case of MHD is decided by the relationship between the

rotational axis of the vortex and the magnetic field direction is a key point as described on above.

As an original hypothesis, the case (2) of subsection.1.4-2, the vortex from the delta-wing is likely to bend in the experiment under the transverse magnetic field. To evaluate this behavior, I have conducted spectral analysis of temperature data on the bottom-wall. In terms of the vortexes location, a pair of vortexes was occupied within the height of the delta-wing on each cross-section of the delta-wing wake. If the behavior of the bending vortex is induced, some signals might be outputted.

(a) Whole-view [40]



(b) The cross-sectional view from the downstream

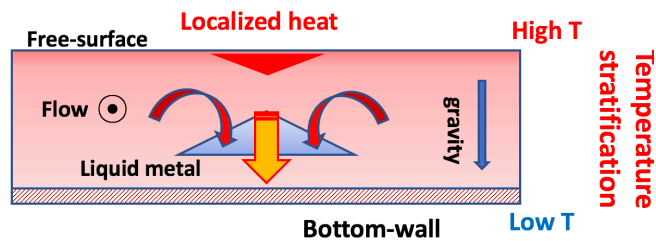


Fig. 1-10. The generated vortex from the delta-wing.

1.5 Objective of this study

From the above descriptions, high performance of the liquid divertor concept should be developed by using liquid metal film-flow. The objectives of this study can be summarized as follows:

- (1) Understanding the characteristic of the vortex behavior under the MHD flow condition.
- (2) Understanding the MHD effect on the thermal mixing.
- (3) Establishment of the fundamental database for the heat transport performance (thermal mixing) of the liquid metal film-flow under the magnetic field.
- (4) Based on (1), (2) and (3) on above, implementing of the cooling method for liquid divertor.

Therefore, I have conducted numerical simulations for understanding flow behavior inside the liquid metal film-flow. In addition, the locally heated liquid metal film-flow under the vertical parabolic and the transverse magnetic-field experiments have been conducted. Sections 1.5 and 1.6 introduce the objective of each numerical and experimental studies.

1.5-1 Numerical simulations

I focused on the fundamental MHD effect to the behavior inside the liquid metal film-flow. To propose that, the study should test suggestions. As concretely, this technical method is a vortex generator as introduced in Chapter 2 Numerical simulation. Here, some objectives of numerical simulations are describing below:

- (1) Determining the optimal shape and size of obstacles for the best performance of heat transport of MHD liquid metal film-flow.
- (2) Understanding the vortex behavior behind the obstacles in the liquid metal film-flow

with/without the magnetic field.

- (3) Investigating the effect of flow velocity distributions on thermal mixing with/without the transverse/vertical parabolic magnetic field.
- (4) Comparison with experimental results for understanding the heat transport characteristic.

1.5-2 Experiments

To understand the fundamental thermal mixing behavior of liquid metal film-flow with/without the transverse/vertical parabolic magnetic fields, temperature distributions by thermocouples and velocity distribution by potential probes have been measured. The main objectives of the experimental study were listed below:

- (1) Measuring the spatiotemporal temperature distributions behind various obstacles at the bottom-wall.
- (2) Measuring the temperature at the free-surface near the heater was measured.
- (3) Evaluating the heat transport performance by temperature analysis.
- (4) Try to measure the spanwise flow velocity distribution.

Chapter 2 Numerical Simulations

The numerical simulation of laminar MHD liquid metal film-flow under the magnetic field was conducted for the investigating the MHD effect to the heat transport by using various shapes and arrangements of obstacles. This chapter introduces the method of numerical simulation and results.

2.1 Introduction

One of the advantages of the numerical simulation is detail information of the fluid dynamics. In case of ordinary transparence fluid, it is possible to visualize or measure the flow structure and the velocity distribution by using some special technique PIV (Particle Image Velocimetry) or the photochromic dye activation technique combined with hot-wire anemometer [41]. However, the measurement technique for opaque liquid is quite difficult such as liquid metal. In addition, the specific physical characteristic of the liquid metal such as the high electrical conductivity of the liquid metal, the chemical reaction, and the relatively large specific gravity makes difficult to conduct the experiment. Thus, the numerical method can give some physical phenomenon of difficulty handling fluid behavior. In this study, I had focused on the understanding of thermal behavior, vortex behavior and flow velocity distribution for enhancement of the thermal mixing/heat transport performance of the localized heated free-surface of the MHD liquid metal film-flow. Therefore, it is necessary for understanding flow behavior and finding the optimum method for the thermal mixing enhancement.

The numerical works concerned about in this chapter bellows:

- (1) For understanding flow behavior, the vortex behavior affected by MHD should be considered.
- (2) To find an optimized shape obstacle, the temperature at the bottom-wall and the vorticity must be simulated.

- (3) For the estimation of method of the best heat transport performance, the best performance of heat transport should be proposed.

The laminar numerical model with using finite volumetric simulation technique “Stream package” was used in this study. The reason for using this model is the typical MHD effect that the flow velocity decreasing due to the induced Lorentz force inside the bulk under the transverse/vertical magnetic field. This effect can be approximated as the laminar condition. The laminar model is essentially the same in terms of the behavior of the flow velocity.

In section 2.2, governing equations were introduced. In section 2.3, a numerical model, boundary conditions and numerical results in case of a uniform transverse magnetic field are introduced and discussed. In section 2.4, some numerical results in case of the vertical parabolic magnetic field are presented and discussed. Finally, section 2.5 was described summaries.

2.2 Governing equations

Continuity equation:

$$\nabla \cdot \mathbf{u} = 0 \quad (2.1)$$

Momentum equation:

$$\rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho g \beta (T - T_0) + \mathbf{j} \times \mathbf{B} \quad (2.2)$$

Ohm's law:

$$\mathbf{j} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \quad (2.3)$$

Electrical current continuity:

$$\nabla \cdot \mathbf{j} = 0 \quad (2.4)$$

Energy conservation:

$$\frac{\partial(\rho c_p T)}{\partial t} + \nabla \cdot (\mathbf{u} \rho c_p T) = \nabla \cdot (k \nabla T) + Q_{Heater} + Q_{Joule} \quad (2.5)$$

where $\mathbf{u}$ is flow velocity, p pressure, μ is dynamic viscosity, $\mathbf{j}$ is electrical current density, T is the fluid temperature, T_0 is the fluid temperature at the inlet of the numerical model, Q_{Heater} is an injected heat power on the free-surface and Q_{Joule} is a joule heating in the test channel. Q_{Heater} and Q_{Joule} were used as same as the experimental condition such as $Q_{Heater} = 91.9\text{W}$ and $Q_{Joule} = 3.18\text{W}$. Combining Eqs. (2.3) and (2.4), the Poisson's equation of electric potential can be deduced as

$$\Delta \phi = \nabla \cdot (\mathbf{V} \times \mathbf{B}) = \mathbf{B} \cdot (\nabla \times \mathbf{V}) \quad (2.6)$$

where $\mathbf{V}$ is an averaged flow velocity vector.

The simulations are focused on fully developed flows. It means that the velocity profile in the film flow does not vary in the numerical test channel. The test channel is placed in three different magnetic field configurations:

$$\text{Transverse magnetic field : } \mathbf{B} = (0, 0, B_0) \quad (2.7)$$

$$\text{Vertical parabolic magnetic field : } \mathbf{B} = (0, 0, B(x, y)) \quad (2.8)$$

The vertical parabolic magnetic field referred to the magnetic field in Fig. 2-19 and it is depending on the span wise coordination. The boundary conditions of this simulation described in each model.

2.3 Uniform transverse magnetic field

2.3-1 Numerical model

The numerical domain was modeled similarly to test channels of LMX (Liquid Metal eXperiment locates on Princeton Plasma Physics Laboratory, USA) illustrated in Fig. 2-1. A heater was installed on the top-wall for localized heated on free-surface to simulate the local heating on divertor surface, the size of the heater was chosen as 0.075m×0.025m. An enlarged view of the numerical model of Fig. 2-1(a) shows a cross-sectional area which is n mm downstream of the obstacle. This area means that the vorticity distribution on this plane as introduced later. The magnetic field was injected as a perfectly uniform transverse magnetic field. To simulate film-flow, the velocity boundary condition of the top-wall set as a free-slip condition and a no-slip condition on walls except top-wall. The material of the wall was assumed as acrylic resin as a perfectly electrical insulated wall. The obstacles were installed under the heater as same as the experiments, the shapes are chosen as a delta-wing, a cube, a hemisphere, and an inline hemisphere arrangement. To find the optimized size for the experiment, the blockage ratio has chosen three different ratios, that is, 4.00% 8.00% and 10.0% in case of installing a single obstacle. The definition of blockage ratio is given by $\beta = d/W$ where d is diameter or equivalent length as diameter as illustrated in Fig. 2-2. The symbolic length of obstacles illustrated in Fig. 2-2 and these values are listed in Table 2-1. The reason for choosing the maximum blockage ratio as 10.0%, the top of the delta-wing exceeds the depth of the film flow and tip appear on the free-surface. In addition, an attack angle θ was chosen as 20°. There are two reasons for $\theta = 20^\circ$: (1) The fluid height of the experiment can be conducted within 15.0mm. If large θ of the delta-wing installed at the bottom-wall, the top of the delta-wing was likely to be exposed over the free-surface due to the high surface tension of the liquid metal and thin thickness of the film-flow. (2) According to Rediniotis [42], the angle over $\theta = 30^\circ$ generates the Karman vortex and relatively high friction coefficient. Based on the comparison of vortex characteristic from the cube, it was inappropriate for comparison. Considering the

significance of the feasibility and experimental condition, $\theta = 20^\circ$ was optimal for this study. Meanwhile, there is not discussed for finding an appropriate height of obstacles because of this numerical simulation does not consider the effect of a behavior of the free-surface fluctuations. For finding the appropriate height, I will discuss the experimental results in Chapter 3. The constant flow rate was applied on the inlet of the numerical model based on the experimental conditions for actual application to liquid divertor. To simulate the flow velocity near the wall, it is strongly depending on mesh size. Thus, the thickness of boundary-layer should be considered. The thickness of Hartmann layer δ_H which is the duct wall perpendicular to the external magnetic field and the side layer δ_S which is the duct wall parallel to the magnetic field is given by [28]

$$\delta_H \sim \frac{1}{Ha}, \quad \delta_S \sim \frac{1}{\sqrt{Ha}}. \quad (2.9)$$

The calculation results in case of this study, $\delta_H \sim 1.62\text{mm}$, $\delta_S \sim 38.2\text{mm}$ at the maximum strength of the transverse magnetic field. To satisfy this thin thickness, it should be used the mesh size of this numerical simulation was chosen as $0.10 \times 0.30 \times 0.10\text{mm}^3$ in all simulation conditions. The working fluid in this experiment was used GaInSn alloy at room temperature 20.0°C , the physical properties of GaInSn were listed in Table 2-2 and these values were used in the numerical condition.

The following assumptions are made for simplicity:

- (1) The flow is in the steady state under the magnetic field.
- (2) The working fluids properties are constant such as density, dynamic viscosity, electrical conductivity, and permeability and thermal conductivity.
- (3) The constant film depth 8.00mm for gravitational direction.
- (4) The induced magnetic field b_{ind} is negligible because of low magnetic Reynolds number $R_m \sim 0.01$.

- (5) The inlet and outlet of the test channel were eliminated in the numerical model.
- (6) The heater size was integrated for comparisons.
- (7) There is no consideration because of Joule heating is much smaller than the heat from the heater in the experimental condition.
- (8) The numerical model was chosen as a laminar model due to the flow condition on the bulk can be approximated as laminar by the flow velocity decreases.

Numerical conditions of reference/a single obstacle cases were referred to the experimental conditions in this study as describes in Chapter 3, Table 2-3 shows the numerical conditions.

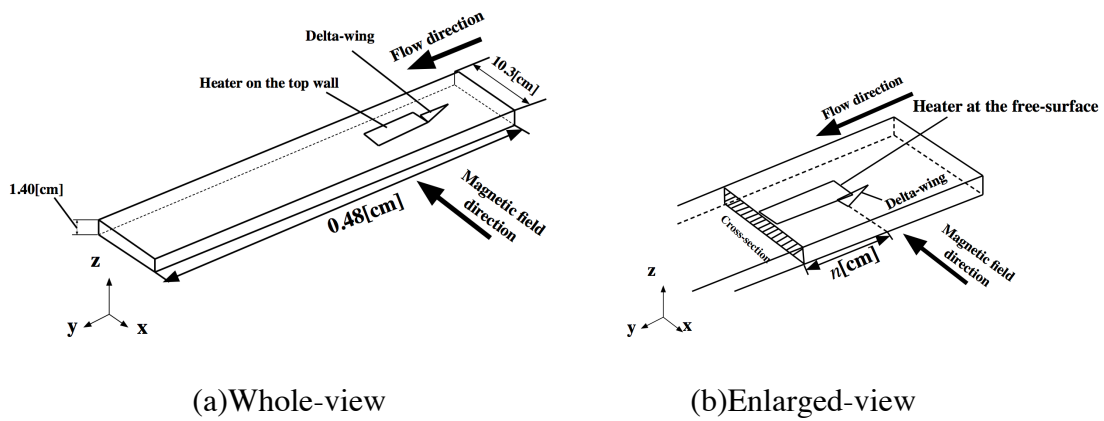


Fig.2-1. The numerical model in case of the delta-wing.

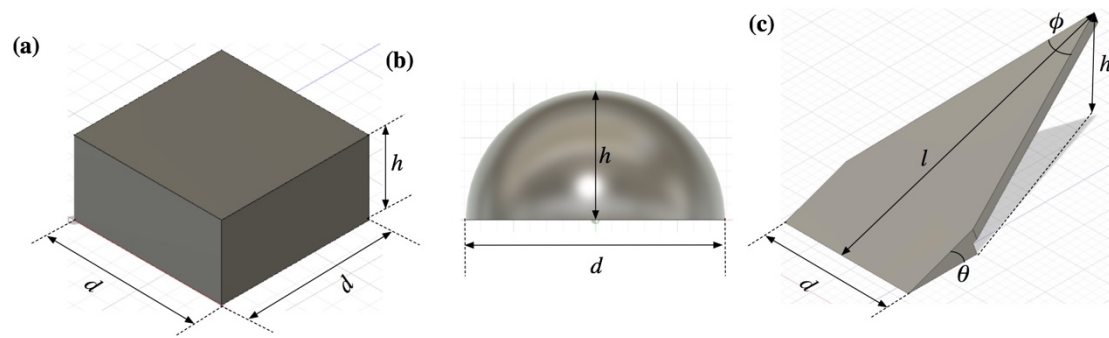


Fig. 2-2. The symbolic length of obstacles: (a) cube, (b) hemisphere, (c) delta-wing.

Table 2-1. The size of obstacles of each blockage ratio (All dimensions are mm).

	Cube			Hemisphere			Delta-wing		
Blockage ratio	4%	8%	10%	4%	8%	10%	4%	8%	10%
d	4.00	8.00	10.0	4.00	8.00	10.0	4.00	8.00	10.0
h	4.00	4.00	4.00	2.00	4.00	5.00	10.3	10.3	10.3
l							30.1	30.1	30.1
θ							20.0	20.0	20.0
ϕ							10.0	20.0	25.0

Table 2-2. The physical characteristic of GaInSn eutectic alloy [48].

Physical Properties	Value
Thermal conductivity [Wm^{-2}]	16.5
Electrical conductivity [Sm^{-1}]	3.60×10^6
Viscosity [m^2s^{-1}]	2.98×10^{-7}
Melting point [$^{\circ}\text{C}$]	10.5
Boiling point [$^{\circ}\text{C}$]	1.30×10^3
Specific heat [$\text{Jkg}^{-1}\text{C}^{-1}$]	295

Table 2-3. Numerical conditions for the simulation under the uniform transverse magnetic field in case of installing a single obstacle.

Reynolds number [-]	1150
Interaction parameter [-]	0-10.0
Mesh size [mm^3]	$0.1 \times 0.3 \times 0.1$
Obstacle shapes	Cube, Hemisphere, Delta-wing
Boundary condition at the top wall	Free-slip condition
Boundary condition except the top wall	No-slip condition
Working fluid	$\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$
Heater power [W]	120
Fluid depth [mm]	14.0

2.3-2 Boundary conditions

As mentioned above, the velocity boundary condition of the top-wall of the test channel set as a free-slip condition for assuming the free-surface, a no-slip condition has been used on walls except the top-wall.

The boundary conditions of electrical potential and electrical current are defined by the electric conductivity and wall thickness described by Shercliff [30] so-called “thin wall assumption”. This assumption introduces the conductance ratio c , defined as $c = \sigma_w \delta_w / \sigma L$, where σ_w is electric conductivity of the wall and δ_w is the thickness of the wall. The conductance ratio affects the flow velocity via an electrical potential field. In this study, the experiment was made by an electrically insulated material acrylic resin as electrical conductivity between 10^{-17} and 10^{-15} at the room temperature, it can be approximated as zero-conductivity for the insulated wall for simplifying calculated in this numerical simulation. Therefore, the conductance ration of this study is given as $c = 0$ and there was no consideration of the thin wall assumption.

To specify the thermal boundary condition at the wall of the numerical model, a thermally insulated condition was defined because that the measurement technique of the experiment used TCs for measuring the liquid temperature near the bottom wall directly and it is not considering the heat conduction of the wall. The heat flux definition q_w in the numerical simulation can be calculated from the bulk temperature of the working fluid T_{b_n} and temperature at the wall T_{w_n} as $q_w \equiv -k(T_{b_n} - T_{w_n})/(H/2)$ in which H is the depth of the fluid. Note that, T_{b_n} is the temperature at $H/2$ and the function of the streamwise coordination. Moreover, the efficiency of heat transport was defined for understanding the actual performance of heat transport from the free-surface to the bottom-wall of the channel due to that measurement technique. The efficiency of heat transport γ was defined as

$$\gamma = \frac{|q'_w|S}{\rho u_0 c_p (T_{out} - T_{in})} \times 100 \quad (2.10)$$

where $|q'_w|$ is $(-q_w + |q_w|)/2$, S is an area of $q_w > 0$, Q_{in} is an input heating power from the localized heated of the free-surface, c_p is a specific heat of GaInSn, T_{out} is a temperature at the outlet of the channel and T_{in} is a temperature at the inlet. Similarly, the same definition of heat flux was used in the experiment.

2.3-3 Flow under non-magnetic field

This section describes some numerical results. The results of a reference case show the numerical results without the magnetic field and comparison of results with using a single various shape obstacle installed at the center of the bottom-wall as Fig. 2-1 for detecting the optimized size. The installed obstacle was chosen as a cube, a hemisphere, and a delta-wing. The word of a “reference case” was defined as the experiment in case of an absence of obstacles. To understand the heat transport mechanism, the vorticity distribution was simulated. All numerical results in this subsection will be referred to the LMX experiment as describes in Chapter 3.

The relation between the efficiency of heat transport and the blockage ratio of each obstacle in the case of the non-magnetic field shows in Fig. 2-3. The obstacle configurations as referred to the Table 2-1. Comparison of the numerical results of the efficiency of heat transport, 10.0% blockage ratio of the delta-wing shows the highest, the second is 8.00% blockage ratio of the delta-wing, the third is 10.0% blockage ratio of the cube. Therefore, this result proposed the delta-wing of 10.0% blockage ratio is likely to enhance thermal mixing in liquid metal film-flow. From this, the result of the numerical simulation used obstacles of 10.0% blockage ratio.

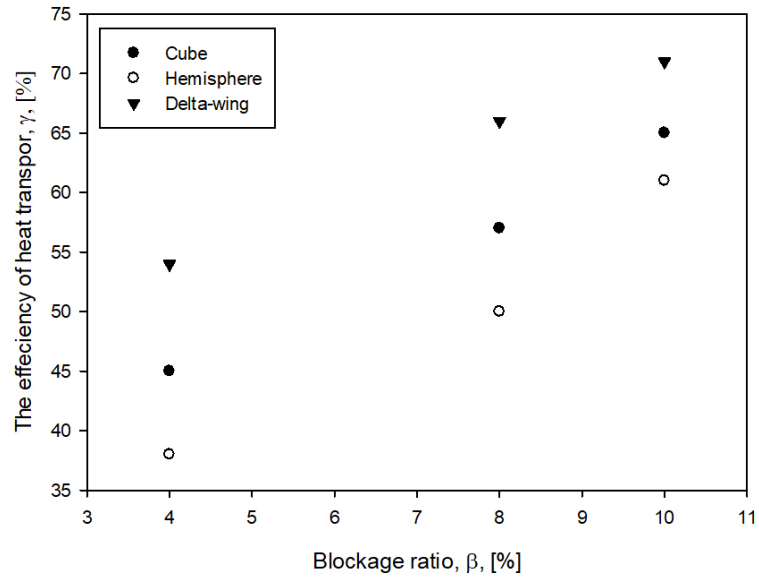


Fig. 2-3. The relation between the efficiency of heat transport and the blockage ratios in case of non-magnetic field.

Figure 2-4 shows temperature distributions at the bottom-wall without the magnetic field for $Re=1150$ in case of installing 10.0% blockage ratios of a cube, a delta-wing, and the flow in case of an absence of obstacle. From the comparison of these distributions, the temperature distributions in case of the delta-wing were higher than any other cases. Moreover, obstacles could be enhancing transport the high temperature fluid from the free-surface to the bottom-wall. Therefore, installing obstacle is one of the technique for thermal mixing enhancement of localized heated free-surface of the liquid metal film-flow.

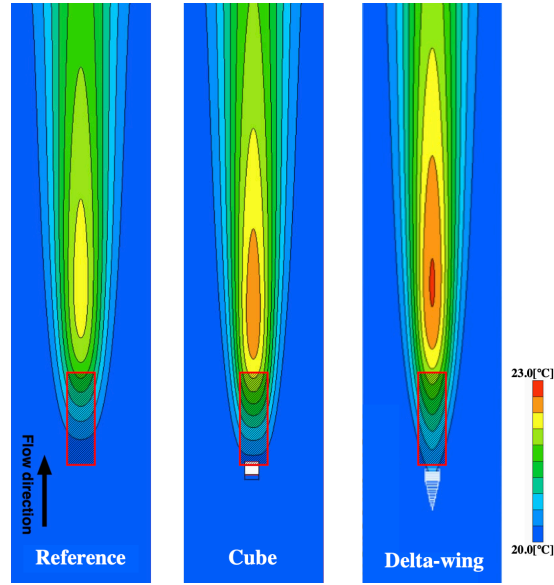


Fig. 2-4. The bottom-wall temperature distributions in case of 10.0% blockage ratio of obstacle without the magnetic field ($B_0=0T$) at $Re=1150$ (Red box shows the location of the heater at the free-surface).

The thermal mixing and vortex behavior can be considered that deep relation. Due to this, suppose vorticity transport equation,

$$\frac{\partial \boldsymbol{\omega}}{\partial t} = \nabla \times (\mathbf{u} \times \boldsymbol{\omega}) + \nu \nabla^2 \boldsymbol{\omega} \quad (2.11)$$

$$\boldsymbol{\omega} = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \begin{pmatrix} \partial u_z / \partial y - \partial u_y / \partial z \\ \partial u_x / \partial z - \partial u_z / \partial x \\ \partial u_y / \partial x - \partial u_x / \partial y \end{pmatrix} \quad (2.12)$$

It is the rotational component of the flow velocity. Based on this equation, the vorticity behavior was simulated. For (1), the reason of this behavior, the delta-wing forms the strong downward flow (called as “suction flow” hereafter) by a pair of vortices on wake from the results of vorticity distributions. The distributions of the vorticity of the flow direction ω_y of each obstacle on 1.00cm, 5.00cm and 10.0cm behind the obstacle are shown in Fig. 2-5, note that the distributions on the cross-sectional area which is the

distance from the obstacle as referred from Fig. 2-1(b). ω_y indicates the rotational component of the flow velocity as mathematical form $\partial u_y / \partial x - \partial u_x / \partial y$, namely the strength of the suction flow. The high $|\omega_y|$ was distributed in case of the delta-wing. In contrast, less vorticity was simulated in case of the cube and the reference. This is because that the characteristic of the vortex generated from the cube is different as introduced in Chapter 1. In addition, there were no simulated such as the horseshoe vortex in this simulation, this indicates that the simulation requires further fine mesh to simulate the horseshoe vortex. For the vertical heat transport enhancement, the delta-wing is likely to enhance inside the liquid metal film-flow from the free-surface to the wall under the non-magnetic.

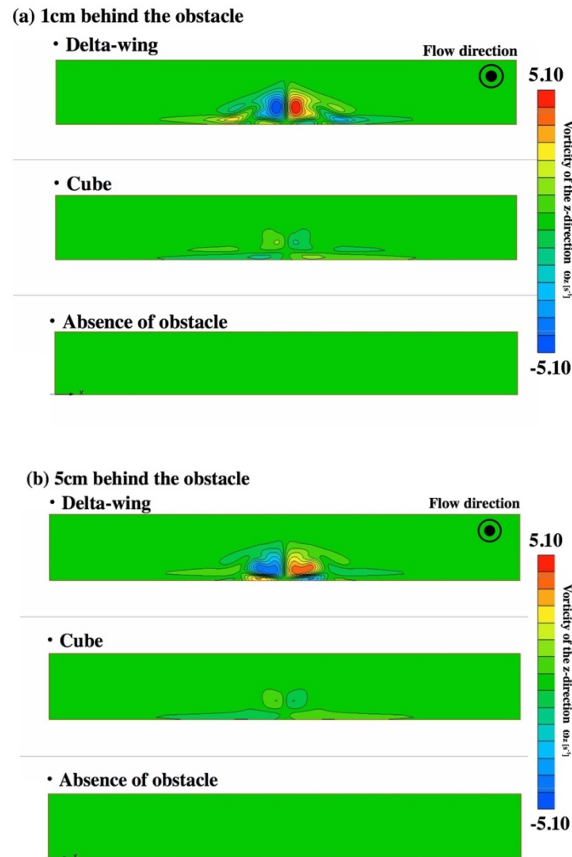


Fig. 2-5. The vorticity of the streamwise direction distributions of each obstacle shapes in case of 10.0% blockage ratio.

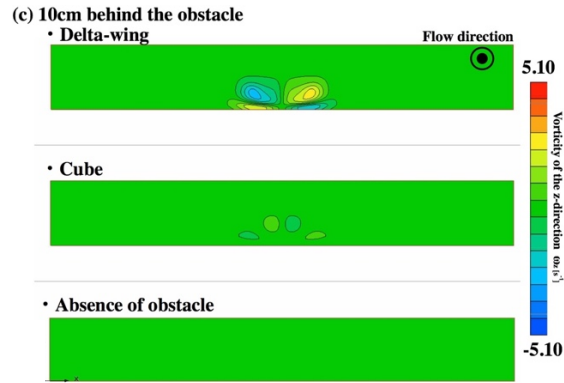


Fig.2-5 (Cont.)

2.3-4 Effect of a single obstacle

Figure 2-6 shows the temperature distributions under the various interaction parameter in case of various single obstacles. The tendency of temperature at the bottom-wall was decreased with increasing the strength of the transverse magnetic field and, the flow with installing the delta-wing shows the highest temperature at the bottom-wall. This is to say, installing the delta-wing can be enhanced thermal mixing in comparison with an absence of obstacle and the flow with installing the cube even under the transverse magnetic field. The reasons for this behavior can be considered as following descriptions.

One of the reasons of the behavior of the decreasing temperature at the bottom-wall, that the changing of the streamwise flow velocity distribution over the depth affected to the heat transport mechanism under the relatively high N . Figure 2-7 shows the streamwise flow velocity distribution over the depth in case of an absence of obstacle under the $N=0.00$ and $N=10.0$ at the center of the test channel. Note that the streamwise flow velocity distribution was divided by the averaged flow velocity due to easy to compare the distribution shape. The flow velocity near the free-surface was the fastest and the velocity on the bulk was suppressed at $N=10.0$ by the effect of the transverse magnetic field. According to Molokov [43], the streamwise flow velocity distribution of the electrically conducted fluids under the transverse magnetic field forms that the

localized velocity near the free-surface faster than the velocity on the bulk under very high N . The same tendency was simulated in this study. This is because that the Lorentz force is not induced near the free-surface by the side-layer effect. Due to this behavior, it can be considered that localized heated high temperature fluid near the free-surface has been transported to the further downstream of the test channel by the relatively high velocity, this behavior affected to the decreasing temperature at the bottom-wall. In contrast, the velocity distributions over the depth under the parabolic vertical magnetic field is completely different from the case under the transverse magnetic field, such as the flow velocity is suppressed near the free-surface by the induced Lorentz force ($\mathbf{J} \times \mathbf{B}$) similar like the bulk of this magnetic configuration. The detail descriptions describe the next section.

The electrical current density and potential distributions on the cross-sectional area of the numerical model under the transverse magnetic field under $N=10.0$ in case of an absence of obstacles were shown in Fig. 2-8. The vertical relation $\mathbf{J} \perp \mathbf{B}$ under the transverse magnetic field existed on the center of the bulk. This relation induces locally the maximum Lorentz force directed to the opposite of the flow direction. Thus, this gives rise to the flow distribution shape as described above. Due to this, the decreasing temperature at the bottom-wall with increasing the strength of the transverse magnetic field. Therefore, I estimated the liquid metal film-flow under the transverse magnetic field in case of an absence of obstacles makes heat transfer deterioration.

Besides the behavior of induced Lorentz force, another reason of decreasing temperature can be considered that the effect of the vorticity on the wake of the delta-wing in Fig. 2-9. The tendency of the vorticity and the interaction parameter is decreasing vorticity with increasing N . Particularly, the vorticity of the flow direction existed on 10.0cm behind the delta-wing in all interaction parameter range, this result means that the suction flow survived even under the relatively high strength of the transverse magnetic field. Therefore, this flow makes enhancement of heat transport performance.

Figure 2-10 gives the relationship between the efficiency of heat transport and interaction parameter for the flow in case of each obstacle. All cases rapidly decreased with increasing the strength of the magnetic field and coverage to $\gamma \sim 20.0\%$ at comparatively high N . In other words, this behavior means the heat transport was suppressed on the relatively low N range by the transverse magnetic field rapidly then it archived the constant heat transport performance on the relatively high N . The efficiency of heat transport of the delta-wing shows the highest under all N cases. The reasons for this behavior can be considered as followings;

- (1) The relatively high flow velocity near the free-surface transported the high temperature fluid to the downstream of the test channel caused by MHD effect and free-slip condition on the top-wall of the test channel.
- (2) Decreasing of the flow velocity leads the heat transport deterioration under high N .
- (3) The delta-wing generates a pair of vortexes even under high N .

For (1) and (2), the fluids near the free-surface in case of the relatively high strength magnetic field was streamed to the downstream of the test channel more than the fluid in case of the relatively low strength of the transverse magnetic field; then the relatively high temperature fluids near free-surface transported to the downstream of the channel and remain heat near free-surface. However, the thickness of the side-layer δ_s was formed as thin thickness under the high strength of the magnetic field from Eq. (2.9). This means that an area of the comparatively high flow velocity near the free-surface may change to thin. Based on this behavior, it can be considered that a part of high temperature fluid was transported to the bulk beyond the side-layer. Therefore, it is required which heat transport mechanism largely affected the liquid metal film-flow under the transverse magnetic field.

For (3), it can be considered that the delta-wing is useful for increasing the performance of thermal mixing for liquid metal film flow under the transverse magnetic field. All of the results mentioned above indicated the delta-wing is likely to enhance thermal mixing.

Based on above descriptions, one of the candidates for an optimized shape obstacle to enhance thermal mixing liquid metal film-flow under the transverse magnetic field should be chosen that, the characteristic of the vortex generator has a forming of a strong suction flow towards the bottom wall for break the relatively high flow velocity near the free-surface on the wake of the vortex generator.

(a) No obstacle

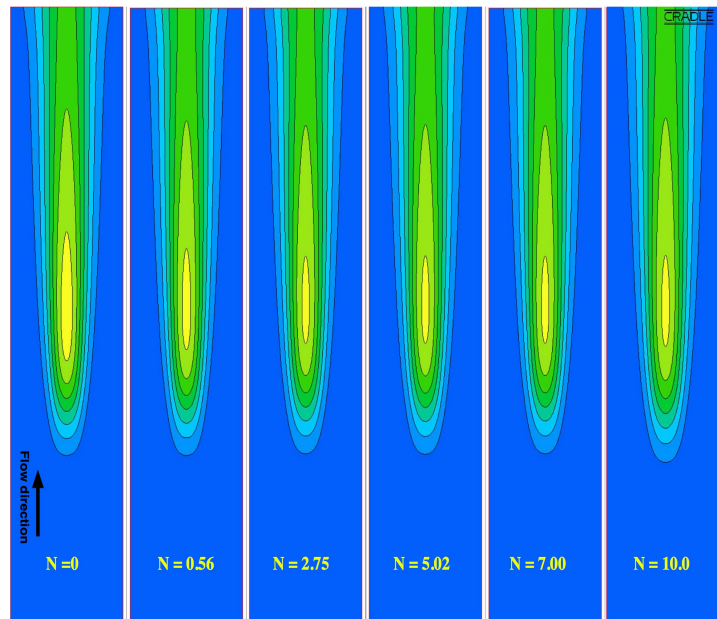
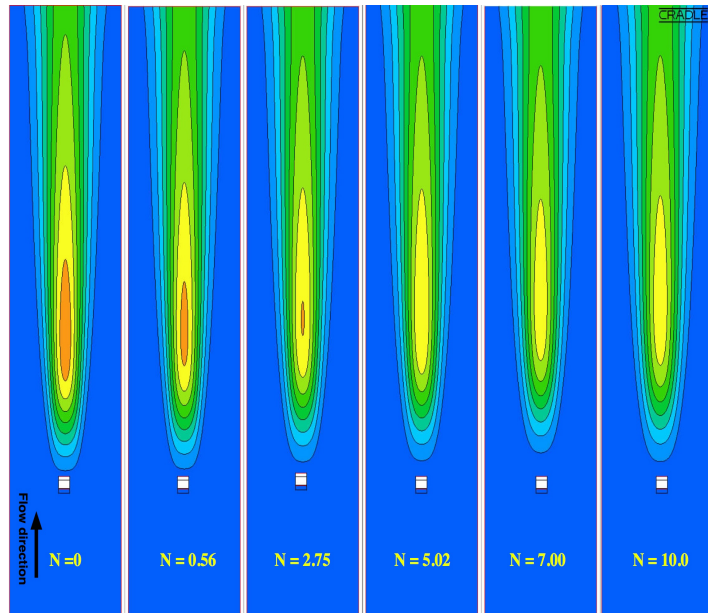


Fig. 2-6. The bottom wall temperature distribution under the various $N=0.00$ to 10.0 of the transverse magnetic field.

(b) Cube



(c) Delta-wing

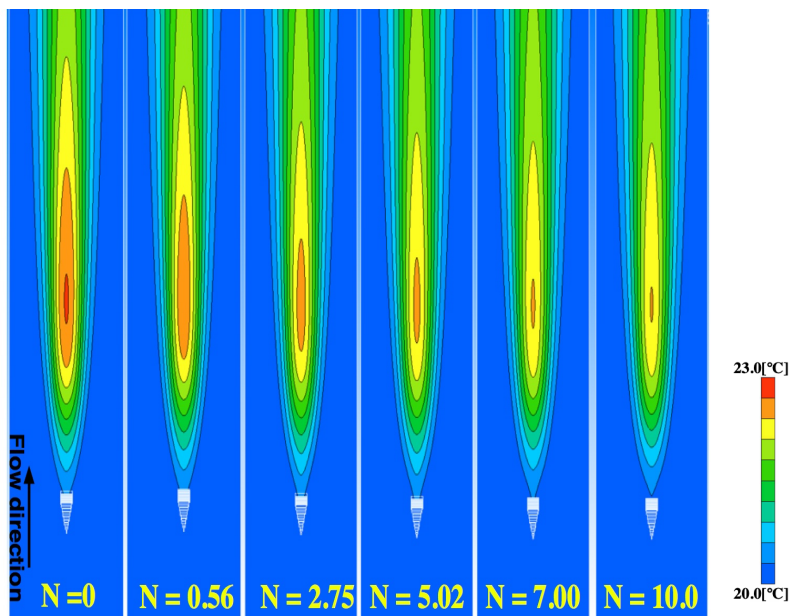


Fig. 2-6 (Cont.)

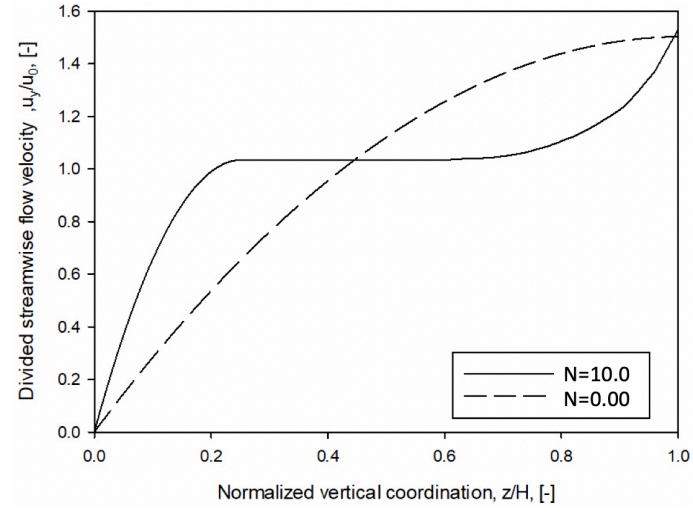


Fig. 2-7. The divided streamwise flow velocity distribution over the depth under the $N=0.00$ and $N=10.0$ of the transverse magnetic field in case of an absence of obstacle at the center of the channel.

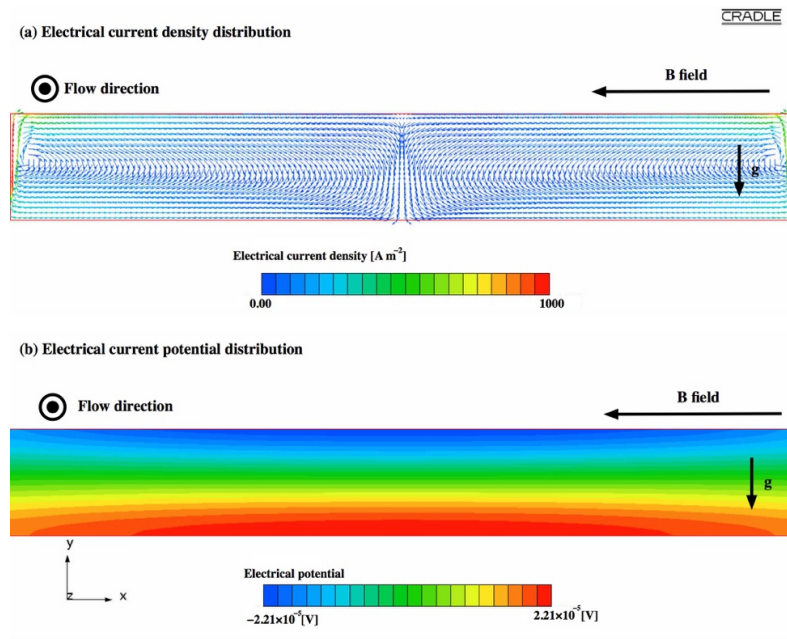


Fig. 2-8. The induced electrical current density and potential field distribution on the cross-sectional area under $N=10.0$ of the transverse magnetic field in case of an absence of obstacle.

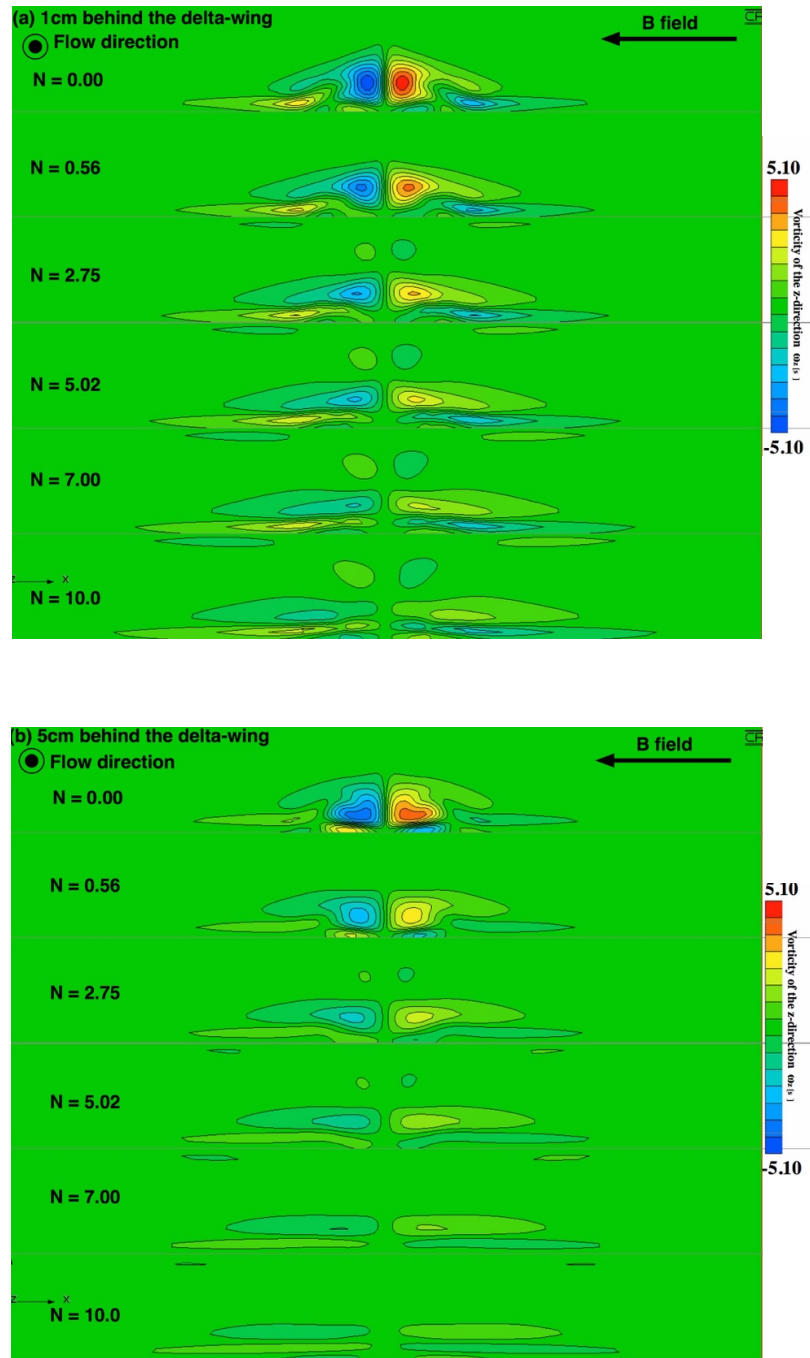


Fig. 2-9. The vorticity of the flow direction ω_y on the cross-sectional area on the behind the cube under and the delta-wing on various N .

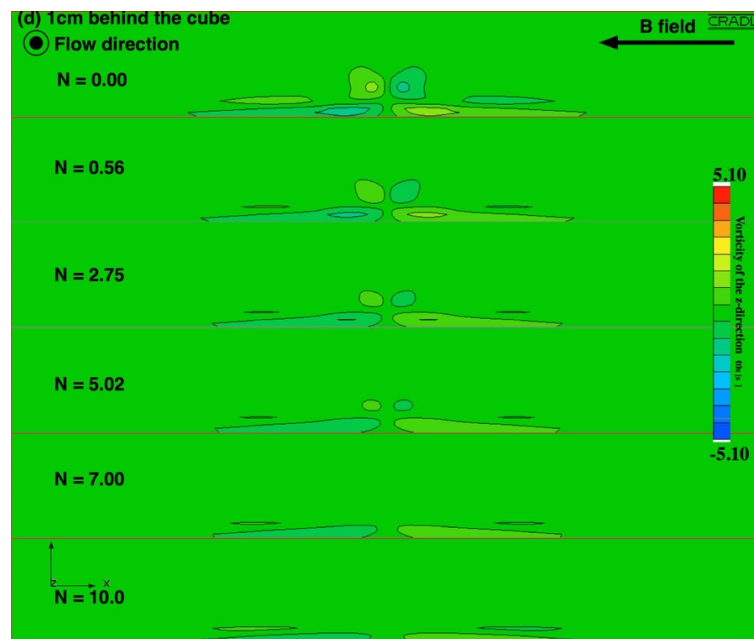
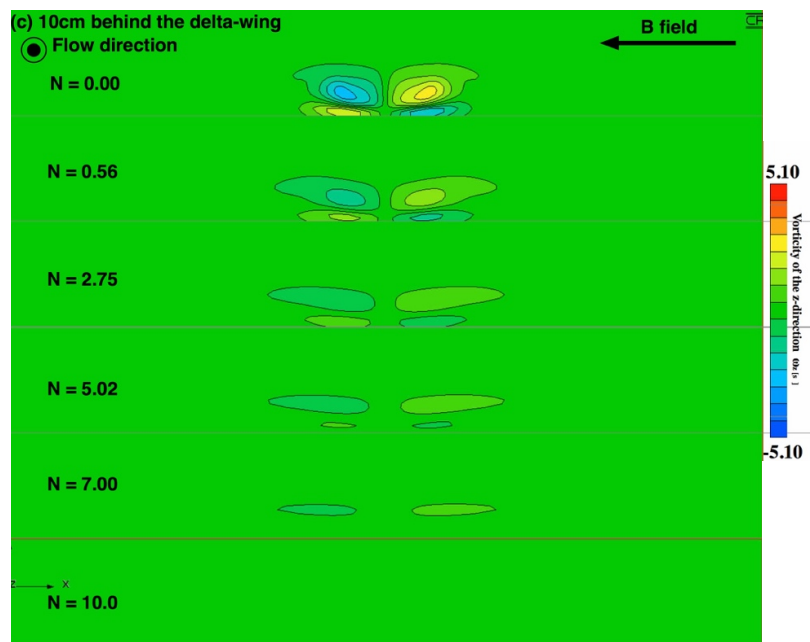


Fig. 2-9 (Cont.)

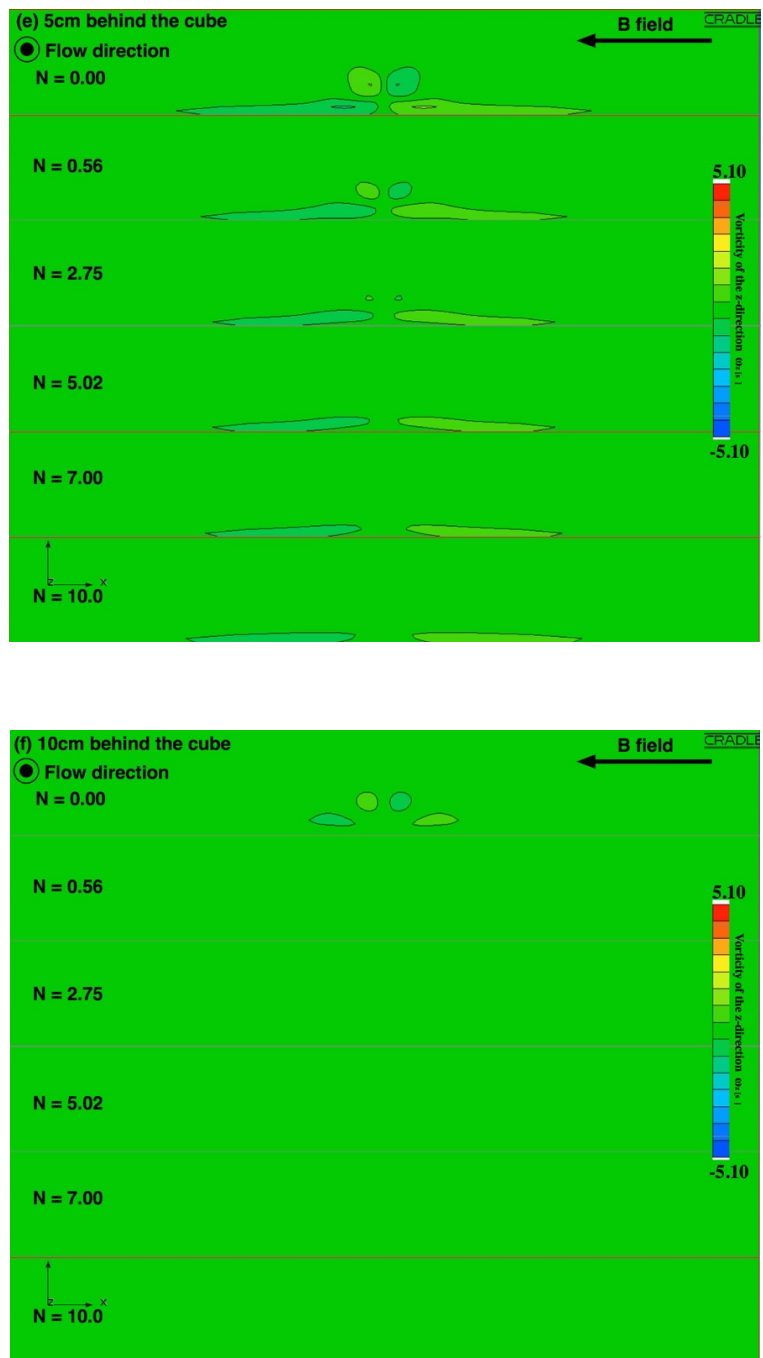


Fig. 2-9 (Cont.)

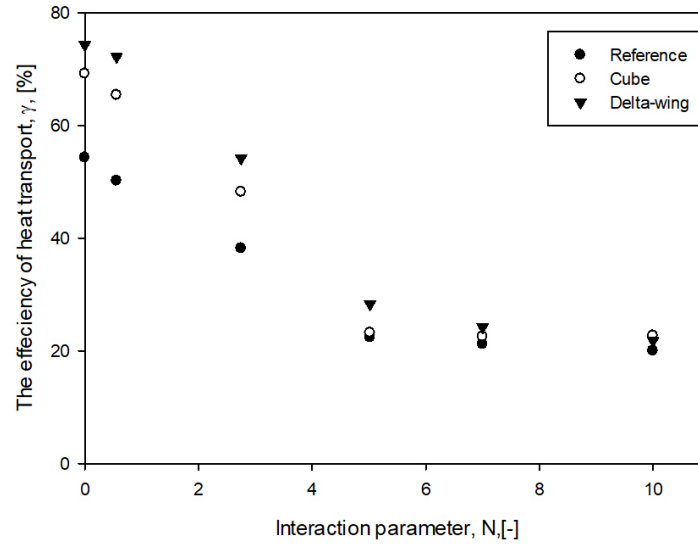


Fig. 2-10. The relationship between the efficiency of heat transport and interaction parameter under the transverse magnetic field in comparison for three different single obstacles.

2.3-5 Effect of inline hemisphere arrangements

In terms of the engineering applicability, obstacles as vortex generators for thermal mixing enhancement must be considered that a fragility, a corrosion, installing easily etc. From the hydrodynamic points of view, a fragility relates to a drag force on any obstacles [39, 44, 46]. Although the drag force is increased by installing the obstacles, an increasing the drag force can be suppressed by an optimum shape of the obstacles and the obstacle arrangement. The hemisphere is the one of low drag coefficient obstacle which is depending on the flow conditions and the fluid properties [45,46]. In addition, a hemisphere obstacle is easy to install rather than the delta-wing. Hence, the numerical simulation in case of installing an inline hemisphere arrangement was conducted.

The numerical model and conditions of this configurations are similar to the previous single obstacle case. Fig. 2-11 shows the top-view of the numerical model of an inline hemisphere arrangement under the transverse magnetic field. The numerical simulations were conducted three different streamwise-pitch-length and a constant

spanwise-pitch-length. A streamwise-pitch-length and a spanwise-pitch-length were defined on Fig. 2-11, that is the distance of the horizontal or flow direction between the center of the hemisphere. From the divertor configuration, there are not available any side-walls. Due to satisfy this, the numerical simulation with installing many obstacles should be installed a half-size hemisphere as illustrated in Fig. 2-11. Table 2-4 shows the configurations of streamwise-pitch-length and numerical conditions.

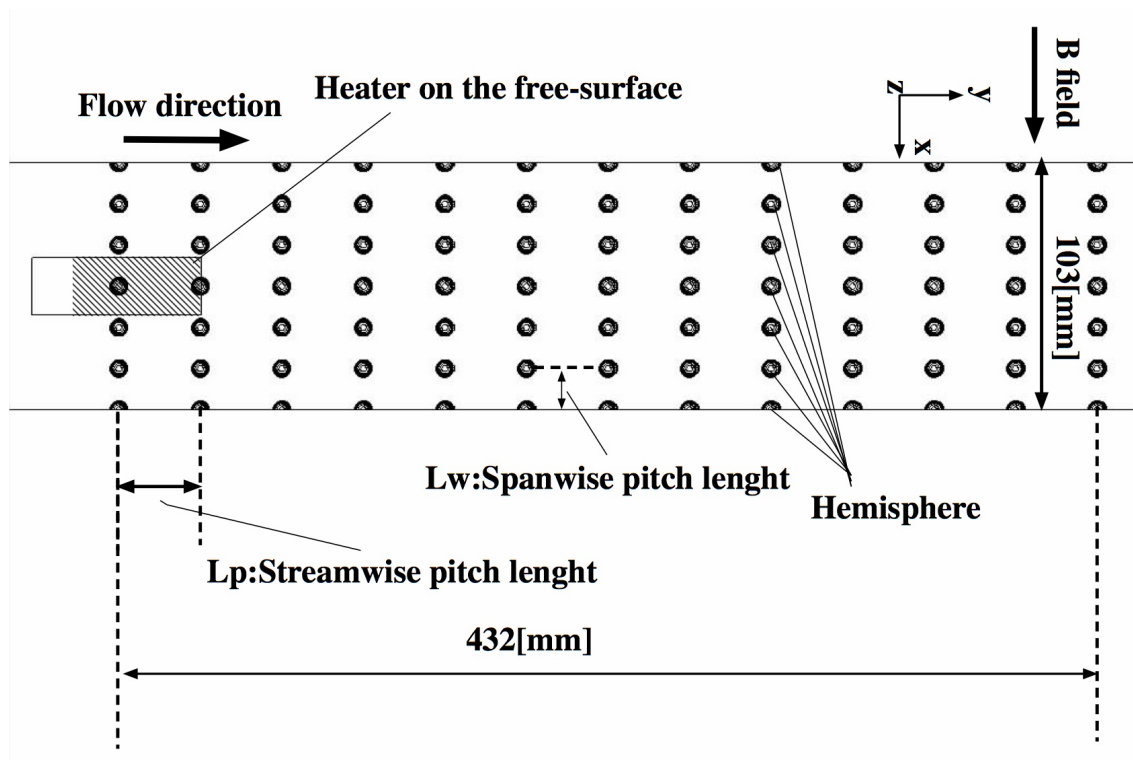


Fig. 2-11. The top-view of the numerical model of inline hemisphere arrangement under the uniform transverse magnetic field.

Table 2-4. The numerical conditions of the inline hemisphere arrangement under the transverse magnetic field.

Reynolds number [-]	1150
Interaction parameter [-]	0-6.72
Mesh size [mm ³]	0.1×0.3×0.1
Thermal characteristic of obstacles	Thermal insulation (Acrylic resin)
The size of a hemisphere [mm ³] (diameter × height)	8.0 × 4.0
Streamwise-pitch-length, L_p , [mm]	17.5, 36.0 and 48.0
Spanwise-pitch-length, L_w , [mm]	19.5
Boundary condition at the top wall	Free-slip condition
Boundary condition except the top wall	No-slip condition
Working fluid	Ga ₆₇ In _{20.5} Sn _{12.5}
Heater power [W]	91.9
Fluid depth [mm]	8.00

Figure 2-12 shows the temperature distributions at the bottom-wall of the three different streamwise-pitch-length configurations at the non-magnetic field. In case of the middle streamwise-pitch-length $L_p = 36.0\text{mm}$ shows the highest temperature than other cases. The second highest temperature was calculated in the case of $L_p = 17.5\text{mm}$ of the relatively shortest length. The tendency of this is due to the flow structure between hemispheres lies in the flow direction. In ideal thermal mixing behavior for enhancement of heat transport, the relatively high temperature fluids near the free-surface must be transported efficiently by flow structure caused by an optimum obstacle arrangement. According to Vorayos [47], they had been investigated the heat transfer performance of air flow by using three different streamwise-pitch-length of the inline hemisphere arrangements experimentally, the result of the experiment the relatively middle

streamwise-pitch-length showed the best for heat transfer. In the case of the relatively low streamwise-pitch-length, fluids near the free-surface were streamed to the downstream of the channel through near the free-surface. In contrast, the relatively long streamwise-pitch-length is not enough to raise the performance of heat transport due to the less power for breaking the temperature stratification. Therefore, the relatively middle streamwise-pitch-length is appropriate for the high thermal mixing performance.

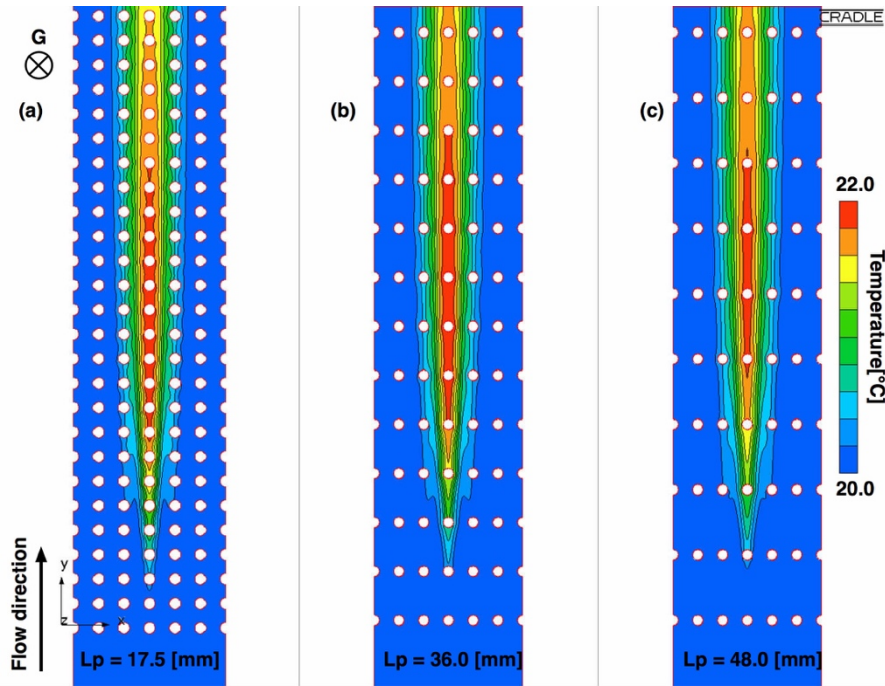


Fig. 2-12. The temperature distributions at the bottom-wall of the three different streamwise-pitch-length arrangements in case of non-magnetic field($B=0T$).

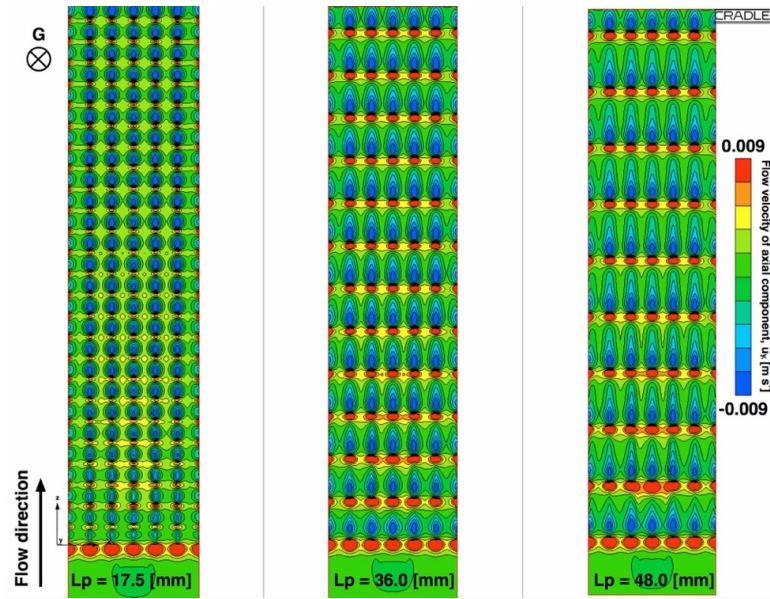
Figure 2-13 shows a vertical flow velocity u_z (In other words, the gravitational direction of the flow velocity) under the non-magnetic field condition for three different streamwise-pitch-length. The negative vertical flow velocity means that the fluid on the negative area is transported to the downward and, enhances heat transport directed to the bottom-wall of the channel. The downward velocity has been induced on the wake of the obstacle. On the contrary, a positive velocity means that the flow directed to the upward.

This is to say; the relatively low temperature fluids near the bottom-wall could be transported to the upward. Comparisons of each streamwise-pitch-length on the plane 8.00mm distance from the bottom-wall, the relatively high velocity can be found in case of the relatively middle and long streamwise-pitch-length $L_p = 36.0$ and 48.0 mm. The upward velocity (the positive u_z) area in the case of the relatively short streamwise-pitch-length $L_p = 17.5$ mm was narrower than others. In addition, from Fig. 2-15, the axial component of the flow velocity at the plane which is the relatively close to the free-surface was higher than the plane on 1.00mm from the bottom-wall. This behavior induced the fluid mixing and decreasing the temperature at the free-surface. Because of this, the upward velocity is one of key point for thermal mixing enhancement.

Furthermore, the negative vertical flow velocity is also important. By comparison of Fig. 2-13, all cases show the relatively low vertical velocity. However, the areas of negative velocity in case of the shortest streamwise-pitch-length are narrower than other cases. This is the reason for less heat transport performance compare than the middle streamwise-pitch-length. The remaining issue is why the case of the longest streamwise-pitch-length showed the worst heat transport performance.

To understand this problem, it should be focused on the area of a zero-vertical flow velocity. In Fig. 2-13 (b), the area of a zero-vertical flow velocity was indicated by “green area”, the zero-vertical flow velocity means that the fluid is not moving on vertical lines and less effect to the heat transport performance. The area of zero-vertical flow velocity in case of the longest streamwise-pitch-length was larger than the middle case. This affected the thermal mixing enhancement performance as decreasing. Therefore, the most ideal inline hemisphere arrangement that induces upwards and downward flows alternately is the middle case.

(a) 7.00mm from the bottom-wall



(b) 4.00mm from the bottom-wall

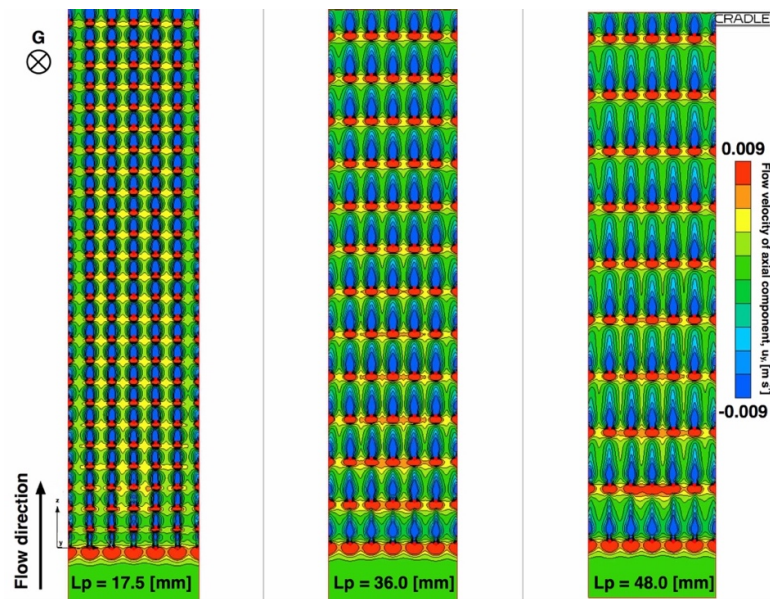


Fig. 2-13. The vertical flow velocity u_z distribution in case of installing three different streamwise-pitch-length of the inline hemisphere arrangements under the non-magnetic field on each axial coordination.

(c) 2.00mm from the bottom-wall

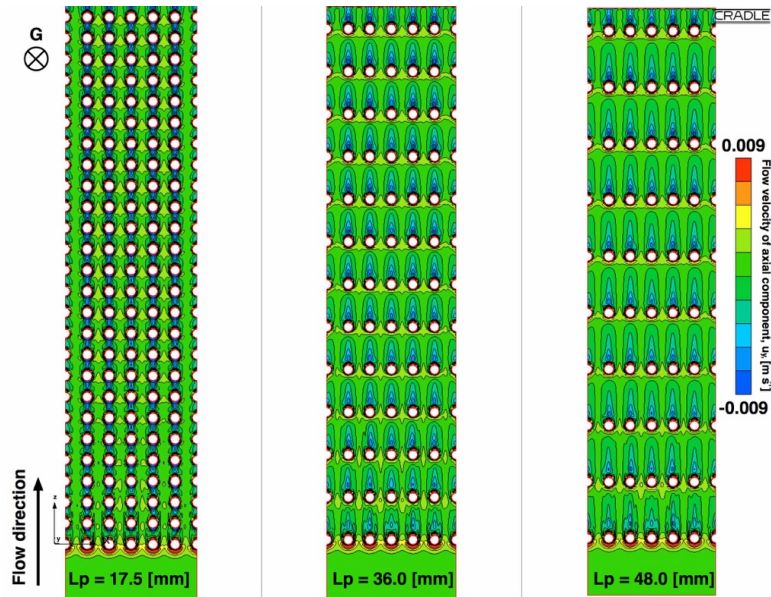


Fig. 2-13 (Cont.)

Figure 2-14 shows the temperature distributions at the bottom-wall of three different streamwise-pitch-lengths of the inline hemisphere arrangement under the various N of the transverse magnetic field. The tendency of the effect of the transverse magnetic field is similar like the previous numerical results of the single obstacle case, decreasing the temperature with increasing the N . For the effect of the different of streamwise-pitch-length, the case of middle streamwise-pitch-length showed the highest temperature at the bottom-wall under $N=6.72$. In contrast, the lowest temperature at the bottom-wall was in case of the longest streamwise-pitch-length. Hence, it can be considered that the middle streamwise-pitch-length is the most appropriate for heat transport even under the transverse magnetic field.

Figure 2-15 shows the vertical flow velocity distribution of this arrangement. The relatively high upward and downward flow velocity on the plane of 4.00mm from the wall existed even under the transverse magnetic field. On the plane of 7.00mm from the wall presents lower flow velocity compared by $N=0.00$ case. This means the effect of the

transverse magnetic field has a large on the plane which is no-obstacle. Based on comparisons of three different streamwise-pitch-length, $L_p=36.0\text{mm}$ case shows the highest flow velocity. This is a cause of the highest temperature distribution. Therefore, $L_p=36.0\text{mm}$ was the best heat transport even under the relatively high strength of the transverse magnetic field.

(a) $N=1.00$

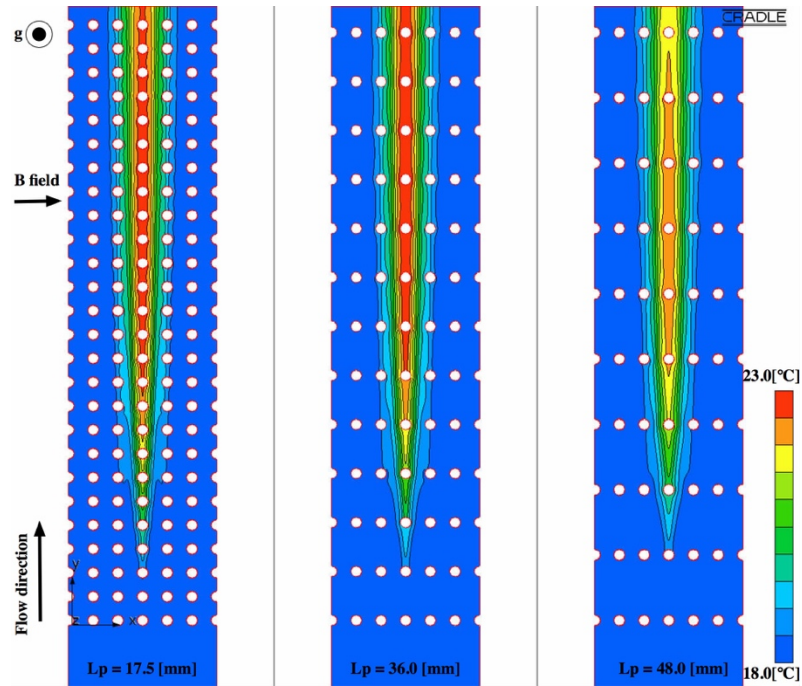
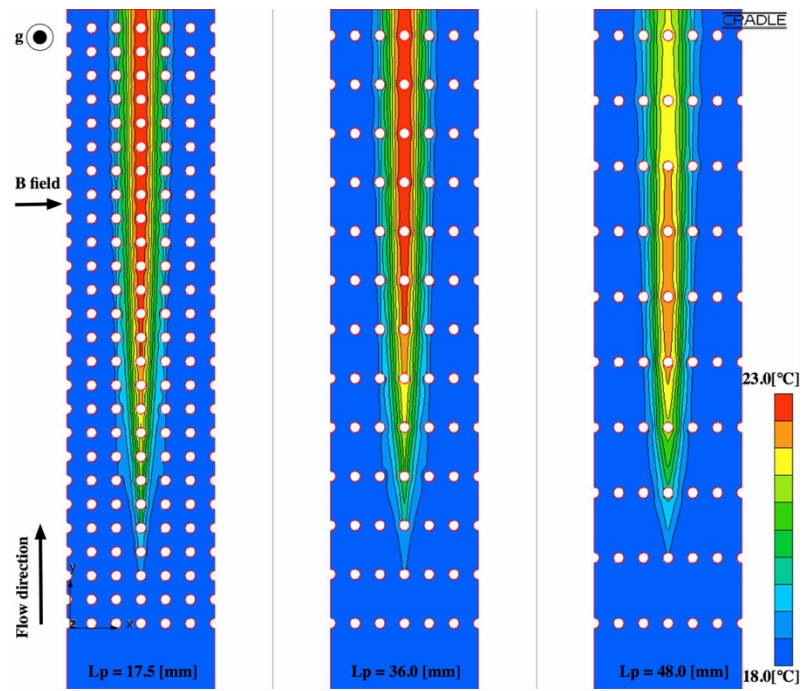


Fig. 2-14. The temperature distributions at the bottom-wall of three different streamwise-pitch-length of the inline hemisphere arrangement under various N of the transverse magnetic field.

(b) $N=2.70$



(c) $N=6.72$

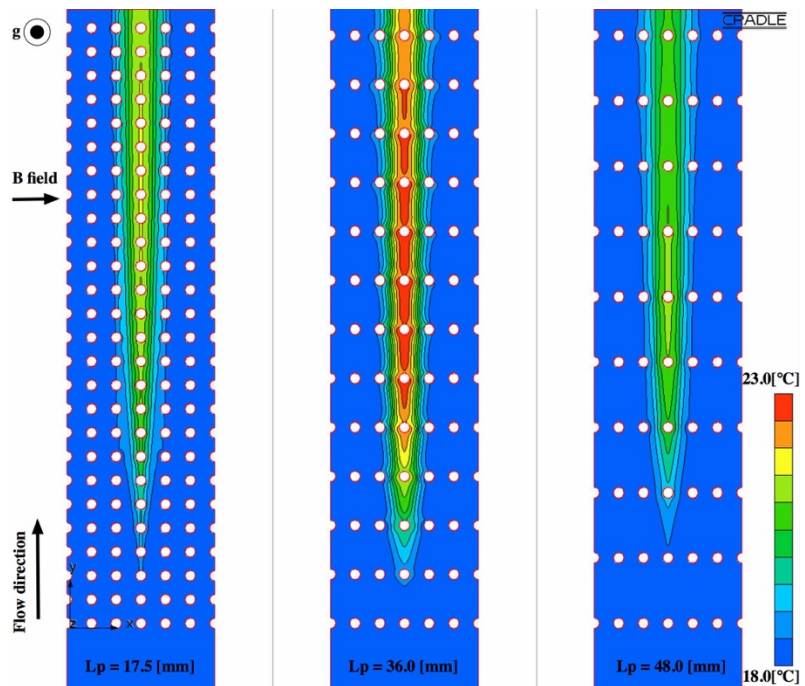
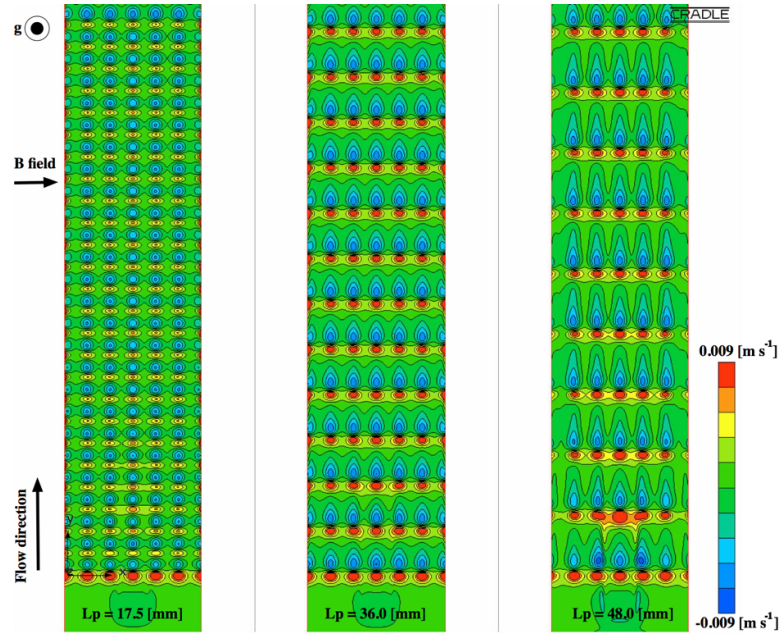


Fig. 2-14 (Cont.)

(a) 7.00mm from the bottom-wall



(b) 4.00mm from the bottom-wall

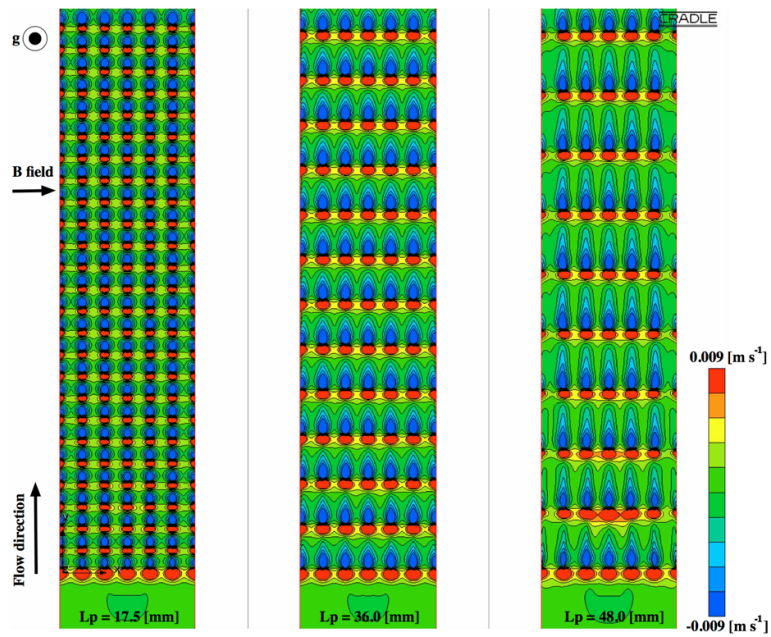


Fig. 2-15. The vertical velocity distribution three different streamwise-pitch-length of the inline hemisphere arrangement under $N=6.72$ of the transverse magnetic field.

(c) 2.00mm from the bottom-wall

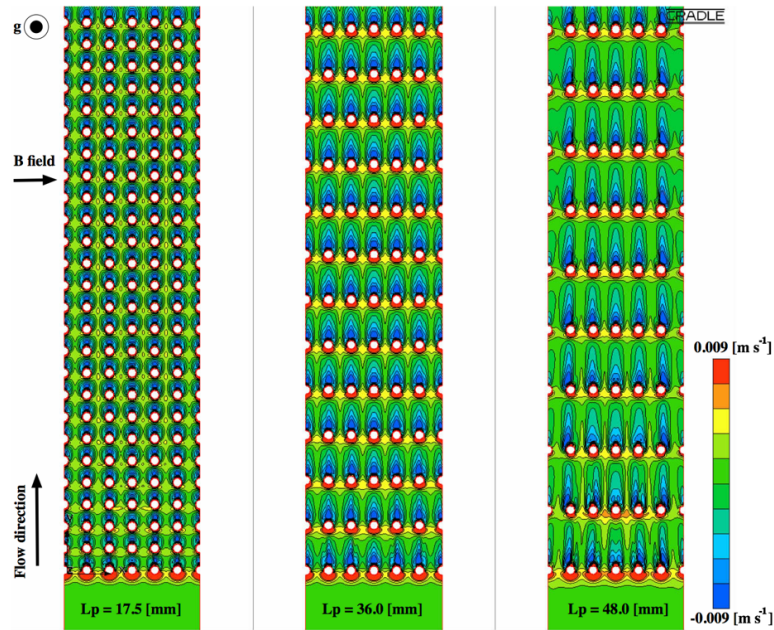


Fig. 2-15 (Cont.)

2.4 Vertical parabolic magnetic field

LMFREX(Liquid-Metal-Free-surface-EXperiment) was installed at Uji Campus, Kyoto University, has the vertical parabolic magnetic field due to the own characteristic of a set of electromagnets as described in Chapter 3. Therefore, the numerical simulations should have to be conducted the simulation in case of input the vertical parabolic magnetic field for comparison the experimental results. In this section, the numerical simulations under this condition are introduced and discussed.

2.4-1 Numerical model

The numerical model is similar like the that in case of the transverse magnetic field as illustrated in Fig. 2-16. The width of the test channel is different from the that of under the transverse magnetic field as 3.00mm difference, another different point is the location

of the obstacle. This numerical model referred to LMFREX. LMFREX could be conducted the experiment under a vertical parabolic magnetic field as plotted at Fig. 2-17 as a normalized magnetic field. Table 2-5 shows the numerical conditions. The mesh size, boundary conditions and the size of obstacles were as same as the previous magnetic conditions. The heater power injected 91.9W in this numerical simulation as referred from the experimental condition. The conducted flow rate in this numerical simulation was 1.7L/min. LMFREX can be conducted at the maximum interaction parameter 250 due to the performance of thermal insulation better than LMX. Therefore, it gives rise to conduct the experiment at low Reynolds number in laminar flow condition at the minimum 438.

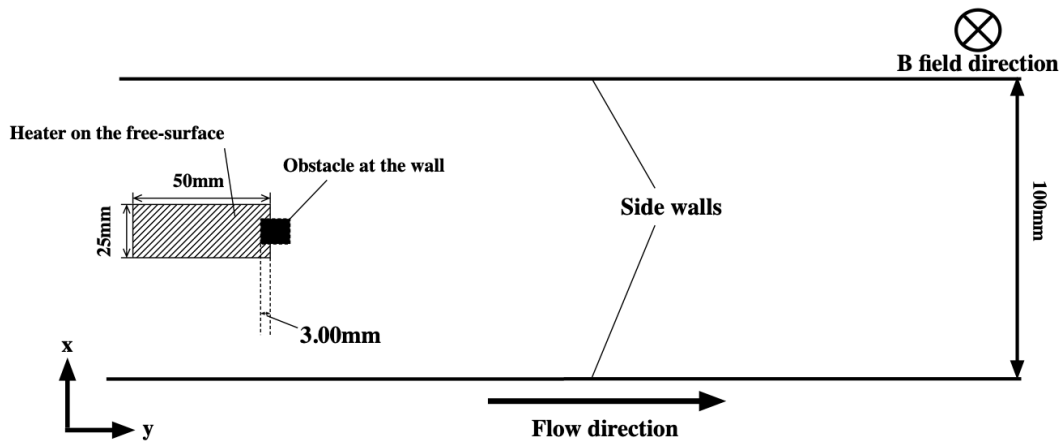


Fig. 2-16. The numerical model in case of installing the single obstacle under the vertical parabolic magnetic field (■ indicates the obstacle location) .

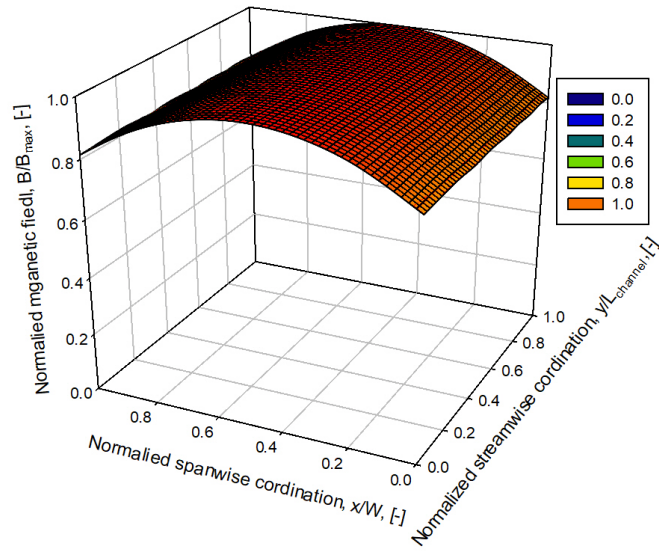


Fig. 2-17. The normalized magnetic field of LMFREX.

Table 2-5. The numerical conditions of the parabolic vertical magnetic field configuration.

Constant flow rate [L min^{-1}]	1.70
Reynolds number [-]	1521
Interaction parameter [-]	0.00-36.2
Fluid depth [mm]	7.00
Mesh size [mm^3]	0.10×0.30×0.10
Obstacle shapes	Cube, Hemisphere, Delta-wing
Boundary condition at the top wall	Free-slip condition
Boundary condition except the top wall	No-slip condition
Working fluid	$\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$
Heater power [W]	91.9

2.4-2 Reference case

Figure 2-18 shows the temperature distributions at the bottom-wall in case of an absence of obstacles under the various strength of the vertical parabolic magnetic field. The tendency is increasing the temperature at the bottom-wall with increasing the strength of the vertical magnetic field as opposite the results under the transverse magnetic field. This difference was described by the vertical velocity distribution. As mentioned above for the changing the shape of the flow velocity distribution, the Lorentz force was induced near the free-surface caused by the induced electrical current toward the side-wall. The relationship between the external magnetic field $\mathbf{B}$ and the induced current density $\mathbf{j}$ is the completely perpendicular relation. Thus, the flow velocity suppression has been induced near the free-surface. The normalized vertical flow velocity distribution in case of $N=0.00$ and $N=38.2$ was shown in Fig. 2-19. The reason for this shape of the distribution was caused by the uniformly Lorentz force except near the wall. Hence Lorentz force was applied isotopically to the bulk and the free-surface. For this behavior, the flow velocity of the bulk and the free-surface are equal. By the no-slip condition near the bottom-wall, the flow velocity decreases as approaching the bottom wall. Thus, this changing vertical flow velocity distribution largely affected to the fluid transport performance. This effect may be enhanced heat transport however it can be considered that the heat transport mechanism is likely to be heat conduction in case of higher N due to the velocity decreasing. Therefore, the high temperature fluid under the high strength of the vertical parabolic magnetic field may be transported heat as heat conduction rather than the thermal mixing.

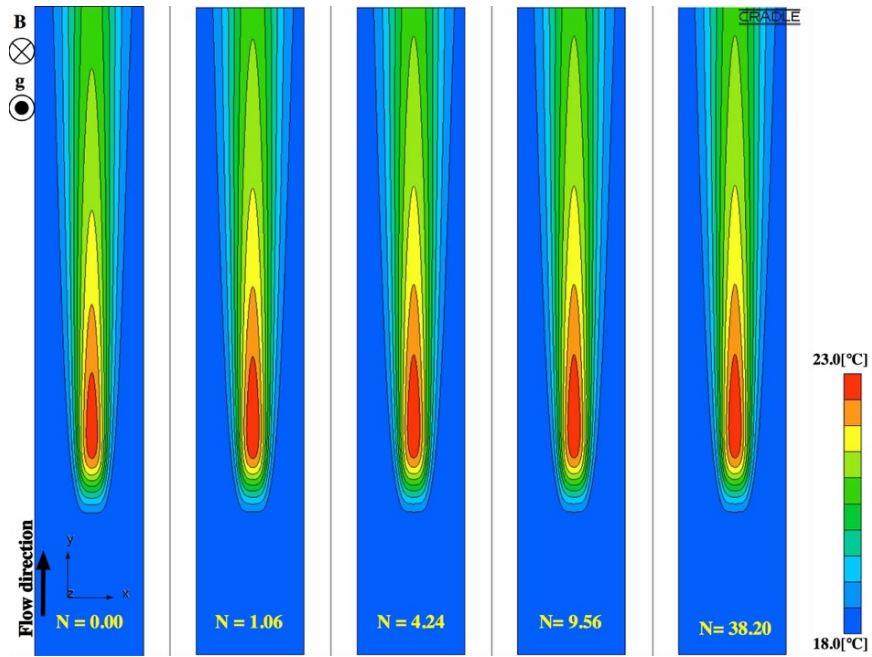


Fig. 2-18. The temperature distribution at the bottom-wall in case of an absence of obstacles under various of the parabolic vertical magnetic field.

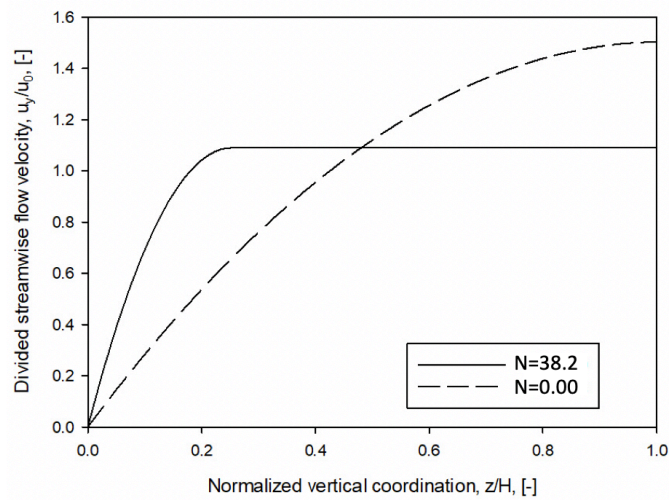


Fig. 2-19. The divided streamwise flow velocity distribution over the depth at the center of the channel in case of an absence of obstacle under $N=0.00$ and $N=38.2$ of the vertical parabolic magnetic field.

In regard to the induced electrical current density distribution and potential field under the vertical parabolic magnetic field were in Fig. 2-20. The current flow directed to the counter clockwise direction. Near the side-wall, there is the current density difference was existed on both walls. This makes the difference of the induced Lorentz force. Due to this, the spanwise velocity near the side-wall has been affected that locally faster than the velocity on the bulk. Fig. 2-21 presents the normalized spanwise flow velocity distribution. There was the velocity gradient between the bulk and that near the side-wall. This behavior was found in the experimental result by using a potential probe describes in Chapter 3.

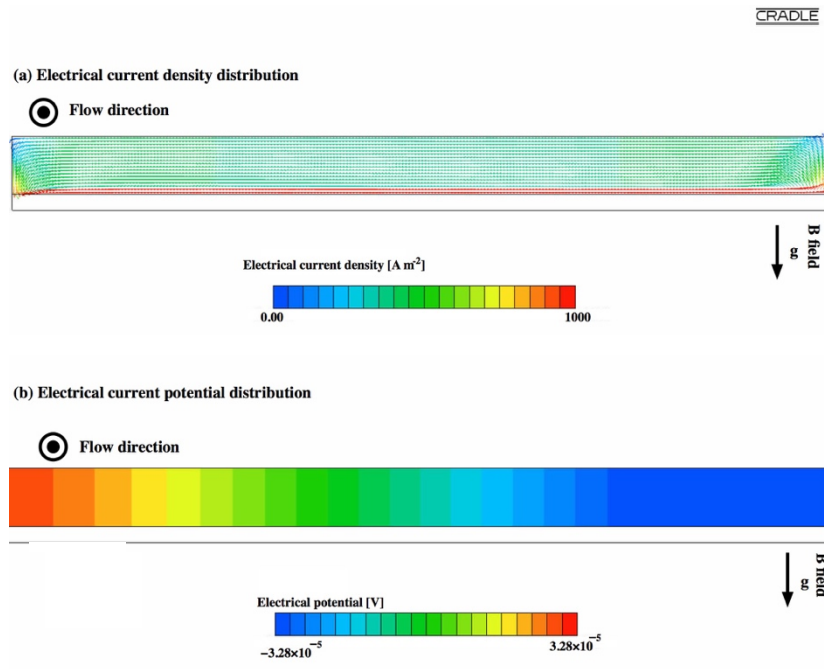


Fig. 2-20. The induced electrical current density and potential field distribution on the cross-sectional area under $N=38.2$ of the vertical parabolic magnetic field in case of an absence of obstacle.

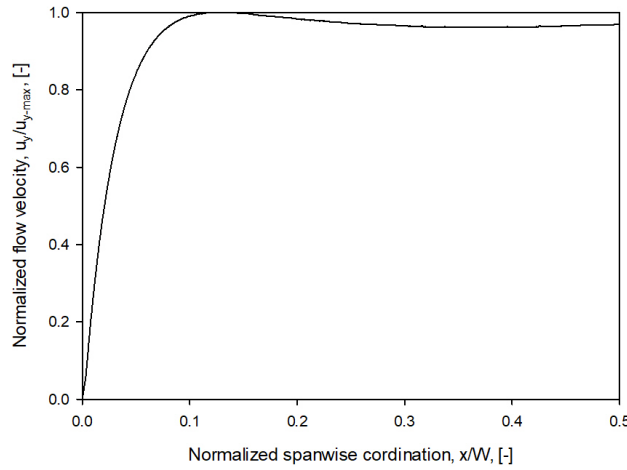


Fig. 2-21. The streamwise flow velocity distribution on the spanwise line in case of the absence of obstacles at $N=36.2$.

2.4-3 Effect of a single obstacle

Figure 2-22 presents the efficiency of heat transport as a function of interaction number with using various shapes of obstacles. The tendency was increasing γ with increasing N as opposed to the results in case of the transverse magnetic field. This is to say that the heat transport performance was increased with increasing the strength of the vertical parabolic magnetic field. The reason for this behavior can be described by localized heat accumulation on the bottom-wall under the low flow velocity, the localized heat near free-surface of film-flow is usually streamed to the downstream. However, the decreasing velocity by MHD effect transports the heat accumulation to the upstream. Thus, the heat is concentrated and makes increasing the efficiency of heat transport. For the γ at relatively high N , there were almost constant. These results correlate the temperature distributions in Fig. 2-18.

To understand the heat transport behavior under the vertical magnetic field, the vortex behavior must be considered. Figure 2-23 gives the vorticity distributions on the cross-sectional area in case of installing the delta-wing under various N . Note that, this cross-sectional area was referred to Fig. 2-1 at the plane on $n[\text{cm}]$ downstream of the obstacle. The absolute value of the vorticity of the flow direction $|\omega_y|$ in case of the

delta-wing was large even under high strength of the vertical magnetic field. This means that suction flow from the free-surface to the bottom-wall are still survived under $N = 9.56$ on the cross-sectional area of 5.00cm from the obstacle.

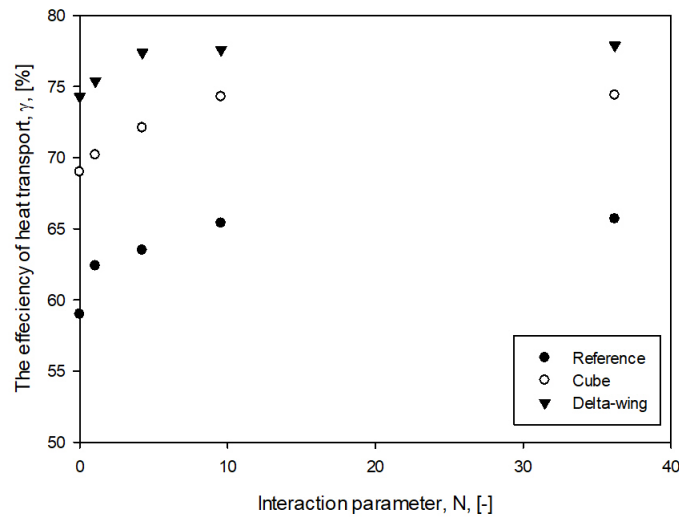


Fig. 2-22. The efficiency of heat transport as a function of interaction parameter in case of an installing a single obstacle under various N of the vertical parabolic magnetic field.

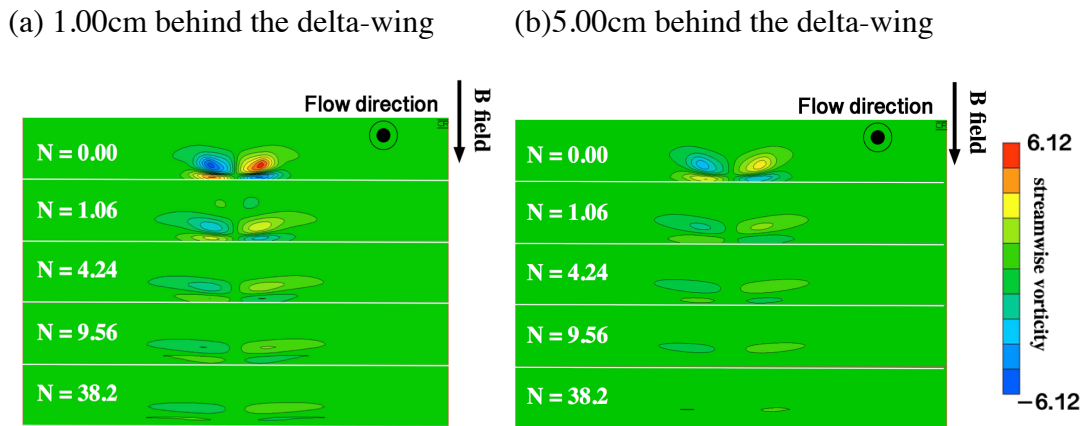


Fig. 2-23. The vorticity distributions on the cross-sectional area of the test channel in case of installing the delta-wing under various N of the parabolic vertical magnetic field.

2.4-4 Effects of inline and staggered arrangement

2.4-4-1 Numerical model

The numerical model and conditions were the same as the previous single obstacle case. The numerical model is also similar to the numerical model of inline hemisphere arrangements. Schematic of the numerical model in case of the inline/staggered arrangement under the vertical parabolic magnetic field was in Fig. 2-24. For inline arrangement, there were defined the different streamwise-pitch-length L_p and the constant spanwise-pitch-length L_w as same as previous. On the other hand, L_p and L_w were also used in case of staggered arrangement. To compare to the inline case easily, L_w was chosen as a constant and three different L_p were conducted for numerical simulation. As shown in previous numerical results, the delta-wing have been given the highest heat transport performance, thus the delta-wing arrangement should be considered for implementation. In this chapter, the numerical simulation with using inline/staggered hemisphere arrangement and the staggered delta-wing arrangement was conducted.

(a) Inline arrangement

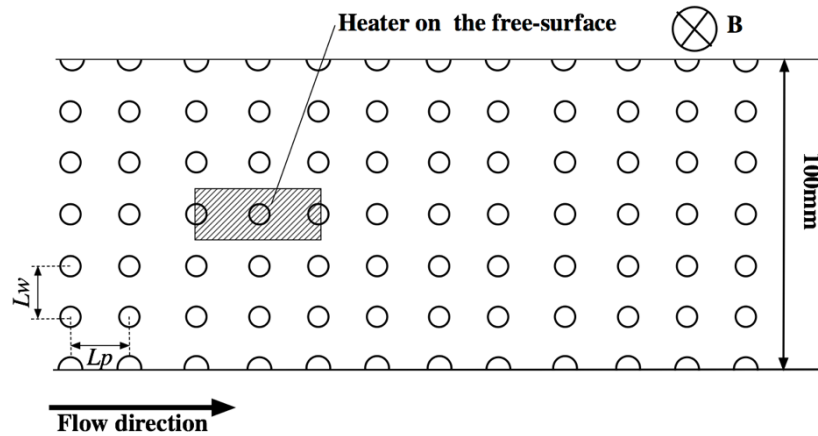


Fig. 2-24. The schematic of numerical model of the inline/staggered arrangement under the vertical parabolic magnetic field.

(b) Staggered arrangement

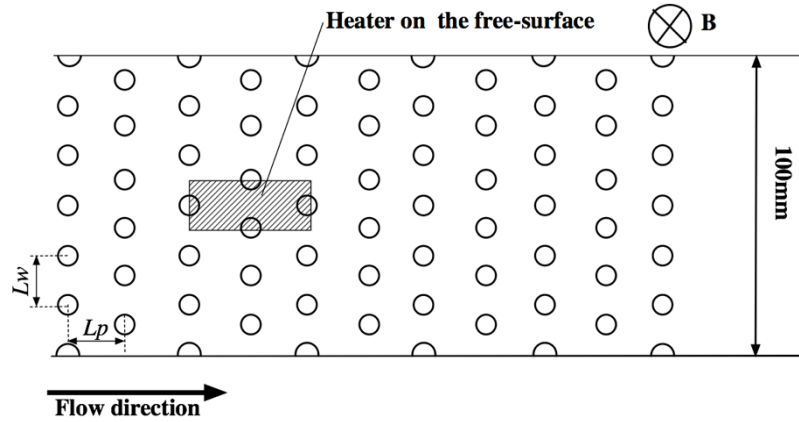


Fig. 2-24 (Cont.)

2.4-4-2 Results and discussions

Figure 2-25 presents the temperature at the bottom-wall at $N=0.00$ and $N=20.0$ in case of installed same streamwise/spanwise-pitch-length of an inline and staggered hemisphere arrangement. The tendency of the temperature in case of $N=20.0$ was higher than that in the case of $N=0.00$. There was horizontal fluctuation in case of installed an inline hemisphere arrangement, this enhances thermal mixing to the horizontal direction rather than vertical direction. Thus, it can be considered that the inline arrangement does not appropriate for vertical thermal mixing. In contrast, the case with installing the staggered arrangement shows the high temperature at the wall and not enhance fluctuation directed to the horizontal direction. To summarized this result, the order of high wall temperature was the staggered, inline, reference case. Therefore, the staggered arrangement was better than the inline arrangement or reference case for vertical heat transport.

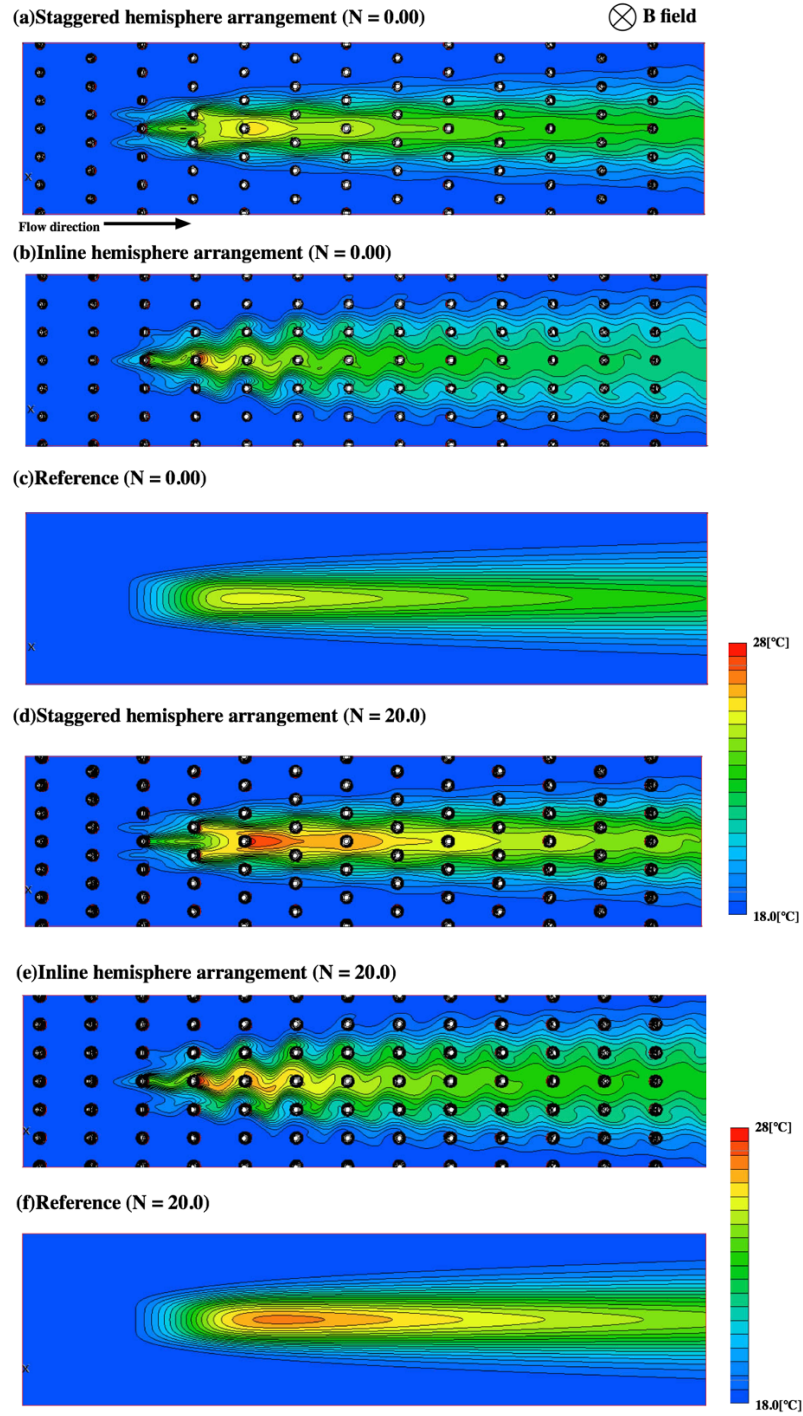


Fig. 2-25. The temperature distribution at the wall under $N=0.00$ and $N=20.0$ of the vertical parabolic magnetic field in case of installed same streamwise/spanwise-pitch-length of an inline and staggered hemisphere arrangement.

In terms of the heat transport mechanism in case of installing the inline/staggered hemisphere arrangement, the vertical flow velocity distributions give the mechanism of the vertical heat transport. Figure 2-26 shows the vertical flow velocity distributions on a few millimeters from the wall in case of installing inline/staggered hemisphere at $N=0.00$ and $N=20.0$. The area of downward vertical velocity which is negative in Fig. 2-26 was wider than the inline arrangement. This means the fluid transport performance to the wall in case of installing the staggered arrangement was better than the that of installed the inline. Due to this vertical flow velocity, the high temperature fluid near the free-surface was transported to the bottom-wall as Fig. 2-25.

From the previous numerical results presented the high heat transport performance by using the delta-wing and the staggered arrangement. Thus, it is worth to conduct the simulation in case of installing the delta-wing staggered arrangement. Figure 2-27 shows the numerical model of the staggered delta-wing arrangement. The simulations have been conducted for three different streamwise-pitch-length. Any other conditions were the same as the previous numerical condition of installing the inline hemisphere arrangement.

At first, it requires the comparisons of the staggered hemisphere arrangement and the staggered delta-wing to know the performance of the fluid transport. Figure 2-28 presents the temperature at the bottom-wall in case of installed the middle size streamwise-pitch-length ($L_p = 36.0$ mm) of the inline/staggered hemisphere and staggered delta-wing arrangement at $N=0.00$. The characteristic of temperature at the wall is the highest temperature in case of installed the delta-wing arrangement. Based on the comparison of the temperature in case of installed the staggered hemisphere and the delta-wing, there was 2.00°C difference at the maximum temperature. Therefore, the staggered delta-wing can be enhanced fluid transport the most efficiently.

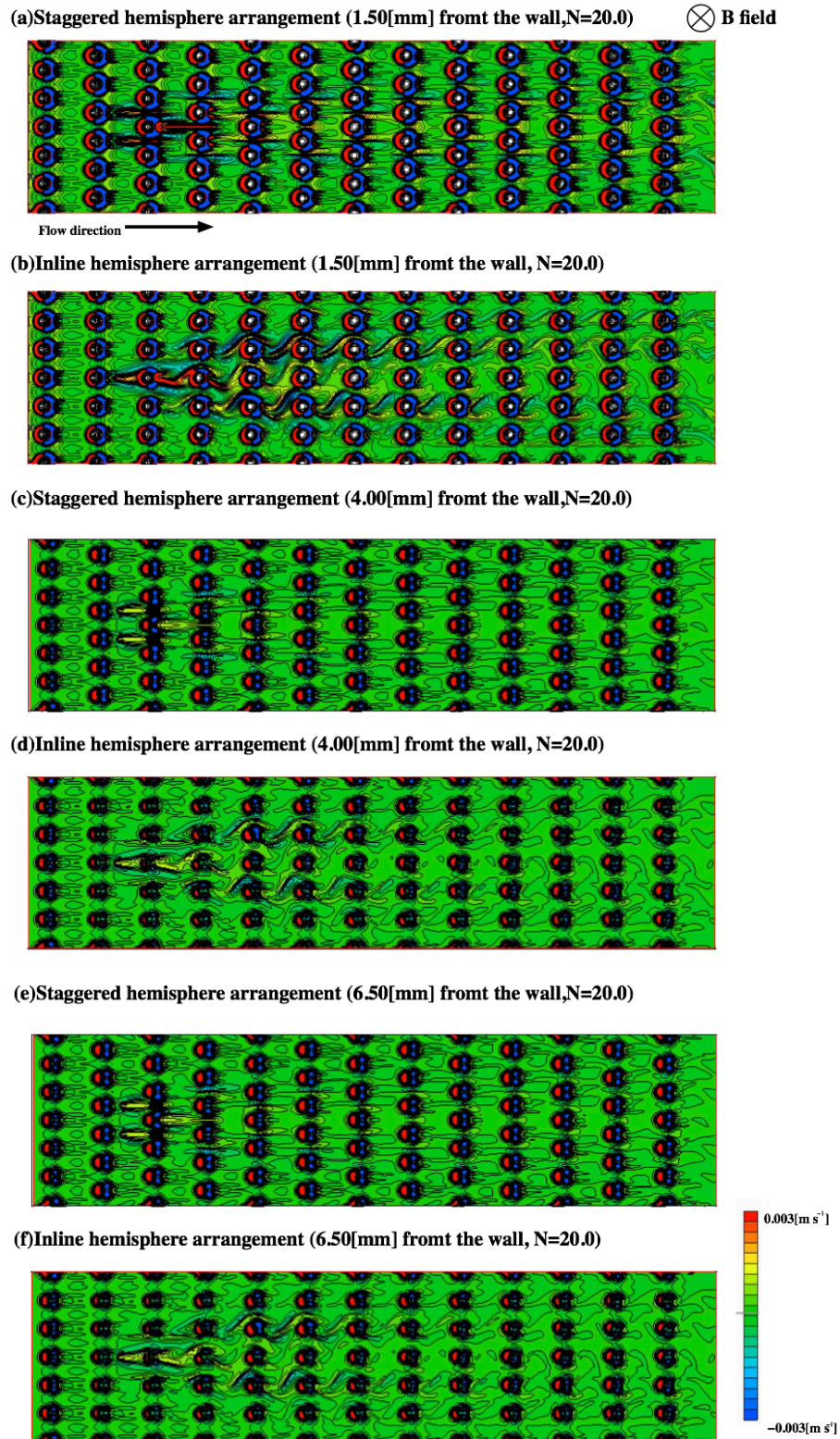


Fig. 2-26. The vertical flow velocity distribution in case of installing inline/staggered hemisphere arrangement at $N=0.00$ and $N=20.0$ of the vertical parabolic magnetic field.

As for the dependency of the different streamwise-pitch-length, three different lengths ($L_p = 15.0, 30.0, 60.0\text{mm}$) have been conducted for the staggered delta-wing arrangement. The temperature at the wall in case of installed three different streamwise-pitch-length of the staggered delta-wing arrangement under $N=20.0$ is shown in Fig. 2-29. The highest temperature was observed in case of $L_p = 60.0\text{mm}$. In contrast, the lowest temperature was shown in case of $L_p = 15.0\text{mm}$. The reason for this behavior was related to the flow structure in Fig. 2-30. Figure 2-30 presents the vertical flow velocity distribution at the 3.0mm from the bottom-wall under same magnetic field condition. As from the Fig. 2-30 of $L_p = 15.0\text{mm}$, there were very high downward flow and upward flow on the behind delta-wings. However, the case $L_p = 60.0\text{mm}$ shows the relatively low vertical flow velocity, thus it can be considered that the vertical flow velocity did not affect the vertical heat transport. Another mechanism should be investigated.

To find the high heat transport performance in case of $L_p = 60.0\text{ mm}$, the streamwise flow velocity distribution gives the understanding of the mechanism in Fig. 2-31. There was significant different characteristic between $L_p = 60.0\text{mm}$ and others. That is the local velocity behind the delta-wing in case of $L_p = 60.0\text{mm}$ slower than other cases. This flow structure makes the high temperature fluid near the free-surface has been transported to the further downstream except $L_p = 60.0\text{mm}$ case. The relatively narrow streamwise-pitch-length makes the flow faster near the free-surface, and this makes the high temperature fluid difficult to transport to the wall. Based on these findings, the appropriated staggered delta-wing arrangement can be considered for implementation: Installing two different height delta-wings alternately. The comparatively high height delta-wing is possibly to enhance vertical heat transport due to the relatively high downward flow velocity. This makes the heat transport from the free-surface to the bulk. Additionally, the low height delta-wing may transport heat to the wall. Hence, two different height of the delta-wings can enhance heat transport efficiently.

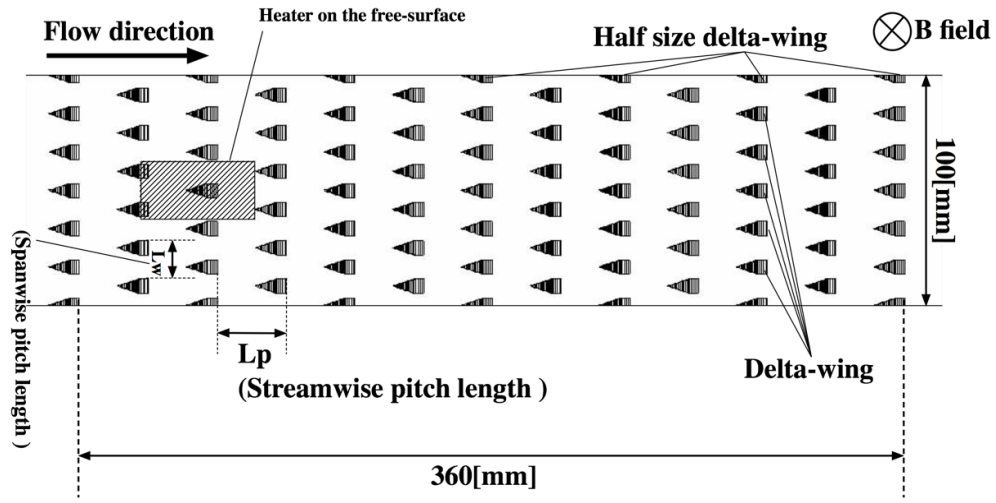


Fig. 2-27. The schematic of the numerical model for staggered delta-wing arrangement.

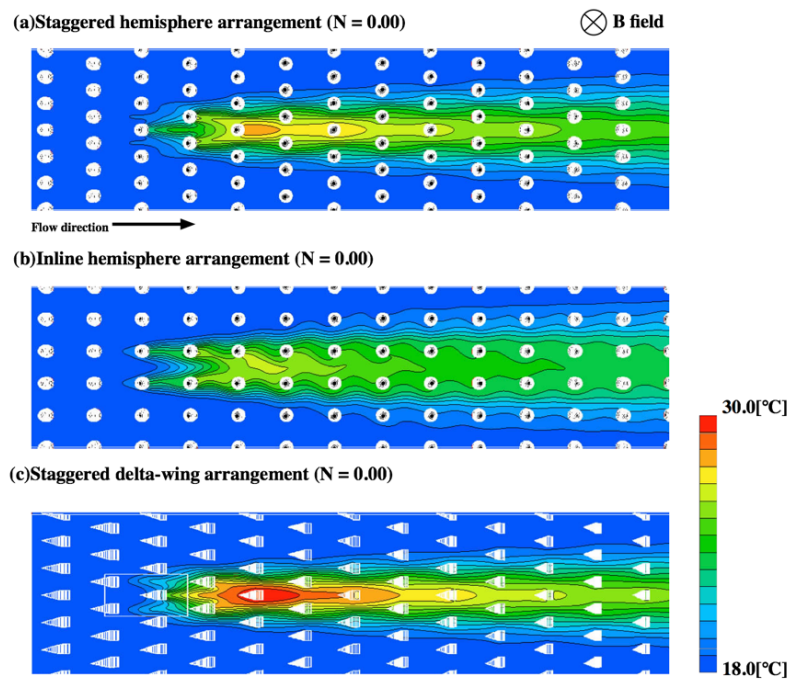


Fig. 2-28. The temperature distributions at the bottom-wall in case of installing the inline/staggered hemisphere and staggered delta-wing arrangement at $N=0.00$.

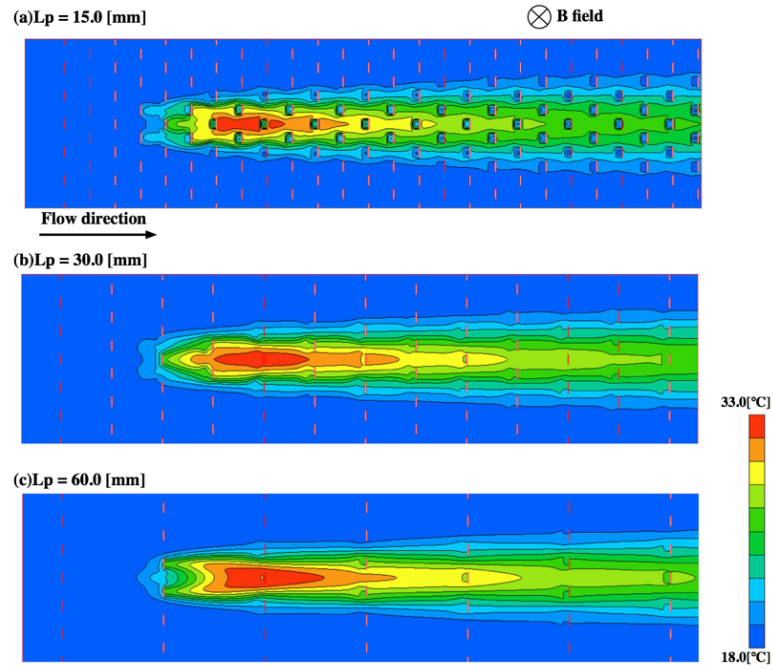


Fig. 2-29. The temperature distributions at the bottom-wall in case of installing the staggered delta-wing arrangement at $N=20.0$.

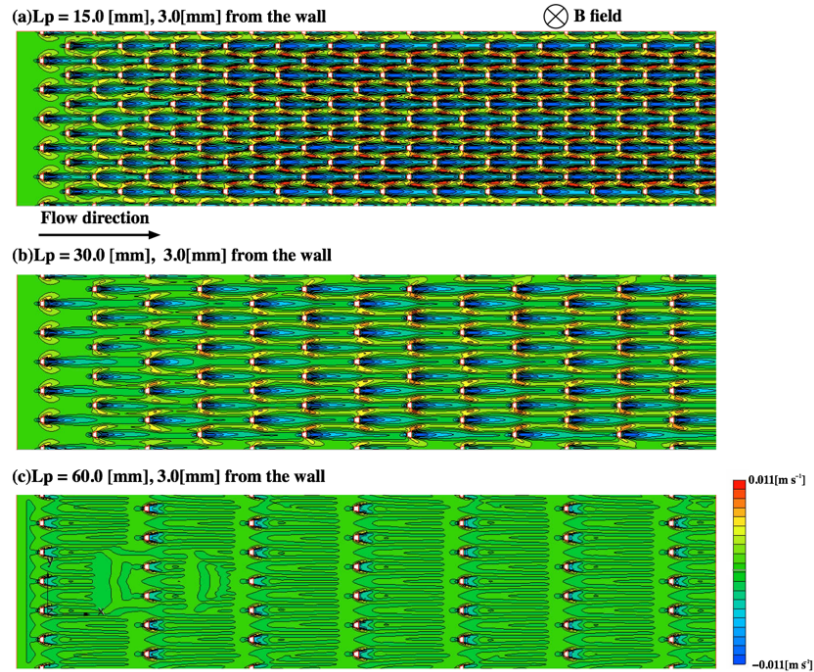


Fig. 2-30. The vertical flow velocity distribution at the 3.0mm from the wall in case of installing the staggered delta-wing arrangement at $N=20.0$.

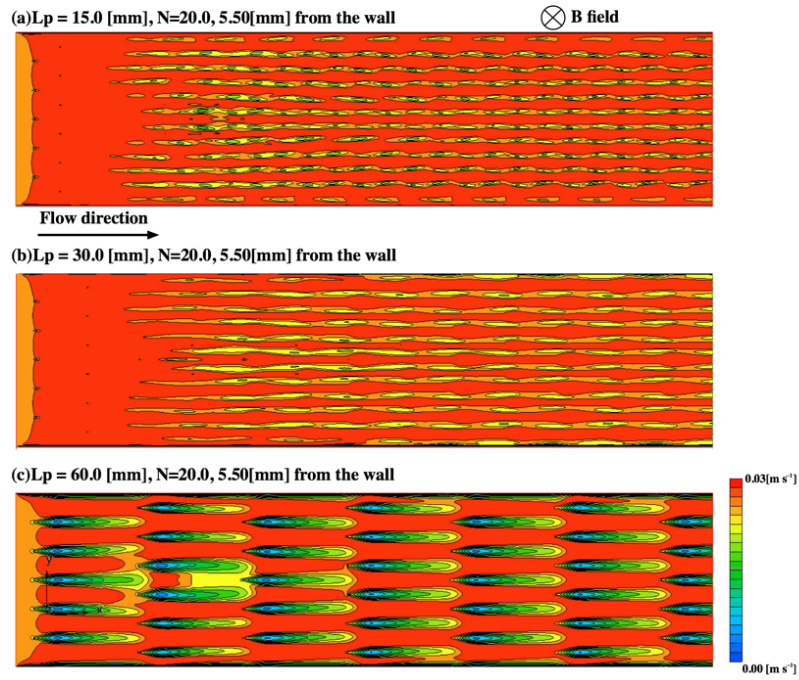


Fig. 2-31. The streamwise flow velocity distribution at 5.50mm from the bottom-wall in case of installing the staggered delta-wing arrangement at $N=20.0$.

2.5 Summary

The numerical simulations of liquid metal film-flow under the transverse and the vertical parabolic magnetic field has been conducted. The liquid metal film-flow in the rectangular channel was partially heated on the free-surface. To understand the behavior inside the liquid metal film-flow using various shape obstacles, temperature, flow velocity, vorticity and the efficiency of heat transport were investigated. These results can be useful for enhancement of the heat transport from the free-surface to the bottom-wall. The results can be summarized as each magnetic configuration:

2.5-1 Reference case

Based on the comparison of the temperature distributions, the highest temperature was observed in case of the delta-wing. This is caused by the vortex behavior on the wake of the delta-wing. From the streamwise vorticity distributions, the delta-wing generated a pair of vortices which makes the strong suction flow directed to the wall. This vorticity

indicates the strength of the suction flow or the upward flow. In contrast, cube generated the relatively low suction flow. Based on this, the delta-wing is a possibility to transport the fluid near the free-surface to the bottom-wall.

2.5-2 Uniform transverse magnetic field

Based on the comparison of the temperature at the wall and vorticity distributions, I concluded that the flow with installing the delta-wing is likely to the most enhance heat transport under the uniform transverse magnetic field. This is caused by the streamwise vorticity on the wake of the delta-wing was the largest even at relatively high N . Therefore, the delta-wing enhances vertical thermal mixing efficiently even under the transverse magnetic field.

In addition, temperature decreased with increasing N . This is due to the changing vertical flow velocity distribution. The characteristic of the distribution was local high velocity near the free-surface, this transported the high temperature fluid to the further downstream. At the bulk, the velocity was decreased by Lorentz force. The reason for this velocity changing was caused by the induced electrical current. The key issue for the shape of the velocity distribution was the relation of $\mathbf{j}$ and $\mathbf{B}$. At the free-surface, $\mathbf{j}$ was directed to the spanwise direction, it gave rise to no-Lorentz force and zero velocity decreasing. This makes local high flow velocity. For the description of the velocity decreasing on the bulk, the relation $\mathbf{j}$ and $\mathbf{B}$ were the inclined angle or the perpendicularity. Due to this, the flow was suppressed. Therefore, the effective method for thermal mixing can be considered that the obstacle touches neatly the free-surface to break local high velocity.

To consider for a practical method for thermal mixing enhancement, the numerical model using the inline hemisphere arrangement has conducted due to easily installing in terms of engineering. The numerical simulations were set three different streamwise-pitch-length arrangement. The best heat transport performance was the middle streamwise-pitch-length arrangement. The reason for this phenomenon, the vertical flow

velocity was strongly depending, such as less area of zero velocity and, large area of downward and upward flow. Based on these findings, the optimized streamwise-pitch-length arrangement should be considered for these factors. This result suggested that the optimized length is existing for heat transport enhancement in the liquid metal film-flow under the uniform magnetic field.

2.5-3 Vertical parabolic magnetic field

In case of installing a single obstacle, the tendency of heat transport performance was increased with increasing N . This is due to the temperature increase on the bottom-wall and the effect of the thermal boundary layer. When the temperature rise occurred that the heat flux was directly affected for increasing at the constant fluid depth. This was one of the reasons for increasing the efficiency of heat transport. On the other hand, the thickness of the thermal boundary layer in case of laminar is given by

$$\delta_{T-l} = 5.0 \sqrt{\frac{\nu X}{u_0}} Pr^{-1/3} \quad (2.13)$$

in which X is the downstream distance from the stating of the boundary layer. $\delta_{T-laminar}$ can be calculated in case of 0.03ms^{-1} as $\delta_{T-l} = 0.021\text{m}$, $\delta_{T-l} = 0.025\text{m}$ in case of 0.02ms^{-1} . Thus, the decreasing flow velocity makes the increasing the thickness of δ_{T-l} . Due to this, the temperature at the bottom-wall was increased under the magnetic field and high temperature fluid was conducted to the wall. Therefore, the heat transport mechanism under the relatively high N was affected by the heat conduction rather than thermal mixing.

However, the flow in case of the obstacle was the higher performance of the heat transport than the reference case. It is suggested that the obstacle is likely to enhance heat transport of the liquid metal film-flow under the vertical parabolic magnetic field. By

quantitate evaluation, there was 10.0 to 15.0% increased. Hence, it can be considered that the practical method for heat transport enhancement is using the obstacle installation.

To develop the heat transport enhancement, the installing many obstacles can be considered for practical heat transport method. This numerical simulation has been conducted the inline/staggered arrangement with using hemispheres and delta-wings. The reason of choosing these two obstacles, hemisphere has some advantages of the engineering aspects as mentioned on above, all results in case of the delta-wing showed the highest heat transport performance as far in this numerical simulation. Based on the comparison of results, I concluded that the staggered delta-wing arrangement of the relatively long streamwise-pitch-length was the best-optimized arrangement for heat transport enhancement under the vertical parabolic magnetic field. There are some reasons are introduced followings; (1) The inline arrangement was likely to induce spanwise fluctuation. Due to this, it is not appropriate for vertical heat transport because the high-temperature fluid cannot be touched on the wall. In contrast, the staggered arrangement has not induced spanwise fluctuation. Thus, it can be considered that the staggered arrangement can transport heat efficiently for vertical heat transport. (2) The relatively short streamwise-pitch-length shows the highest streamwise vorticity on 3.0mm from the wall based on the comparison of three different streamwise-pitch-length of the staggered delta-wing arrangement. However, the streamwise flow velocity in case of the relatively short streamwise-pitch-length was the fastest near the free-surface. This flow structure transports the high temperature fluid to the further downstream. This is the reason for the worst heat transport performance in case of the relatively short streamwise-pitch-length. On the other hand, the longest streamwise-pitch-length showed the low streamwise vorticity and the local low streamwise flow velocity. This low velocity makes the heat accumulation near the free-surface, then a pair of vortexes from the delta-wing has transported the conducted heat to the wall. Therefore, it can be considered that the high heat transport performance is a possibly to realize using this effect. Based on these findings, some proposals were introduced in Chapter 5.

Chapter 3 Liquid metal experiment

3.1 Introduction

The experimental facility used in this study is LMX (Liquid-Metal-eXperiment) at Princeton-Plasma-Physics-Lab, USA, and LMFREX (Liquid-Metal-Free-surface-EXperiment) at Kyoto University. The LMX generates a uniform transverse magnetic field, the length of the test channel is 1.00m, and the width is 0.103m. The experimental apparatus and pictures of LMX are shown in Figs. 3-1 and 3-2. The LMFREX generates a parabolic vertical magnetic field, the main difference between LMX and LMFREX is the magnetic field direction and the size of the test channel. Both experimental facilities used GaInSn eutectic alloy as working fluids which is called as "Galinstan". Physical properties of GaInSn are listed in Table 2-2. The reason for choosing this working fluid is that the melting point is low, the relatively high electric conductivity, and no toxicity. Besides GaInSn, the low melting point alloys are sodium, lead-bismuth, lithium lead, tin, U-alloy, mercury etc. The physical properties of these materials as shown in Table 1-1. Comparison of these materials and GaInSn, the melting point is higher than GaInSn and some materials have toxicity. Therefore, these materials are technically less onerous material in academic experiments.

Without the inert gas environment, the free-surface would develop an oxide film that would change the flow behavior. When the experiment was conducted with poor control of the argon gas, an oxide layer formed across the entire surface of the liquid metal within a few seconds to minutes and become a static film floating on the flowing liquid metal beneath.

3.2 Uniform transverse magnetic field experiment

One of the remarkable points of the experiment under the transverse magnetic field is a key issue for the fundamental thermal characteristic of liquid divertor design. The experiment was conducted to investigate the characteristic of heat transport/thermal mixing behavior in this section.

Due to the effect of the transverse magnetic field described in Chapter 2, the characteristic of heat transport behavior in case of an absence of obstacles was investigated by Rhoad [49], he reported that the relatively high temperature fluids near free-surface were not touched on the area of TCs bottom wall in his experiment because of vortex damping behavior of the perpendicular relation to the applied magnetic field. On the contrary, this study estimates for this behavior as changing the shape of the vertical flow velocity distribution. Some numerical study and numerical simulation in this study support that the flow velocity near free-surface faster than the velocity on the bulk/near the bottom-wall caused by the free-slip condition on the top wall of the test model. As best our knowledge, there are not studied for investigating thermal mixing behavior of MHD liquid metal film flow under magnetic field with using some characteristic obstacles and, it is not clear the heat transport performance of obstacle as the vortex generator installed at the bottom-wall of the test channel in a high electric conductivity fluid.

The experiment under the uniform transverse magnetic field was conducted with LMX. The localized heated on the free-surface of the upstream of the test channel. The shape of obstacles adopted as delta-wing/cube/ hemispheres. The experiment with using many obstacles was conducted with using an inline-hemisphere arrangement and a staggered-hemisphere arrangement.

This chapter describes as following contents: Sections 3.2-1 and 3.2-2 present the characteristic of LMX and diagnostics, the experimental results in case of reference and the comparison to the numerical results are introduced in Section 3.2-3. The experimental results with installing the delta-wing and the comparison to the numerical simulation

results are introduced in Sections 3.2-4. 3.2-5 shows the results of three different arrangements of the inline-hemisphere arrangements are described. Section 3.2-6 described the summary of the experimental results under the uniform transverse magnetic field.

3.2-1 LMX

LMX has the uniform transverse magnetic field by a set of electromagnets on the external side-walls of the test channel. The experimental facility LMX is illustrated in Fig. 3-1. LMX has consisted of Archimedes type screw pump, an electromagnetic flow meter, the set of electromagnets, a ceramic heater for localized heated free-surface of the liquid metal film-flow, a storage tank for the working fluid, argon gas lines, argon gas suppliers and a heat exchanger for cooling heated liquid metal by de-ionized water. The picture of LMX is attached in Fig. 3-2. The detail of these facilities is described on following.

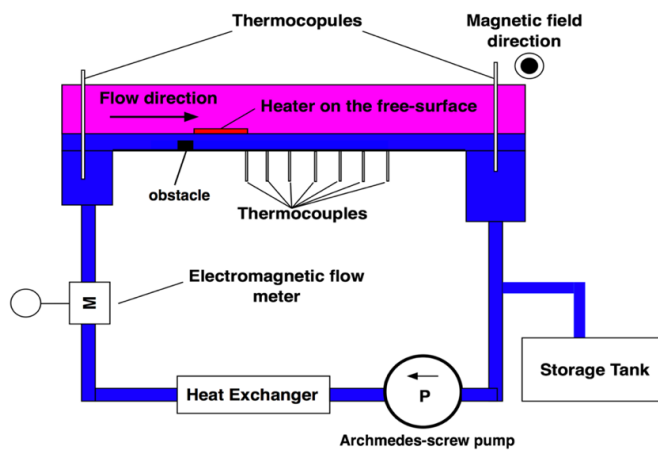


Fig. 3-1. The experimental apparatus of LMX.

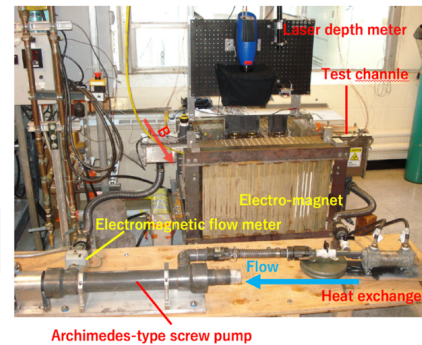


Fig. 3-2. Whole view.

- Archimedes type screw pump

Flow in the apparatus was driven by an Archimedes-style screw pump, designed and developed in PPPL to minimize both oxidations of the metal and disintegration of internal components that can occur due to the chemically aggressive characteristic of GaInSn [48]. This pump can make the flow rate between 1.50GPM and 4.0GPM. I had used this pump for the experiment using an obstacle under the transverse or non-magnetic field. In recently, they changed the pump as a mechanical gear pump for generating high flow rate. I used it in the experiment under the transverse magnetic field with using inline arrangements of hemispheres.

- Electromagnetic flow meter

The electromagnetic flow meter was used for measurement of flow rate. The measurement principle uses Faraday's law of electromagnetic induction to measure the flow process flow. When the electric conductivity of fluid flows in the pipe, an electrode voltage E is induced between a pair of electrodes placed at right angles to the direction of the magnetic field. The electrode voltage E is directly proportional to the average flow velocity V . The mathematical form can be given as $E \propto VBD$. A pair of electrodes installed on the wall of the electromagnetic flow meter. The schematic of the principal of electromagnetic flow meter is illustrated in Fig. 3-3. In this study, OMEGA FMG80A was used. The data acquiring system is used Lab-View for correcting a signal from the flow meter and convert to the flow velocity as output.

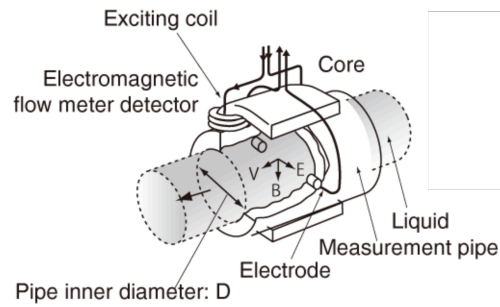


Fig. 3-3. The working principle of the electromagnetic flow meter [50].

- Electromagnets

The magnetic field was generated with iron core electromagnets clearly seen later in Fig. 3-4 that was powered by a Neeltran 12-pole DC rectifier. The dimension of a set of electromagnets was measured 14cm width and 74cm length. The coils were actively cooled capable of steady state operation 2000amps. The strength of the magnetic field can be produced at 0.28T between a set of electromagnets. The magnetic field also varied less than 1.00% in the spanwise direction, though in this configuration the peak field strength occurred at the edge of the flow due to the flux concentration at a set of electromagnet faces. The magnetic field strength varied less than 1.00% in the stream-wise direction over the experimental region. However, the main test section is 0.00% difference of the magnetic field so that the uniform field was generated.

- Ceramic heater

The heater was installed on the free-surface of the liquid metal film flow as heated locally and parallel to the free-surface. To the less influence the induced current distribution, the heater material was made of ceramic as low electrical conductivity. In this experiment, a heater made of "Walton Ultramic Advanced Ceramic Heater" was used. The size of the heater is 75.0mm for the flow direction and 25.0mm for the spanwise direction. The heater was a simple resistive element ensconced in Aluminum Nitride Ceramic. As the heater increases the resistance value, the temperature increases linearly

and generates a constant heat flux. The size of ceramic heater was used in the experiment with using the single obstacle in this experiment. On the other hand, $50.0 \times 25.0 \text{ mm}^2$ size ceramic heater made from “Sakaguchi-dennetsu” was used in case of the inline hemisphere arrangement.

- Circulation pump

To set the pump flow rate as a constant value for engineering aspect, the depth increases with increasing the strength of the magnetic field, therefore the height of the heater should be adjusted by the heater installation jig on each strength of the magnetic field. To keep the fluid temperature as constant with steady-state heating by the heater on the free-surface, a heat exchanger in this experiment implemented on the return line to the pump. The building de-ionized water was used as the coolant, which typically provided temperature control to approximately 1.0 to 2.0°C over the experiment of a day. While not ideal, the changes to viscosity, thermal conductivity, and heat capacity are still small over this small change in temperature.

- Argon gas lines

As mentioned above for oxidation process of GaInSn, the experiment must prevent GaInSn oxidation with using Argon gas due to the less chemical reactivity. The physical characteristic of Argon gas was listed in Table 3-1. Argon gas line could control by gas lines. Gas lines connected to the test channel and a storage tank of the working fluid. When injecting GaInSn to the flow channel, the pressurized to the GaInSn inside a storage tank for makes high pressure, and push GaInSn to the flow circulation.

Table 3-1. The physical characteristic of Argon gas at 26.9°C [51].

Properties	Value
Thermal conductivity [$\text{Wm}^{-1}\text{K}^{-1}$]	0.018
Specific heat [$\text{J kg}^{-1}\text{K}^{-1}$]	0.125
Density [kgm^{-3}]	1.335
Viscosity [m^2s^{-1}]	19.78

3.2-2 Diagnostics

To measure the fluid temperature for understanding thermal mixing performance of localized heat free-surface liquid metal film flow under the transverse magnetic field by various shapes of protrusions, 76-micron K-type thermocouples (chromel-alumel) were installed at the inlet, outlet and the bottom of the test channel. The temperature of the heater was monitored by a thermocouple installing inside the heater. The thermocouple signals were fed into NI PXIe-4353 24-bit, 32-channel thermocouple input module with 8 built-in cold-junction compensation channels. This module allowed for sampling rates up to 90samples/s/ch. To avoid strong aliasing of electrical noise from the rectifier for the magnetic field at harmonics of 120Hz, the thermocouples were sampled at 83Hz and smoothed in post-processing using a 0.25s window to filter the unavoidable pickup from the magnet coil current ripple.

The flow rate in this experiment was controlled through the data acquisition (DAQ) system by setting the speed of a 2hp DC Leeson electric motor directly coupled to the pump. It should be noted that the actual flow rate depended on not only the pump speed but also the fill level since the fill level dictated the required pressure gradients needed to raise the fluid to the height of the free-surface. Therefore, the relationship between pump speed and flow rate from one fill to another was not repeatable. However, for a given fill level, the flow rate was a linear function of pump speed. A small quadratic correction accounted for the roll-off observed at high flow rate when the pump efficiency began to drop.

The diagnostics were controlled and recorded with a LabVIEW routine coupled with NI PCI-6225 16-Bit 80-channel multifunction data acquisition card and NI PXIe-1073 chassis. For most experiments, a 1kHz sample rate was more than sufficient to resolve the timescales of importance in the experiment, though some surface fluctuation experiments were recorded at 5kHz to capture more of the turbulent spectrum.

3.2-3 Flow under the non-magnetic field

Before starting the MHD experiment, it should have to measure the own characteristic of the test facility for evaluating the fundamental behavior. In this section shows some experimental results in case of installed the cube, the delta-wing and no-obstacle under the no-magnetic field as the reference case. Note that all data analysis was referred from Appendix.

3.2-3-1 Experimental apparatus and conditions

The experimental conditions in case of reference are listed in Table 3-2. Some specific points of reference case experiment are described as follows:

- (1) The obstacle located on the upstream of the heater on the free-surface. The locations of obstacles, the heater on the free-surface and TCs on the bottom-wall are illustrated in Fig. 3-4.
- (2) The heater in this experiment was used as the same heater used in the experiments [49]. The size was $75 \times 25\text{mm}^2$. The heater power was injected as 0.18MW/m^2 .
- (3) The fluid depth was 15.0mm as a constant.
- (4) The obstacles used in this experiment were the cube and the delta-wing. The size configuration in Fig. 3-5. From the numerical simulation results, the blockage ratio of 10.0% is appropriate for heat transport. Thus, this size was used in this experiment. Both of obstacles were made of acrylic resign.
- (5) The heat loss is very important for discuss thermal characteristics, it is proportional

to the averaged flow velocity u_0 and the temperature difference between the temperature at the bottom-wall T_m and the bulk temperature T_b as referred to Appendix. In addition, it could be affected by the thermal characteristic of the wall material. The material of walls of LMX is not perfectly covered by the thermal insulation, some parts are made by SUS316 such as on the inlet/outlet of the test channel. The heat loss of the LMX experiment was between 2.20% to 15.1%.

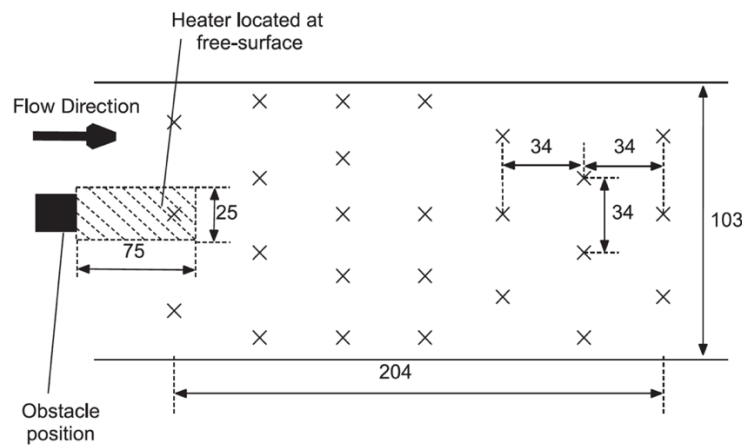


Fig. 3-4. Schematic of obstacle location, heater location and TCs mapping on the bottom-wall of the test channel (all dimensions are in [mm]; x-marks show TCs locations).

Table 3-2. The experimental conditions of reference case.

Parameters	Symbols	Value
Reynolds number [-]	Re	$1.15 \times 10^4, 1.20 \times 10^4, 1.80 \times 10^4$
Flow rate [Lmin^{-1}]	Q_f	5.67, 7.57
Injected heater power [W]	Q_{in}	338

Note that the Reynolds number was based on hydrodynamic perimeter $L = 4S/(2H + W)$ where, S is a cross-sectional area of the channel, H is a depth of film-flow and W is a width of the channel.

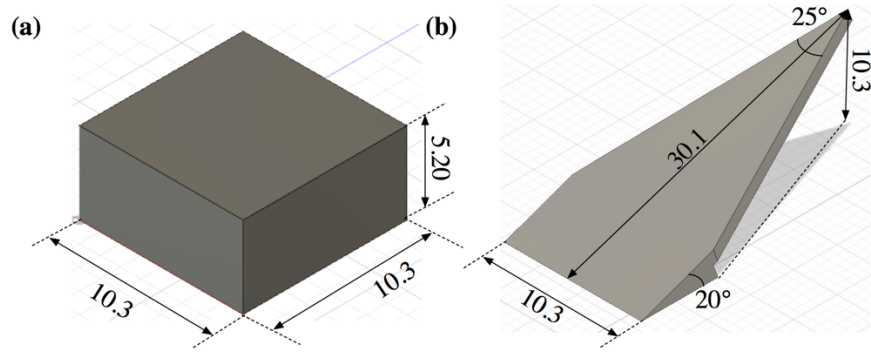


Fig. 3-5. The obstacle size configurations (all dimensions are in [mm]) : (a) Whole-view of the cube and (b) Whole-view of the delta-wing.

3.2-3-2 Temperature rise at the bottom-wall

For many practical purposes, the liquid metal in a fusion reactor would have constraints on the maximum allowance of increasing the fluid temperature caused by increased evaporation, joule heating effects that occur at elevated temperature. To prevent this significant problem, it should be transported heat from the free-surface to the bottom wall efficiently described in Chapter 1. Due to this, a temperature rise at the bottom-wall is very important for comparison of the heat transport performance of each configuration and, it is possible to understand the thermal characteristic at the bottom-wall for proposing the method of cooling. Additionally, a normalized temperature distribution on the bottom-wall gives a knowledge of some characteristic of temperature distribution such as the shape, the location of the distribution and hot spot.

• In case of an absence of obstacle

The temperature rises distributions in case of an absence of obstacles on $Re=1.20 \times 10^4$ and 1.80×10^4 are shown in Fig. 3-6. The reason of the maximum temperature rise was valued 2.5°C , this makes easier to compare for other cases. In case of temperature rise at $Re=1.20 \times 10^4$ was higher than the temperature rise at $Re=1.80 \times 10^4$. This was caused by the fluid transport behavior near the free-surface.

Due to this, the high temperature fluid was transported to farther downstream of the channel. This tendency has been also observed on the normalized temperature distributions in Fig. 3-7. The whole distribution at $Re=1.80 \times 10^4$ located on further downstream compare than the distribution at $Re=1.20 \times 10^4$. From these results, it can be found that localized heated high temperature fluids near the free-surface have been transported to the downstream under high Reynolds number.

In addition, the maximum temperature at the $Re=1.20 \times 10^4$ are 0.5°C higher than the case of the $Re=1.80 \times 10^4$, the relatively high temperature fluids have been transported to the downstream of installing TCs area. This behavior suggests that the experiment for detecting the temperature characteristic at the bottom-wall should be conducted under the relatively low Reynolds number.

• **In case of the cube**

Figure 3-8 shows the temperature rises distributions in case of installed the cube at the bottom-wall under two different Reynolds numbers. Comparison with the case of an absence of obstacle in Fig. 3-6, there are very similar temperature rises. At $Re=1.20 \times 10^4$, the area of the temperature rise over 1.50°C was wider than that of the no-obstacle case. From the normalized temperature distributions in case of installed the cube under the same Reynolds number in Fig. 3-8. The location of distributions was same as the reference case which means the temperature distribution concentrates at the wall near the cube.

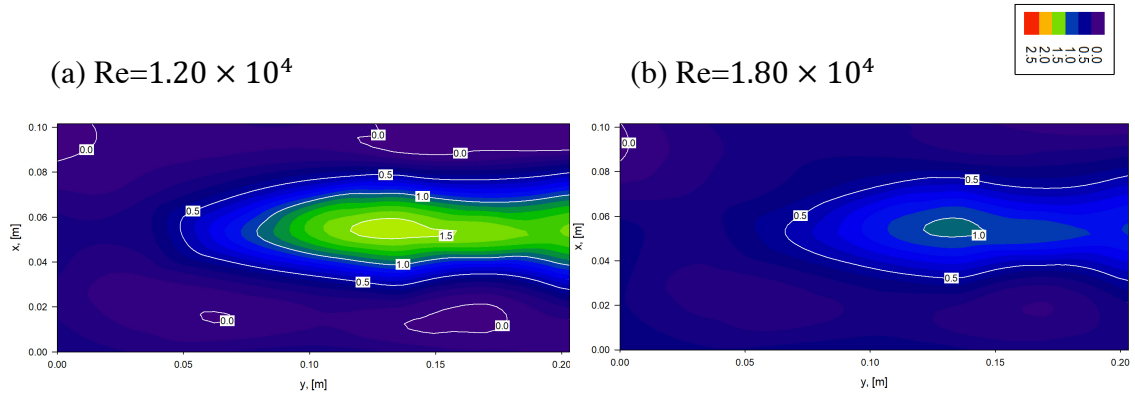


Fig. 3-6. The temperature rise distribution at the bottom-wall of the test channel in case of an absence of obstacles without the magnetic field.

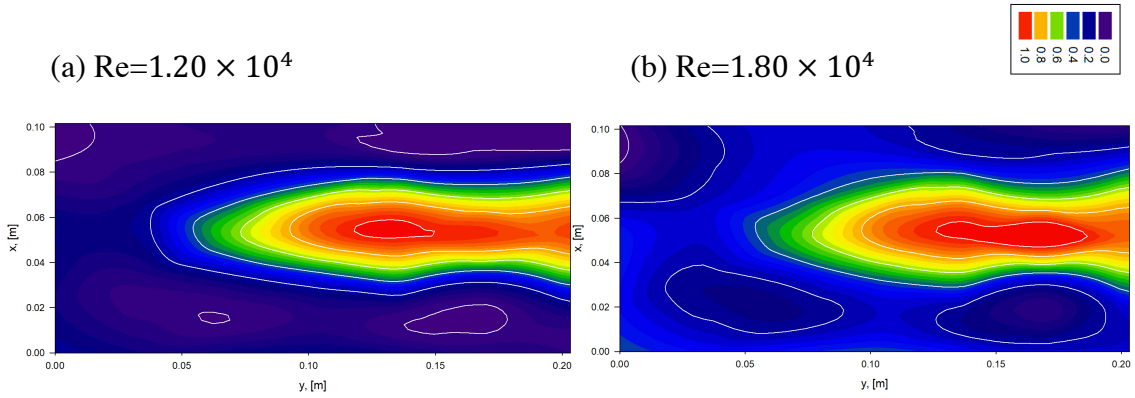


Fig. 3-7. The normalized temperature distribution at the bottom-wall of the test channel in case of an absence of obstacles without the magnetic field.

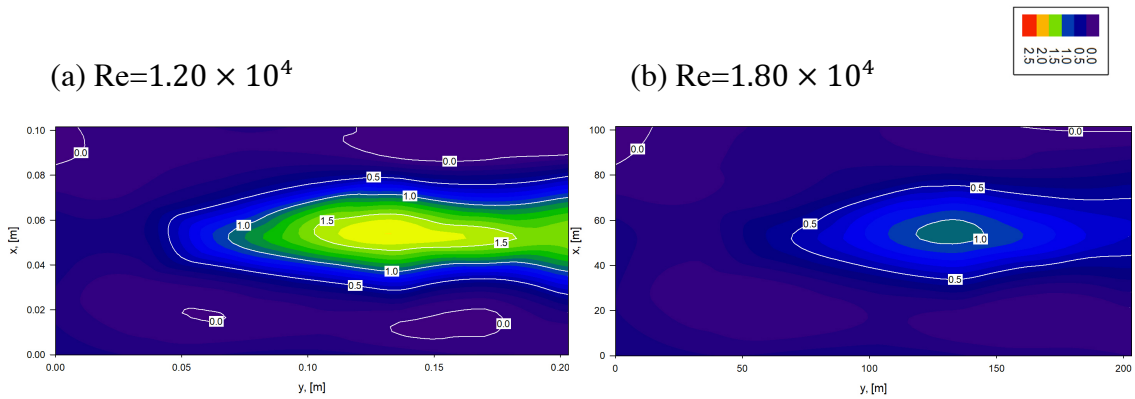


Fig. 3-8. The temperature rise distribution at the bottom-wall of the test channel in case of installed the cube without the magnetic field.

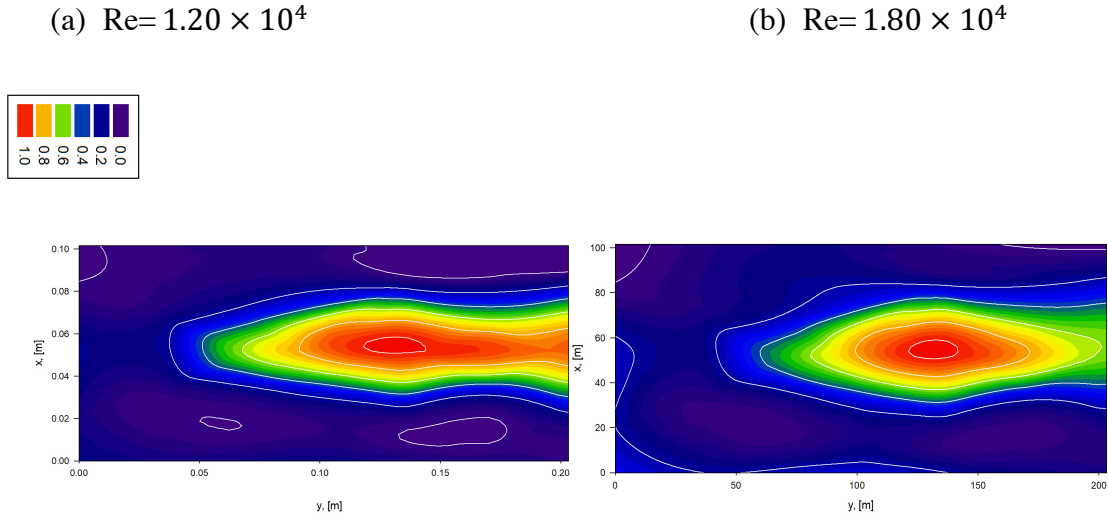


Fig. 3-9. The normalized temperature distribution at the bottom-wall of the test channel in case of installed the cube without the magnetic field.

• **In case of the delta-wing**

The temperature rises in case installed the delta-wing of reference case was shown in Fig. 3-10. The temperature rise is reached on 2.43°C at the maximum under $Re = 1.15 \times 10^4$. Even 500 difference of Reynolds number between $Re = 1.15 \times 10^4$ and $Re = 1.20 \times 10^4$, there are scientifically difference of temperature rise. In addition, comparison to other configurations, the temperature rise in case of installed the delta-wing 0.5°C higher than others at $Re = 1.80 \times 10^4$. This is to say, the delta-wing transported the relatively large amount of high temperature fluids comparison to the case installed the cube and the case of an absence of obstacle.

Figure 3-11 shows the normalized temperature distributions in case of installed the delta-wing. The shape of the distributions was symmetry on the center of $y = 5.15 \times 10^{-2}\text{m}$ line. Another characteristic is the peak temperature rise located on the most upstream. This is also an important factor for increasing the performance of heat removal. The detail discussions are described in subsection 3.3-3-E.

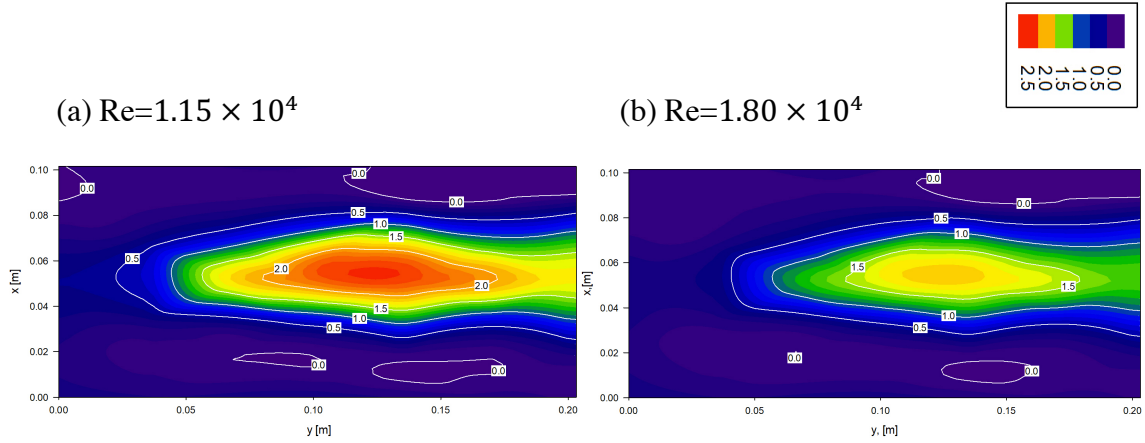


Fig. 3-10. The temperature rise distribution at the bottom-wall of the test channel in case of installed the delta-wing without the magnetic field.

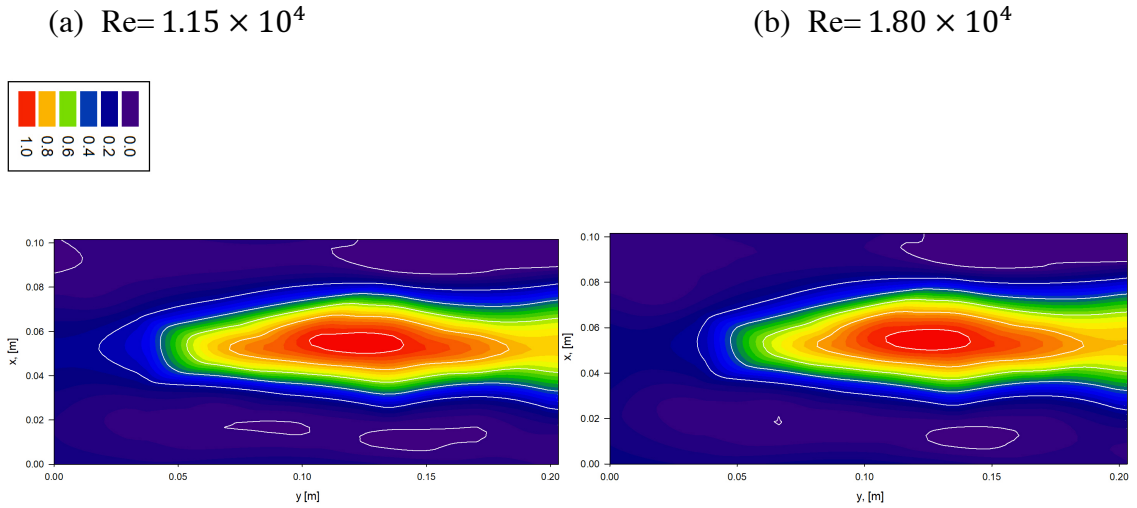


Fig. 3-11. The normalized temperature distribution at the bottom-wall of the test channel in case of installed the delta-wing without the magnetic field.

3.2-3-3 Heat flux at the bottom-wall

The measured temperature data can be deformed to the defined heat flux as Eq. (4) on Appendix. The heat flux analysis indicates the area which is heated or cooled by negative or positive heat flux. It is not only depending on the temperature at the inlet of the channel like the temperature rise distribution introduced on the previous subsection,

that includes the energy balance of the test channel. For the quantitative discussion, it can be considered that the heat flux analysis is better than the discussion using temperature rise distributions.

Figures 3-12, 3-13 and 3-14 show the heat flux distributions in an absence of obstacle case, the case of installing the cube at $Re=1.20 \times 10^4$, the case installed the delta-wing at $Re=1.15 \times 10^4$ and three configurations at $Re=1.80 \times 10^4$. Note that, the minus heat flux means the heat flux directed to the bottom-wall from the bulk of fluids so that the area was heated. The relatively high heat fluxes appeared on the centerline of the wall along the streamwise line and have a heat flux of: over $|q_w| = 6000$ for the case of the delta-wing, $|q_w| = 3000$ for the cube and $|q_w| = 2000$ for the no-obstacle case at $Re=1.15 \times 10^4$ and $Re=1.20 \times 10^4$, respectively. The heat flux over $|q_w| = 4500$ for the case of the delta-wing, $|q_w| = 1500$ for the cube and $|q_w| = 1000$ for the delta-wing case at $Re=1.80 \times 10^4$. This tendency is similar to the order of the temperature rise distributions. Comparison of the case of installed the cube and no-obstacle case, there is 1.50 times difference of the relatively high heat flux. Particularly, the relatively high heat flux in case of installed the delta-wing was three times higher than the no-obstacle case at the relatively low range Reynolds number. In addition, the relatively high heat flux at $Re=1.80 \times 10^4$ shows four times difference between the case of no-obstacle and the delta-wing. Therefore, the heat flux analysis suggested the delta-wing induces high heat transport performance.

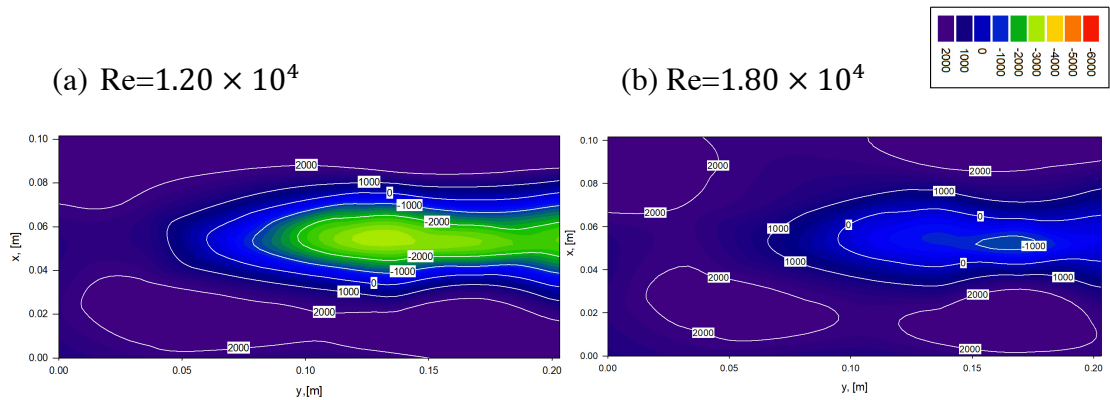


Fig. 3-12. The heat flux distribution at the bottom-wall of the test channel in case of an absence of obstacles without the magnetic field.

(a) $Re=1.20 \times 10^4$

(b) $Re=1.80 \times 10^4$

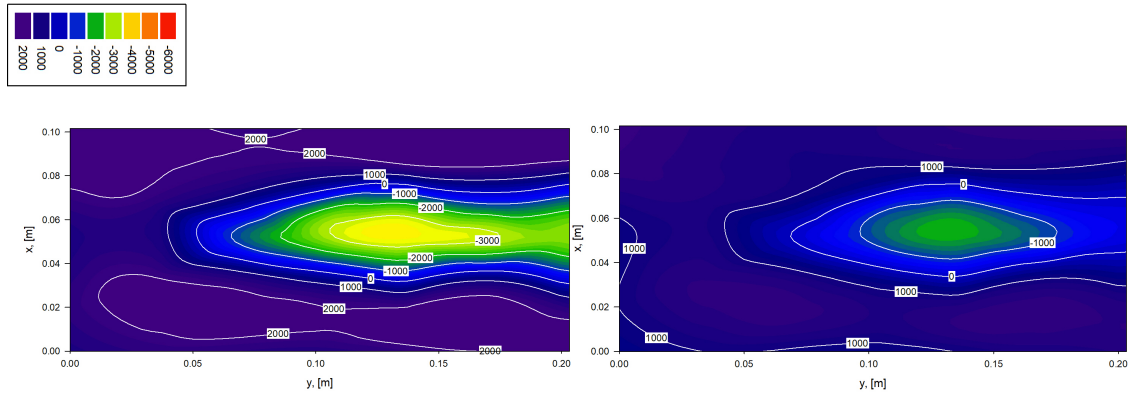


Fig. 3-13. The heat flux distribution at the bottom-wall of the test channel in case of installed the cube without the magnetic field.

(a) $Re=1.20 \times 10^4$

(b) $Re=1.80 \times 10^4$

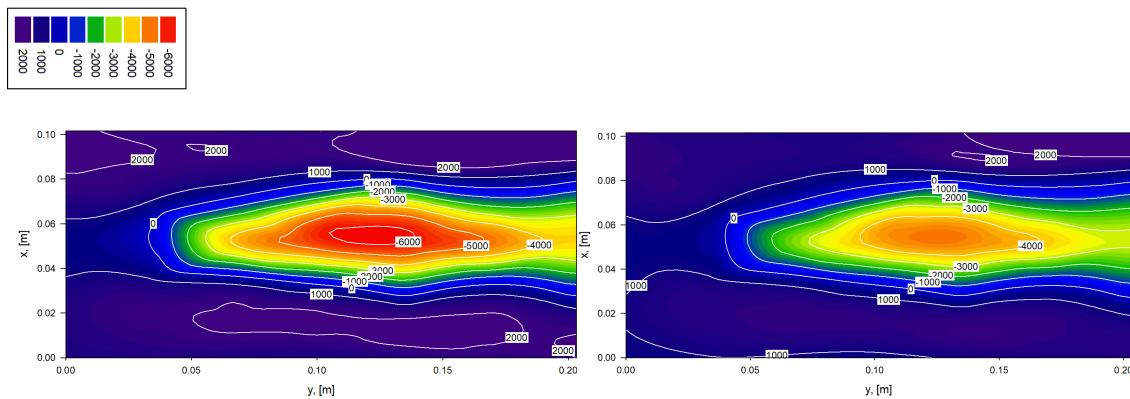


Fig. 3-14. The heat flux distribution at the bottom-wall of the test channel in case of installed the delta-wing without the magnetic field.

3.2-3-4 Comparisons

Due to the opaqueness of liquid metal, the experimental results are not enough for understanding the thermal characteristic of the liquid metal film flow. The comparison of the experimental results and numerical results should be conducted. In this subsection, comparison of numerical results which is introduced in Chapter 2 and above experimental results for finding the mechanism of heat transport.

From the vorticity distribution on the cross-sectional area of the channel in Fig. 2-7. The delta-wing generates a pair of vortices which the rotational direction is directed to the bottom-wall as the suction flow on the center behind of the delta-wing. This behavior is one of the reasons for the best heat transport performance in the experimental result. As regard to the experimental results under high Reynolds number, the temperature rises and heat flux decreases. However, it should be increased the vorticity under the relatively high Reynolds number and enhance thermal mixing. This is to say; an effect of the suction flow makes larger than that under relatively low Reynolds number. It can be considered the reason that an inertial effect might be stronger than vertical transport effect by a pair of vortices. Therefore, the high temperature fluid was transported to the further downstream of the channel.

3.2-3-5 Discussions

In this study, the delta-wing and the cube were used as vortex generators, and their wake effects on thermal mixing in liquid metal ($\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$) free-surface flow were investigated by using LMX at PPPL. To understand the thermal mixing induced by these obstacles, the liquid metal film-flow in the channel without magnetic fields was partially heated and the temperature distributions on the channel bottom were measured.

Based on the comparison of the temperature rise distributions, we conclude that the delta-wing transports the high temperature fluid heated at the free-surface to the bottom-wall more efficiently than the cube and the reference case.

Based on the comparison of the normalized temperature distributions, the location of the distribution in case of installed the delta-wing was the most upstream. In contrast, that location in case of no-obstacle located on the further downstream. In other words, the location of distribution and hotspot is physically same meaning. This is a very important characteristic for rising the heat removal performance. It is because that the if hot spot located near the heating area, there are possibilities to remove heat from the

liquid metal film flow as quickly as possible. Therefore, the delta-wing is possible to transport the high temperature fluid near the free-surface to the bottom-wall in short time.

Based on the comparison of heat flux contours and the maximum heat flux points, it is found that the obstacle enhanced the thermal mixing of the fluid, and the delta-wing allows the faster mixing of the higher temperature fluid from the free-surface to the wall compared to the cube.

3.2-4 A single delta-wing experiment

Before starting the MHD experiment, it should have to measure the own characteristic of the test facility for evaluating MHD effect. In this section shows some experimental results in case of installed the cube and the delta-wing and no-obstacle under no-magnetic field. Note that all the data analysis was referred from Appendix.

3.2-4-1 Experimental apparatus and conditions

The experimental condition was the same as the previous experiment, and the transverse magnetic field conditions were added to this experiment. At LMX, the maximum interaction parameter was conducted as $N_{\max}=5.02$ based on the pump makes a constant flow rate as 5.67Lmin^{-1} . Figure 3-15 shows the relation between the heat loss and interaction parameter. Error bars are induced by the fluctuations of flow rate. The heat loss in this experiment was increased with increasing the strength of the transverse magnetic field due to the velocity suppression by the actual magnetic field. The suppression velocity affected the energy balance. The maximum heat loss of this experiment 9.80%. The velocity suppression occurred under the transverse magnetic field, it should be normalized the experimental conditions for various N . In this study, the pump head can be detected by own setting as the same constant for all experimental cases. Hence, pump head was handled at constant flow rate 5.67Lmin^{-1} in all experiments. The experimental conditions in this study were summarized in Table 3-3.

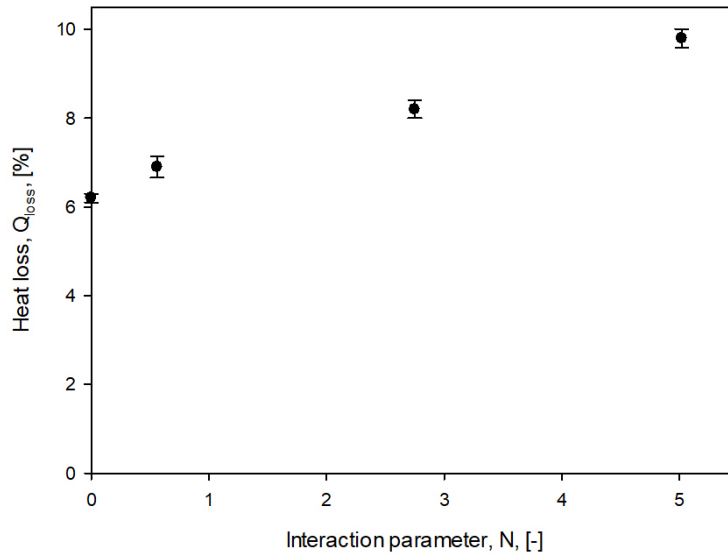


Fig. 3-15. The relationship between the heat loss and interaction parameter in case of the experiment with installing a single delta-wing under the uniform transverse magnetic field.

Table 3-3. The experimental conditions in case of installed the delta-wing under the uniform transverse magnetic field.

Parameters	Symbols	Value
Reynolds number [-]	Re	1.20×10^4
Interaction parameter [-]	N	0 – 5.02
Flow rate [Lmin ⁻¹]	Q_f	5.67
Injected heater power [W]	Q_{in}	338

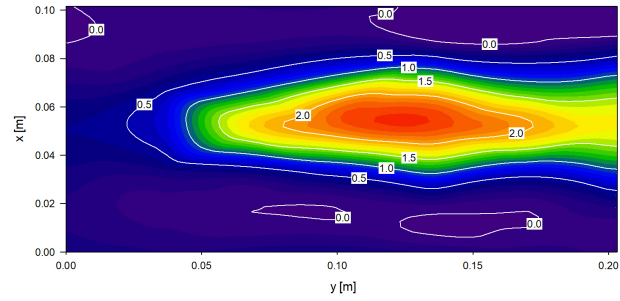
3.2-4-2 Temperature rise at the bottom-wall

Figure 3-16 shows the temperature rise distributions under various N. The tendency of distributions is decreasing the temperature rise with increasing Interaction parameter. This to say, the uniform transverse magnetic field suppressed thermal mixing. According to Rhoad [49], he had reported that the temperature at the bottom-wall decreased with

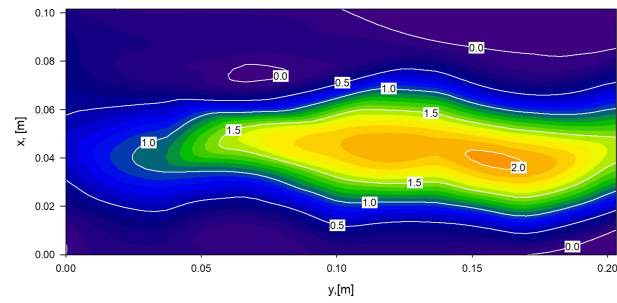
increased the strength of the transverse magnetic field. Thus, the similar results were obtained in this experiment. The non-symmetrical distribution was observed under $N = 0.56$. The reason of this distribution, it can be estimated that two factors: (1) The misalignment of obstacle generates a pair of vortexes which the axis directed to the direction inclined relative to the flow direction. (2) The magnetic field affected the vortex as bending as described on subsection.3.2-1. In case of (1), the vortex transported the heat to the right or left of the bottom-wall. Hence, the distribution makes non-symmetrical. On the other hand, the vortex might be affected as bending by the transverse magnetic field in case of (2). The detail description was described later about which is the cause for this results.

Figure 3-17 shows the normalized temperature distribution under various N . Based on the comparison the distribution under $N=0.00$, $N=2.75$ and $N=5.02$, the locations of the peak of the distribution were different between $N=0.00$ and $N=5.02$. The location of the peak was moved to the downstream with increasing N . The reason for this behavior was caused by the changing the streamwise velocity distribution on the vertical direction. From the numerical result, the local velocity near the free-surface was faster than that on the bulk under the transverse magnetic field. This flow structure may be transported the high temperature fluid near the free-surface to the downstream. Another characteristic was the symmetrical distribution on the center of the channel except for $N=0.56$ case. In contrast, the shape is no-symmetrical in case of $N=0.56$. This can be considered that vortex bending behavior may have occurred or the misalignment of the delta-wing. I will introduce distributions under various conditions later. Since this is an only asymmetric shape, it can be considered that this result was a strange result.

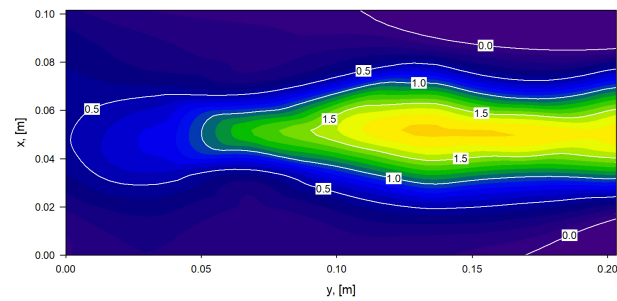
(a) $N=0.00$



(b) $N=0.56$



(c) $N=2.75$



(d) $N=5.02$

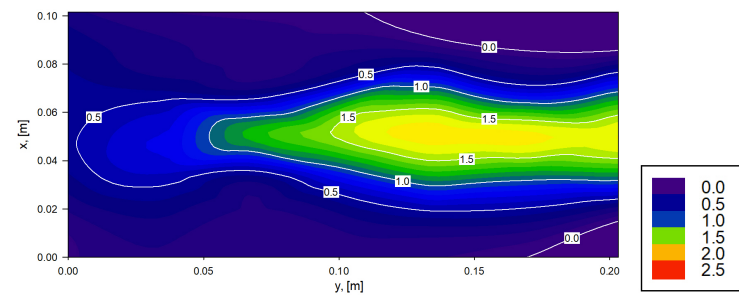
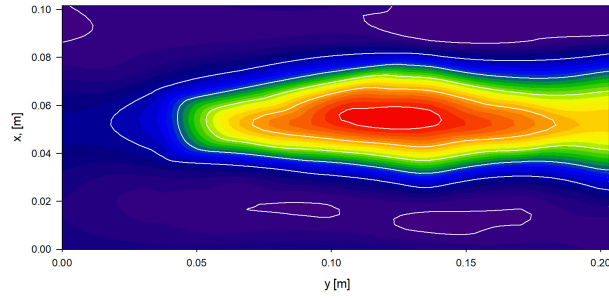
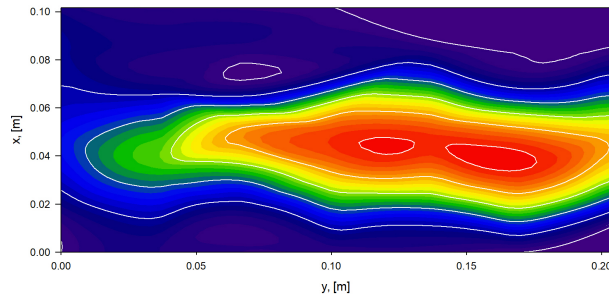


Fig. 3-16. The temperature rise distribution at the bottom-wall of the test channel in case of installed the delta-wing under the uniform transverse magnetic field.

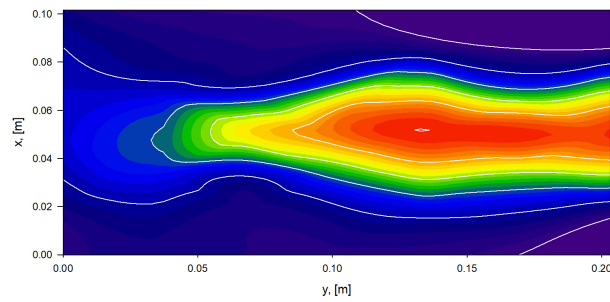
(a) $N=0.00$



(b) $N=0.56$



(c) $N=2.75$



(d) $N=5.02$

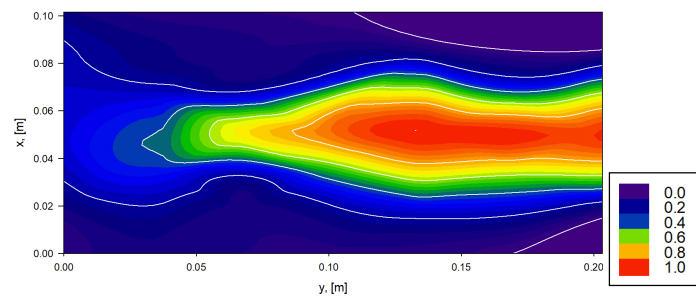


Fig. 3-17. The normalized temperature distributions at the bottom-wall of the test channel in case of installed the delta-wing under the uniform transverse magnetic field.

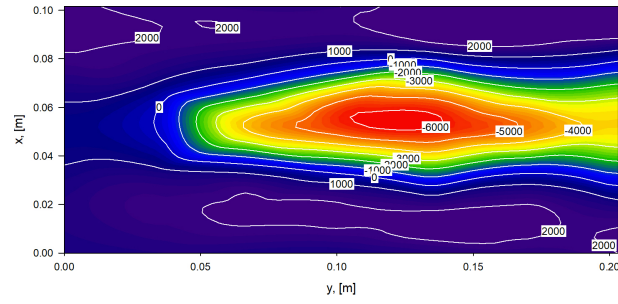
3.2-4-3 Heat transport performance

To evaluate the heat transport performance, heat flux analysis and the efficiency of heat transport are useful. In this subsection, the results of heat flux analysis and the dependency of interaction parameter for the efficiency of heat transport were described.

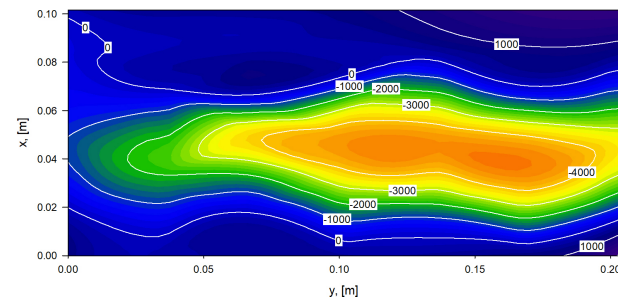
Figure 3-18 shows the heat flux distributions at the bottom-wall under various interaction parameters. The effect of the transverse magnetic field makes the decreasing heat flux. The relatively high heat flux was 2.00×10^3 difference between $N=0.00$ and $N=5.02$ so that approximately 30.0% decreasing. In addition, there are similar heat flux at $N = 2.75$ and $N = 5.02$. This is to say, the heat flux converged to one value $|q_w| = 4.00 \times 10^3$. Between $N=0.00$ and $N=0.56$, there are scientifically drop 1.00×10^3 . Thus, it can be found that the thermal characteristic changed drastically when input the transverse magnetic field.

The relationship between the efficiency of heat transport and interaction parameters are plotted in Fig. 3-19. The tendency of the effect of the magnetic field shows that the efficiency of heat transport decreased with increasing interaction parameter (N). In addition, Fig. 3-19 shows that there was an inflection area between $N=0.56$ and $N=2.75$, the efficiency of heat transport decreased 23.0% decrease. These are to say, the transverse magnetic field suppressed heat transport performance and the effect of the magnetic field would be strong even the relatively low strength of the field. However, there was no big difference between $N=0.00$ and $N=0.56$. The behavior of this can be considered that the liquid metal film-flow under $0.56 > N$ which is the inertial force stronger than the electromagnetic force can be transported heat similar to the reference case. In contrast, the heat transport performance in case of $2.75 < N$ would be affected by the relatively strong electromagnetic force. Therefore, there is some behavior of changing the heat transport performance across $0.56 < N < 2.75$.

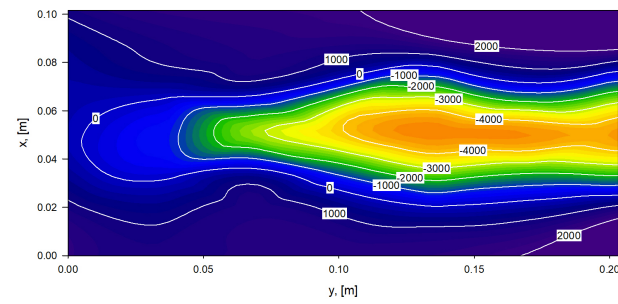
(a) $N=0.00$



(b) $N=0.56$



(c) $N=2.75$



(d) $N=5.02$

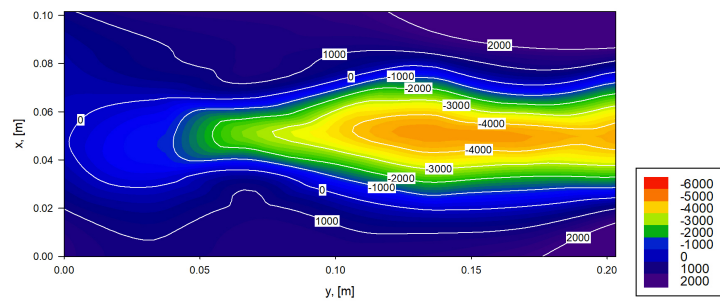


Fig. 3-18. The heat flux distributions at the bottom-wall of the test channel in case of installed the delta-wing under the uniform transverse magnetic field.

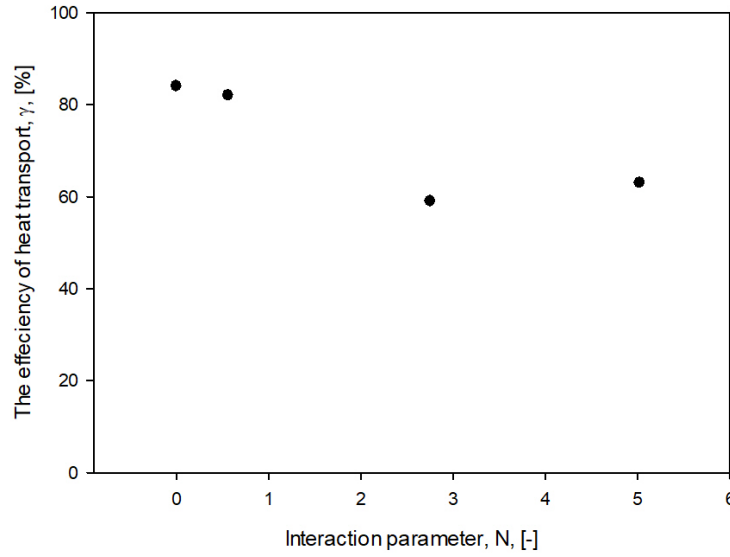


Fig. 3-19. The efficiency of heat transport as a function of interaction parameter in case of installed the delta-wing under the uniform transverse magnetic field.

3.2-4-4 Thermal fluctuations

The thermal fluctuations were primarily induced by vortex shedding from the delta-wing, and by the turbulence of the flow. Additionally, the characteristic of vortex near the bottom-wall could be detected. Based on the experimental data we measured the temperature at the bottom-wall, the fluctuations of temperature as thermal fluctuations were evaluated.

The amplitudes of average wall temperature fluctuations were obtained by spectral analysis for various interaction parameters as shown in Fig. 3-20. Note that, the specific amplitudes were very small in case of $N=0.56$. This may be caused by some diagnostics problems. Except for the case $N=0.56$, the results presented that the amplitudes of temperature fluctuations decreased with increasing N . Especially, high amplitudes were observed in the wake of the delta-wing. On the other hand, the relatively low amplitudes located near the side-wall and the further downstream of the delta-wing. This means the thermal fluctuation was induced on the behind the delta-wing due to a pair of vortices. Based on this consideration, there are not observed vortex bending behavior.

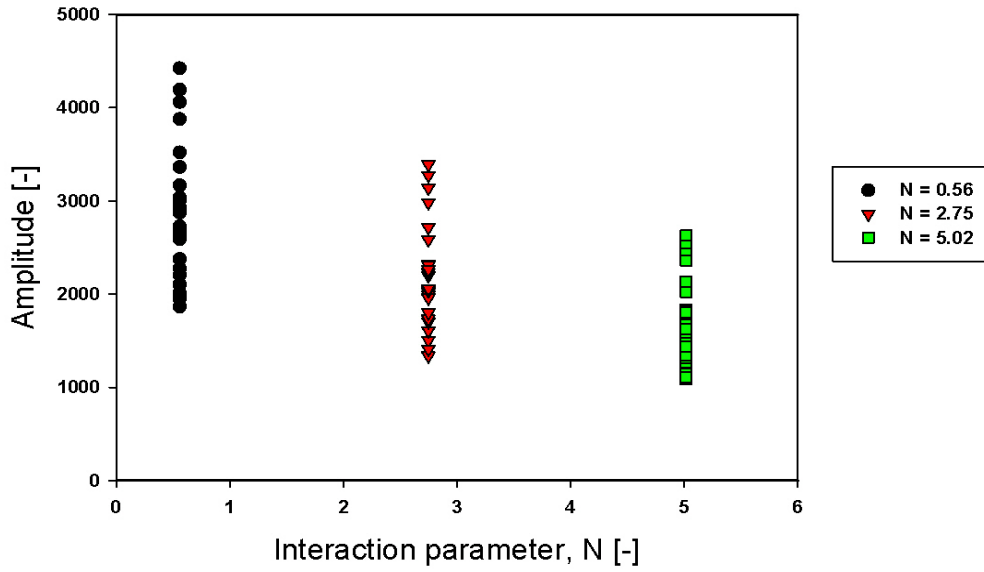


Fig. 3-20. Amplitudes of average wall temperature fluctuations for various interaction parameters.

3.2-4-5 Comparisons

This subsection described some findings by the comparison to the experimental results of transverse magnetic field case, reference case, and the numerical simulation results.

From the heat flux distributions with/without the transverse magnetic field at $Re = 1.20 \times 10^4$, an area of $q_w < -4.00 \times 10^3$ in case of MHD condition in case of installed the delta-wing larger than the reference case with installed the cube and no-obstacle case. This fact suggests that the heat transport performance of the delta-wing is higher than any other obstacles used in this study.

Based on the comparison of the vorticity distributions of the numerical results in Fig. 2-9 and the relation between amplitudes and N, both parameters were decreased with increasing interaction parameter N. Thus, these two results suggested that the vortex strength showed the same tendency as the amplitude. Therefore, the amplitude can indicate the vortex strength variation if the presence of a magnetic field. The amplitudes

decreased with increasing interaction parameter, so the vortex strength may be weakened due to the transverse magnetic field.

As the comparison of each normalized temperature distributions under various N , the peak in case $N=2.56$ and $N=5.02$ located on the further downstream than the peak location in case of the non-magnetic field. This is caused by the effect of the flow velocity field. From the numerical results of the vertical flow velocity distribution (Fig. 2-9), the velocity near the free-surface was faster than the bulk. It can be considered that this locally higher velocity transported the distribution to the downstream.

Based on the comparison of numerical and experimental results of the temperature/temperature rise distributions on the wall, the same tendency was observed. However, the experimental result has no results between $0.56 < N < 2.75$. The numerical results suggested that the temperature decreased gradually with increasing N . In addition, the vorticity distribution of the numerical results showed that the vorticity decreased with increasing N . If the vortex behavior related to the temperature data as mentioned on above, the temperature rise T_w in experimental results between $0.56 < N < 2.75$ should be decreasing gradually with increasing N . Therefore, the temperature distributions were likely to be affected by vortex behavior. For understanding the distribution shape in case of $N=0.56$, the numerical result in case of $N=0.56$ can be referred. The shape of the distribution was symmetrical in the numerical result. This means that the vortex bending behavior was not observed. In addition, $N=0.56$ is relatively low. If the vortex bending has occurred at $N=0.56$, the result over $N=0.56$ should be generated. Therefore, the vortex bending behavior may not occur at $N=0.56$.

3.2-4-6 Discussions

The main findings of this experiment were summarized below:

- (1) Temperature rise/heat flux/the efficiency of heat transport decreased with increasing the strength of the uniform transverse magnetic field.
- (2) No-symmetrical temperature/heat flux distributions were observed under $N=0.56$.

- (3) In case of high interaction parameter range, the distributions were very similar.
- (4) The normalized temperature distributions moved to further downstream with increasing N .
- (5) Heat transport performance in case of installed the delta-wing was better than the reference case of an absence of obstacle even under the relatively highest interaction parameter.
- (6) The thermal fluctuation occurred at the center of the downstream of delta-wing. This is to say; there are not induce the vortex bending behavior.

The following discussions based on the findings above:

For the finding (1), the reason for this behavior caused by the effect of the changing the velocity distribution. From the result of the numerical simulation of velocity distribution, there is the velocity gradient between the free-surface and the bulk under the uniform transverse magnetic field. This is caused by MHD effect that makes the velocity near the free-surface faster than the velocity at the bulk. Locally fast flow velocity transported the relatively high temperature fluid near the free-surface, to the further downstream of the area of thermocouples installed at the bottom-wall. This behavior induced the temperature decreasing at the bottom-wall and affect the finding (4).

For the finding (2), No-symmetrical distributions caused by two factors as mentioned in the result section: (A) The misalignment of obstacle generates a pair of vortexes which the axis directed to the direction inclined relative to the flow direction. (B) The magnetic field affected the vortex as bending. From the numerical results, there were not existed vortex bending behavior and just weakened under low interaction parameter range. These suggested that a pair of vortexes damped with increasing the strength of the transverse magnetic field.

As regard to finding (3), this can be considered that the heat transport mechanism changed from the thermal mixing to the heat conduction. From numerical results in Fig. 2-6(c), there are similar results have been simulated. The reason for this behavior would

be affected by the vortex damping. If the vortex damped on the wake of heating location, there is no mechanism to transport the high temperature fluid near the free-surface to the bottom-wall. This is to say, the temperature inside the liquid metal film-flow stratified on the vertical direction. Therefore, heat conduction was given rise under the relatively high strength of the uniform transverse magnetic field.

In terms of increasing the performance of heat transport, the delta-wing makes the hotspot of the relatively high temperature on the wall. In other words, the delta-wing enhanced thermal mixing even under the field. Therefore, it can be considered that delta-wing is most appropriate for heat transport technique for MHD liquid metal film-flow under the transverse magnetic field.

3.2-5 An inline hemisphere arrangement

The experiment was performed with using an inline hemispheres arrangement because that the characteristics of the hemisphere as a vortex generator is technically appropriate as some advantages for the engineering. For example, the relatively low friction coefficient compare than any other obstacles in this study, easily metal-working and easy to install. In addition, hemisphere generates complex vortex structure and inducing turbulent. To make lower friction and high heat transport performance, the hemisphere arrangements can be chosen rather than other obstacles arrangements. In this section, the experimental results of the thermal characteristic in case of installing the inline hemispheres were introduced.

3.2-5-1 Experimental apparatus and conditions

The experiment has been conducted at LMX. In the previous experiment under the transverse magnetic field, the highest interaction parameter had conducted at $N=5.02$. In this experiment, the maximum interaction parameter was $N_{\max}=9.25$ based on 7.26Lmin^{-1} and 10.0Lmin^{-1} . Regarding the flow meter in this experiment, it was upgraded that can measure as higher resolution than the previous flow meter. Thus,

Reynolds number in this experiment could be evaluated as more details, the range of Reynolds number was $5.53 \times 10^3 \leq Re \leq 6.38 \times 10^3$. The characteristic number for dimensionless parameters was chosen as half of the hydrodynamic diameter. In addition, the pump was also upgraded to make flow circulation on higher flow rate, the heater on the free-surface was changed to the size $25.0 \times 50.0\text{mm}^2$. Additionally, the location of the heat exchanger was changed to the downstream of the electromagnetic pump due to the thermal generation inside the pump. The experimental parameters were listed in Table 3-4. The experimental apparatus illustrated in Fig. 3-21.

Hemispheres have been allied on parallel to the streamwise and spanwise direction as an inline arrangement. The schematic of arrangement was in Fig. 3-28. L_p is a streamwise-pitch-length: $1.75 \times 10^{-2}\text{m}$, $3.60 \times 10^{-2}\text{m}$ and $0.48 \times 10^{-2}\text{m}$. L_t is the distance from first TCs array: $L_t = 0.41 \times 10^{-2}\text{m}$ for $L_p = 1.75 \times 10^{-2}\text{m}$, $L_t = 0.41 \times 10^{-3}\text{m}$ for $L_p = 3.60 \times 10^{-2}\text{m}$ and $L_t = 0.17 \times 10^{-1}\text{m}$ for $L_p = 4.80 \times 10^{-2}\text{m}$. L_w is a spanwise-pitch-length of $1.95 \times 10^{-2}\text{m}$ in all cases. Thus, the experiment was three different streamwise-pitch-length arrangements. The summarized experimental configurations in this study is listed on Table 3-5.

Table 3-4. The experimental parameters in case of an inline hemisphere arrangement under the uniform transverse magnetic field.

Parameters	Symbols	Value
Reynolds number [-]	Re	$5.53 \times 10^3 - 6.38 \times 10^3$
Interaction parameter [-]	N	0.00 – 9.25
Flow rate [L min^{-1}]	Q_f	7.26, 10.0
Injected heater power [W]	Q_{in}	91.9

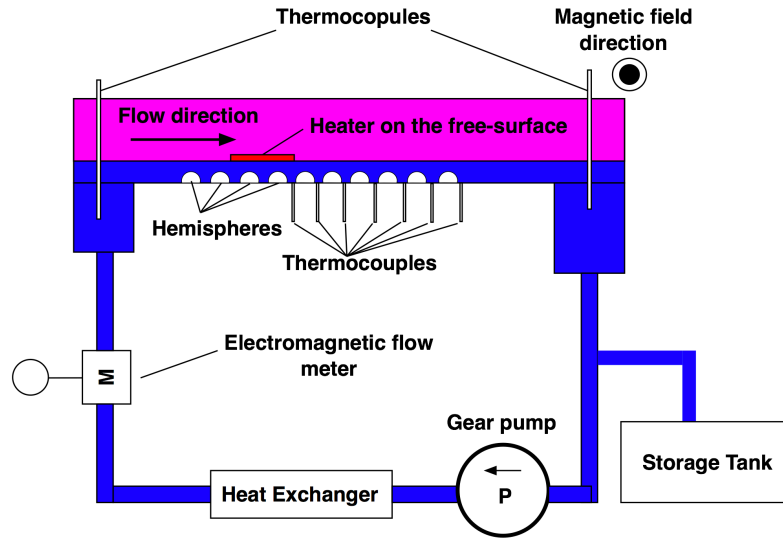


Fig. 3-21. The experimental apparatus of the experiment under the uniform transverse magnetic field.

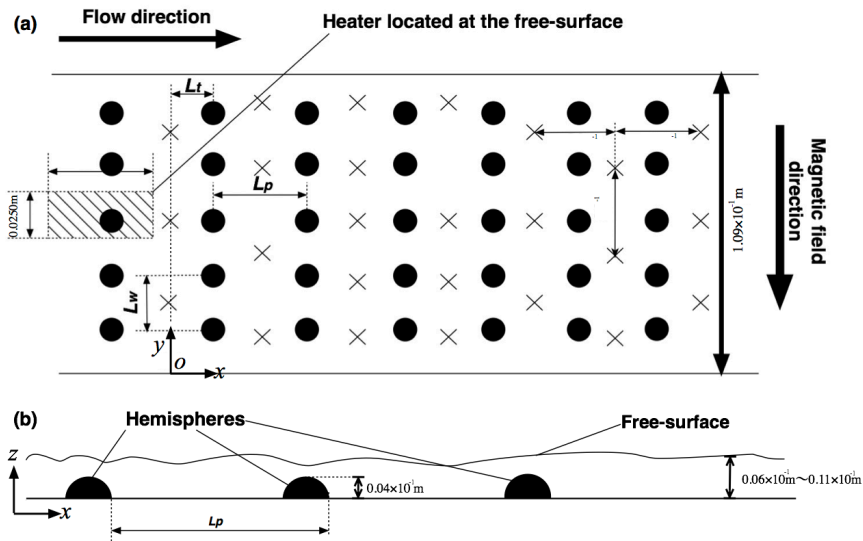


Fig. 3-22. Schematic of heater location, hemispheres locations and TCs mapping on the bottom-wall of the test channel(“x” marks show TC locations, “●” show hemispheres locations on the bottom-wall, x, y, z show the coordination, “o” is the origin of the coordination) .

Table 3-5. Experimental configurations for an inline hemispheres arrangement under the uniform transverse magnetic field.

Experimental index	Flow rate $Q_f[\text{L min}^{-1}]$	Streamwise-pitch-length $L_p[\text{m}]$	Interaction parameter $N [-]$
A	1.21×10^{-4}	1.75×10^{-2}	0.00 – 9.03
B	1.21×10^{-4}	0.36×10^{-1}	0.00 – 7.92
C	1.21×10^{-4}	0.48×10^{-1}	0.00 – 7.95
D	1.67×10^{-4}	1.75×10^{-2}	0.00 – 9.25
E	1.67×10^{-4}	0.36×10^{-1}	0.00 – 7.92
F	1.67×10^{-4}	0.48×10^{-1}	0.00 – 9.18

3.2-5-2 Temperature rise at the bottom-wall

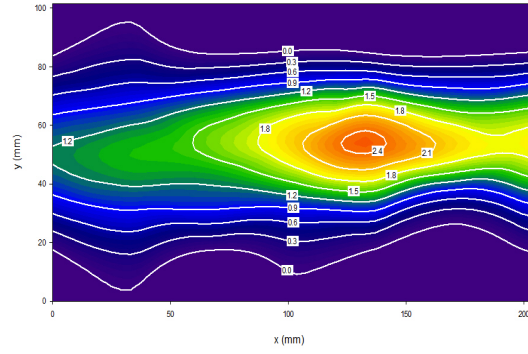
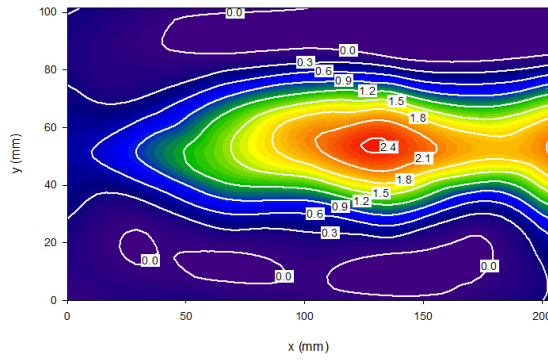
Figure 3-23 shows the temperature rise distributions at the bottom-wall of each streamwise-pitch-length in case of non-magnetic field ($N=0.00$) at near arbitrary Reynolds number. The temperature rises in case of (a) $L_p = 1.75 \times 10^{-2}\text{m}$ $\text{Re}=5.79 \times 10^3$ shows higher than the case (b) and (c). The temperature rises in case of the middle size of streamwise-pitch-length ($L_p = 0.36 \times 10^{-1}\text{m}$, (a)) were higher than any other cases and the high temperature rise region in case of the middle streamwise-pitch-length was the nearest location to the heater than other cases. This can be considered that the middle streamwise-pitch-length arrangement can transport heat to the bottom-wall relatively efficiency. In addition, the peak temperature rise of the distribution in case of $L_p=0.36 \times 10^{-1}\text{m}$ showed the highest temperature rise among three L_p cases, and it was found that the higher temperature rise region was bigger than others. This means in $N=0.00$ that the heat transport of the locally heated fluid on the free-surface to the bottom wall for the case of the middle streamwise-pitch-length ($L_p = 0.36 \times 10^{-1}\text{m}$) is larger than that of shorter $L_p = 1.75 \times 10^{-2}\text{m}$ or longer pitch length ($L_p = 0.48 \times 10^{-1}\text{m}$) cases. According to the previous studies [47, 52], the case of the 1.25 times longer the streamwise-pitch-length (middle length case) than the shortest streamwise-pitch-length

was shown the best heat transport performance of the obstacles in the inline arrangement. Moreover, it was worse the heat transport performance in case of the 1.50 times longer the streamwise-pitch-length than the shortest case.

(a) $L_p = 1.75 \times 10^{-2} \text{m}$; $\text{Re}=5.79 \times 10^3$

(b) $L_p = 0.36 \times 10^{-1} \text{m}$; $\text{Re}=5.79 \times$

10^3



(c) $L_p = 4.80 \times 10^{-2} \text{m}$; $\text{Re}=5.79 \times 10^3$

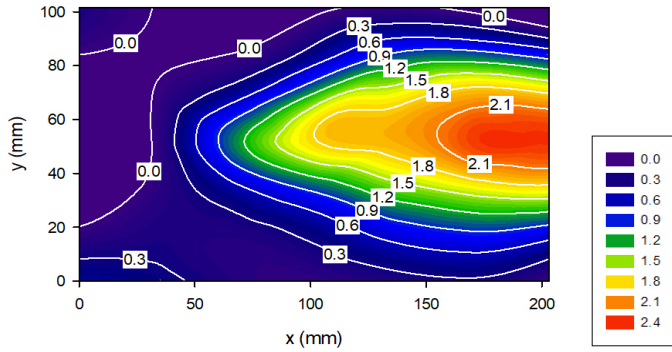
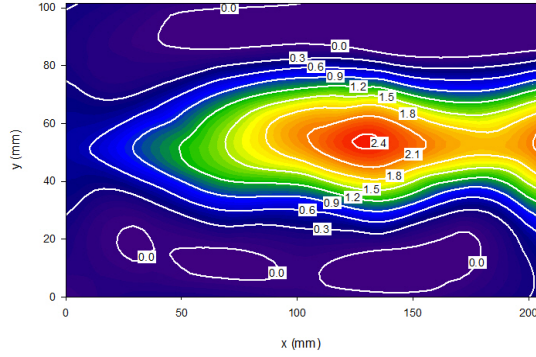
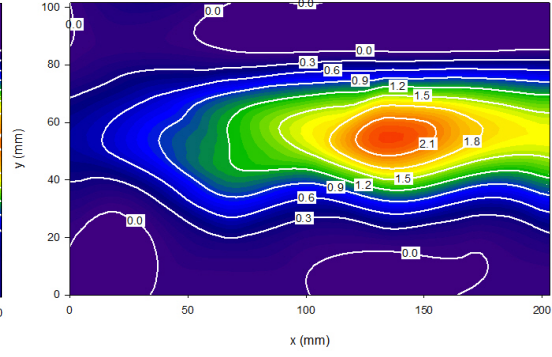


Fig. 3-23. Temperature rise distributions of each different L_p arrangements in case of $N=0.00$ at the near Reynolds number $\text{Re}=5.79 \times 10^3$ under no-magnetic field condition (“ $\times$ ” marks show the peak temperature rise location) .

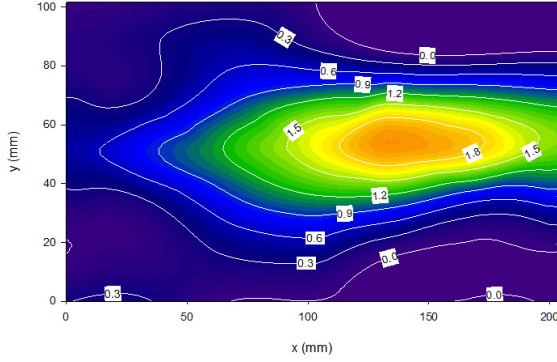
(a) $N = 0.00$, $Re = 5.76 \times 10^3$



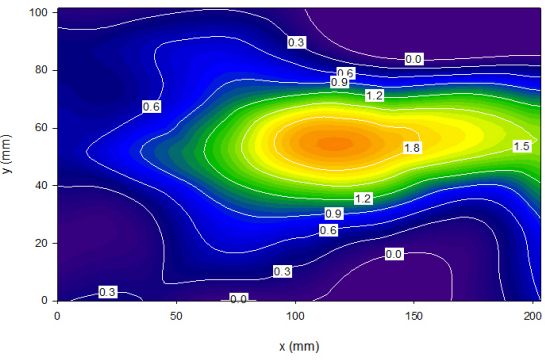
(b) $N = 0.36$, $Re = 5.73 \times 10^3$



(c) $N = 2.42$, $Re = 5.68 \times 10^3$



(d) $N = 5.59$, $Re =$



(e) $N = 9.03$, $Re = 5.53 \times 10^3$

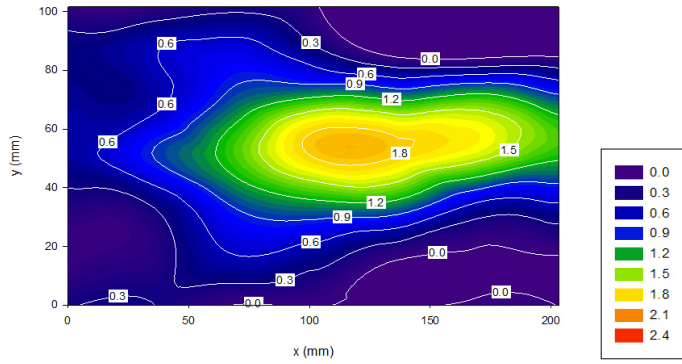


Fig. 3-24. Temperature rise distributions of $L_p = 1.75 \times 10^{-2}$ m arrangements under various interaction parameters (N) of the uniform transverse magnetic field (“ $\times$ ” marks show the peak temperature rise location).

Figure 3-24 shows the temperature rise distributions in case of the shortest streamwise-pitch-length $L_p = 1.75 \times 10^{-2}\text{m}$ arrangements under various strength of the transverse vertical magnetic field. The tendency of distributions is decreasing the temperature rise with increasing interaction parameter. Additionally, all distributions above $N=2.42$ were a similar shape and temperature rise. This means heat transport mechanism changed rather than thermal mixing. This tendency has been observed in the previous transverse magnetic experiment. Moreover, the tendency was observed in other cases in Figs. 3-25 and 3-26. Therefore, it can be considered that there some specific interaction parameter which makes changing the heat transport mechanism.

Figure 3-25 shows the temperature rise distributions under the field of $L_p = 0.36 \times 10^{-1}\text{m}$ that is the middle size streamwise-pitch-length. The maximum difference of temperature rise between $N=0.00$ and $N=7.92$ case, there is 0.60°C difference. This number was almost the same as the temperature rise in case of the shortest streamwise-pitch-length that is 0.54°C . Regardless of the arrangement configuration, the temperature rise decreases with almost the same value. As another feature, comparing the distribution under the non-magnetic field and the field, the temperature range is shortened. This can be considered the reason that the influence of flow velocity changing. The effect of MHD to the flow velocity field makes the relatively fast flow near the free-surface and suppressed on the bulk fluid. This might be high temperature fluid flow to the short distance of downstream.

Figure 3-26 shows the temperature rise distributions in case of $L_p = 4.80 \times 10^{-2}\text{m}$ arrangement under various N . Based on the comparison of $L_p = 3.60 \times 10^{-2}\text{m}$, there are the high temperature rise area was located on the downstream of the channel and, it was narrower than that of $L_p = 3.60 \times 10^{-2}\text{m}$ under relatively high N . This is to say; the high temperature fluid was transported to the further downstream and it is likely to increase the fluid temperature. In terms of temperature rise analysis, $L_p = 3.60 \times 10^{-2}\text{m}$ case showed the highest temperature rises and located on the upstream of

the test section. Based on these result, the middle streamwise-pitch-length gave the highest heat transport performance in this experiment.

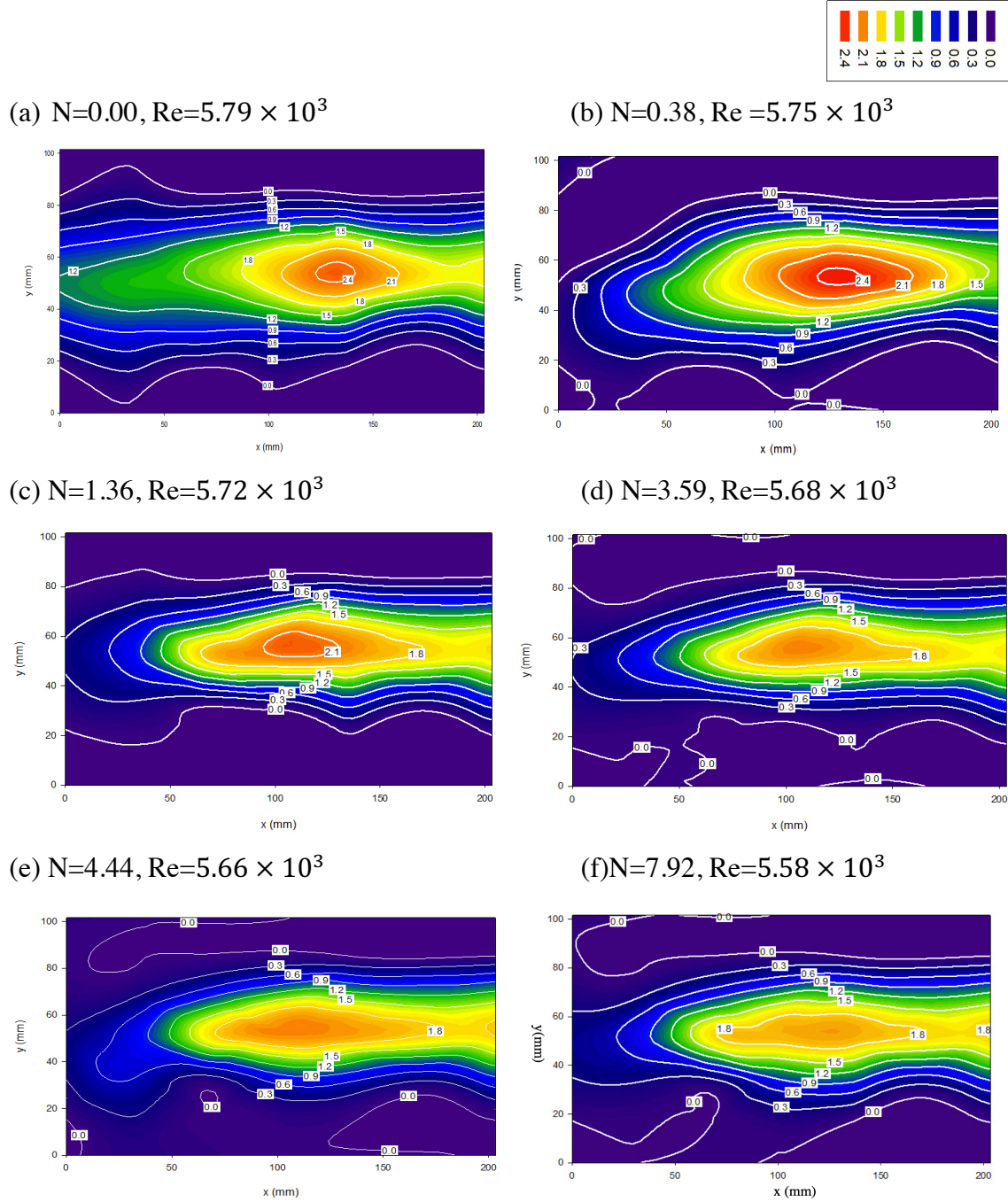
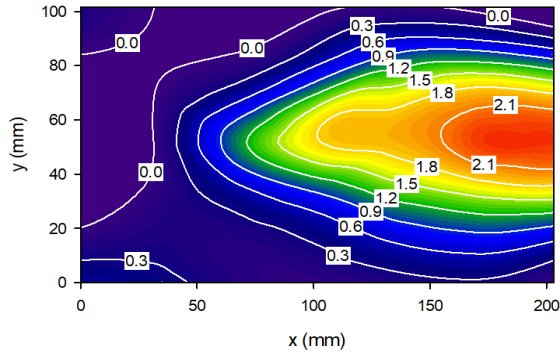
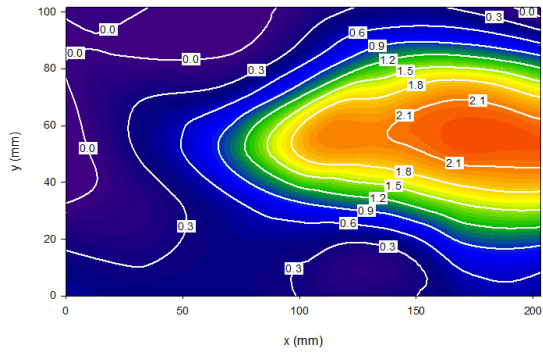


Fig. 3-25. Temperature rise distributions of $L_p = 0.36 \times 10^{-1} \text{ m}$ arrangements under various interaction parameters (N) (“×” marks show the peak temperature rise location).

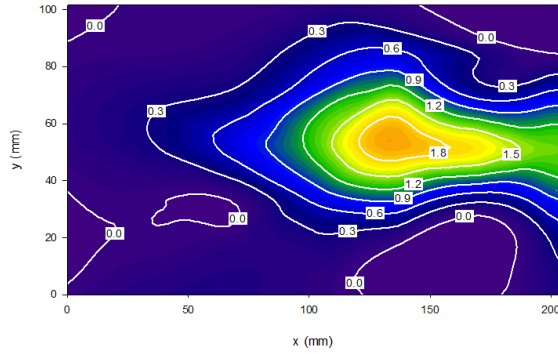
(a) $N=0.00$, $Re=5.79 \times 10^3$



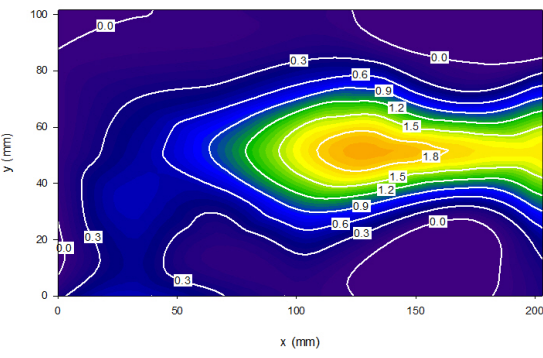
(b) $N=0.36$, $Re=5.75 \times 10^3$



(c) $N=4.25$, $Re=5.68 \times 10^3$



(d) $N=5.45$, $Re=5.63 \times 10^3$



(e) $N = 7.95$, $Re=5.60 \times 10^3$.

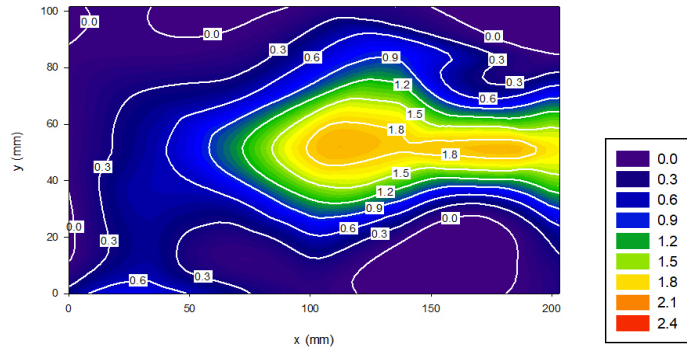
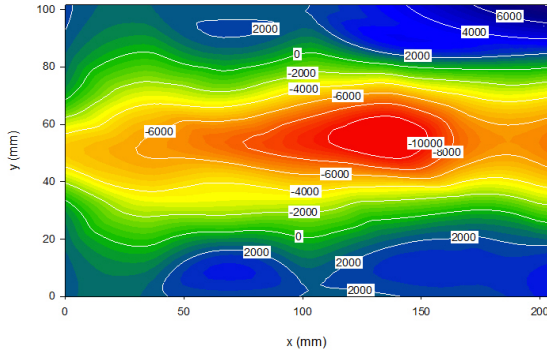


Fig. 3-26. Temperature rise distributions of $L_p = 4.80 \times 10^{-2}$ m arrangements under various interaction parameters (N) of the uniform transverse magnetic field (“×” marks show the peak temperature rise location).

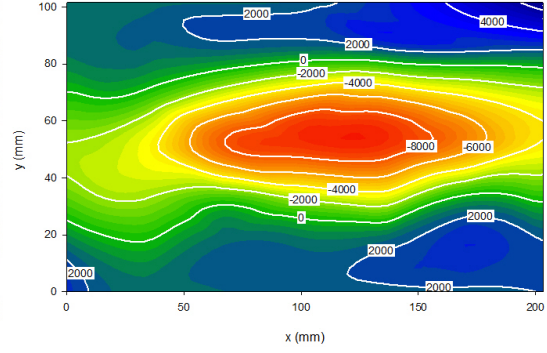
3.2-5-3 Heat flux at the bottom-wall

Figure 3-27 shows the heat flux distributions of $L_p = 3.60 \times 10^{-2}\text{m}$ arrangement under various interaction parameters. The heat flux decreased with increasing N. This tendency correlates to the temperature rise distributions. The maximum heat flux difference between the N=0 and N=9.03 was 5.12×10^3 decreased, it is almost half of heat flux has been loosed. However, the peak of heat flux moved to the upstream with increasing N. This characteristic was same as the temperature rise characteristic. From the point of heat accumulation time, this can make shorter time. Therefore, it is necessary to grasp the shortest heat flux peak point L_{peak} which is the distance from the $x=0.00\text{mm}$ to the location of the maximum heat flux.

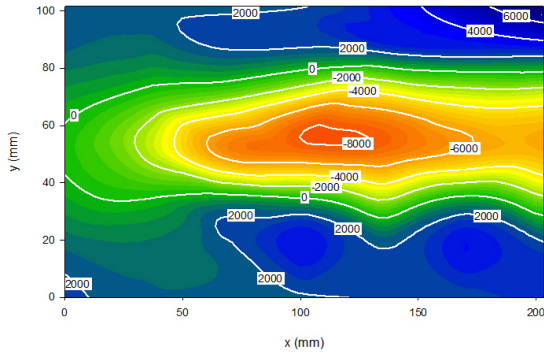
(a) $N=0.00$, $Re=5.79 \times 10^3$



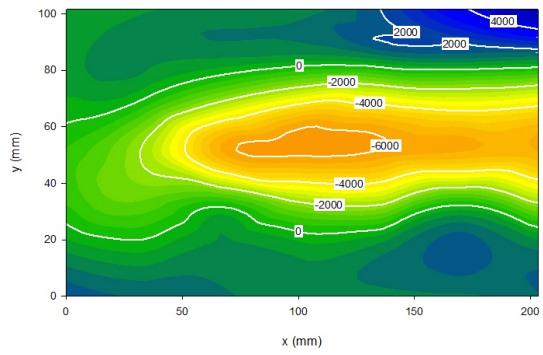
(b) $N=0.38$, $Re=5.75 \times 10^3$



(c) $N=1.36$, $Re=5.72 \times 10^3$



(d) $N=5.59$, $Re=5.70 \times 10^3$



(e) $N=9.03$, $Re=5.53 \times 10^3$.

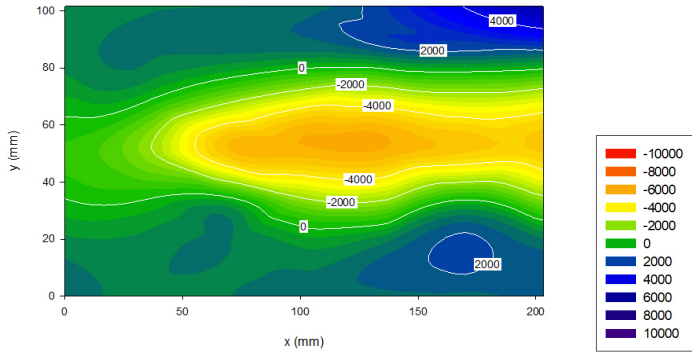


Fig. 3-27. Heat flux distributions of $L_p = 3.60 \times 10^{-2}$ m arrangements under various interaction parameters of the uniform transverse magnetic field (“ $\times$ ” marks show the peak temperature rise location).

3.2-5-4. The efficiency of heat transport

Figure 3-28 shows the relationships of the heat transport efficiency and the peak heat flux location (L_{peak}) in cases of (a) $Q_f=1.21 \times 10^{-4} \text{m}^3 \text{s}^{-1}$ and (b) $Q_f=1.67 \times 10^{-4} \text{m}^3 \text{s}^{-1}$. The origin of L_{peak} is the thermocouples at the most upstream location on the bottom wall. The efficiencies decrease with the increase of the transverse magnetic field strengths and converge to a certain value ($\gamma=20.0\%$) at the relatively high transverse magnetic field on each L_p arrangement. The reason of the decrease of γ at relatively high transverse magnetic field is that the thermal mixing enhancement is decreased by suppressing the flow velocity due to the MHD effect, and the jet flow near the free-surface caused by the protrusions transports the relatively high temperature fluids to the downstream, and the heat loss increases with increase of the magnetic field. As shown in Fig. 5(a), the peak heat flux location L_{peak} for various N in case of $L_p = 0.36 \times 10^{-1} \text{m}$ at $Q_f=1.21 \times 10^{-4} \text{m}^3 \text{s}^{-1}$ was shortened, this means that it is possible to remove heat quickly from the bottom-wall if the peak heat flux location is close to the heated surface location of the film flow, that is the shortest distance for the heat removal, and thus the inline arrangement with $L_p=0.36 \times 10^{-1} \text{m}$ showed the best heat transport performance.

Figure 3-29 presents the relationships between the heat transport efficiency γ and the streamwise-pitch-length L_p in cases of (a) $Q_f = 1.21 \times 10^{-4} \text{m}^3 \text{s}^{-1}$ and (b) $Q_f = 1.67 \times 10^{-4} \text{m}^3 \text{s}^{-1}$. The γ -plots in case of $N=0.00$ were $\gamma=57.8, 52.9$ and 44.4% for $L_p = 3.60 \times 10^{-2} \text{m}$, $1.75 \times 10^{-2} \text{m}$ and $4.80 \times 10^{-2} \text{m}$ respectively in case of $Q_f = 1.21 \times 10^{-4} \text{m}^3 \text{s}^{-1}$. Thus, the heat transport performance in case of $L_p = 3.60 \times 10^{-2} \text{m}$ was the best on $N=0.00$. The heat transport efficiency in case of MHD conditions cannot be made directly compared because N values were not same, when compared with relatively low N value cases, the heat transport efficiency for $L_p = 1.75 \times 10^{-2} \text{m}$ showed better than any other cases under the relatively low flow rate: $Q_f = 1.21 \times 10^{-4} \text{m}^3 \text{s}^{-1}$.

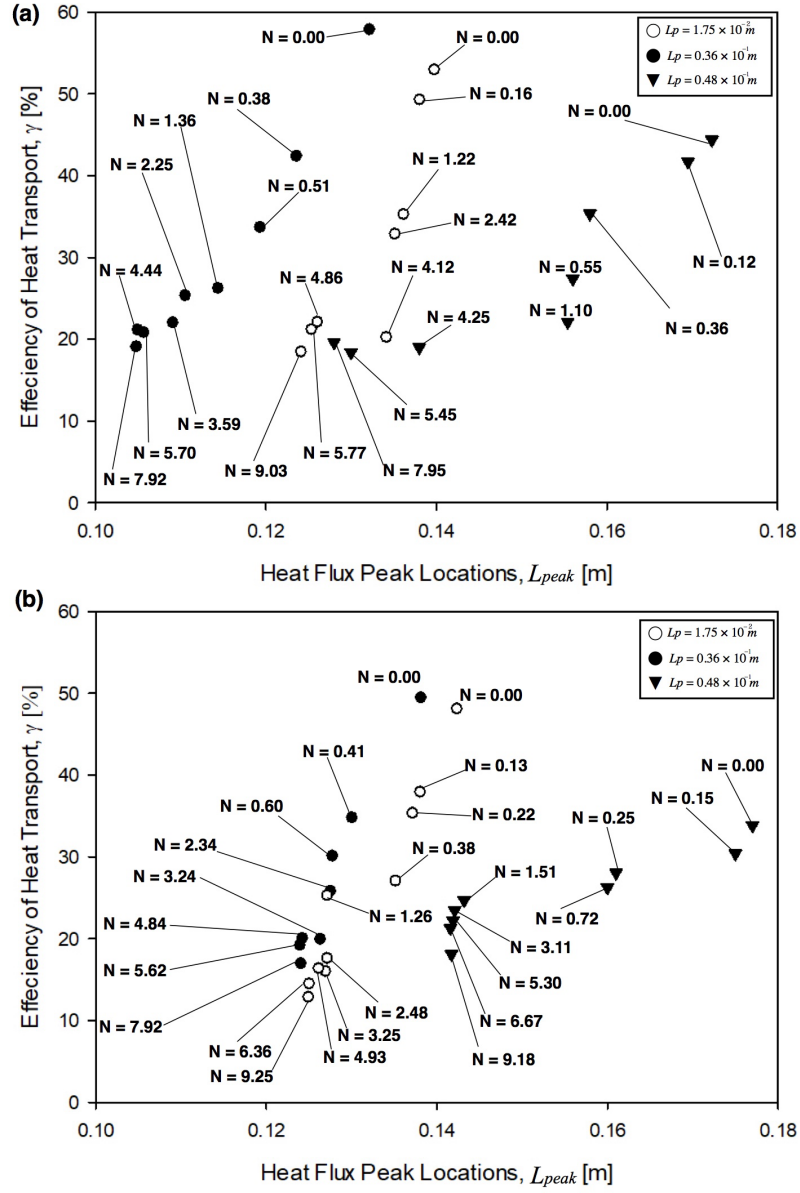


Fig. 3-28. The relationship between the heat transport efficiency and heat flux peak locations: (a) $Q_f = 1.21 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$, (b) $Q_f = 1.67 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

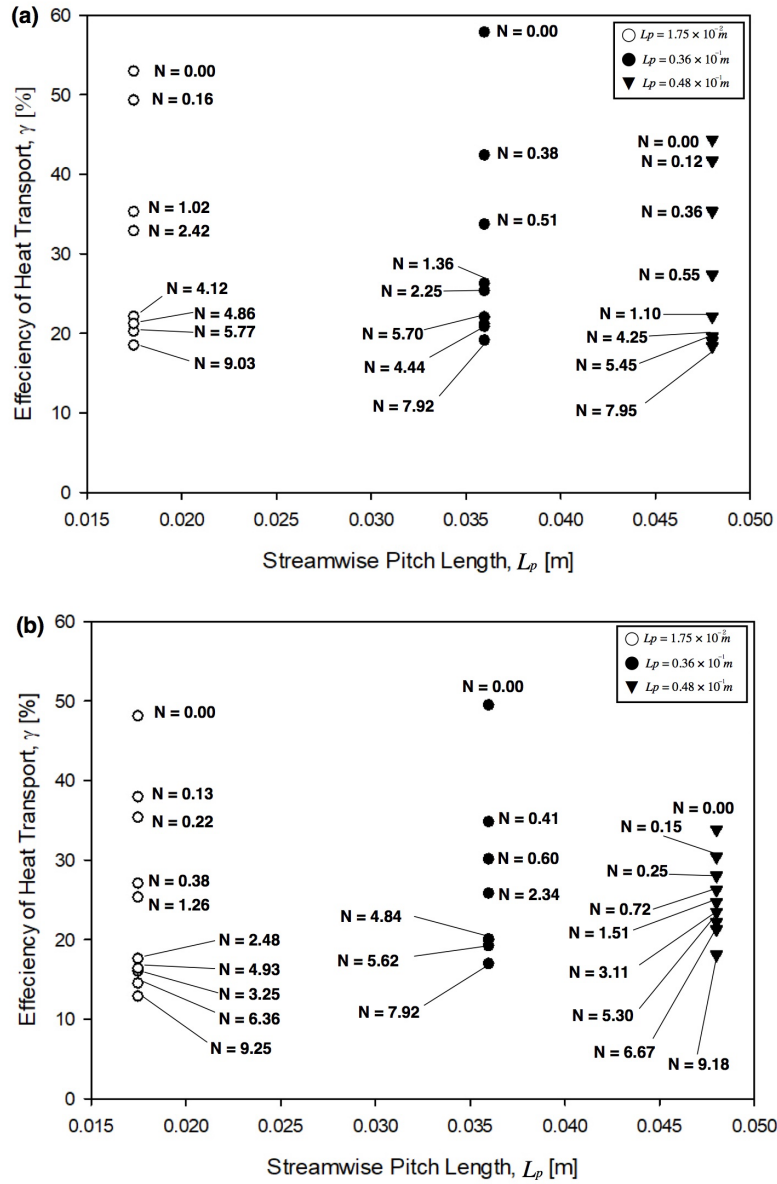


Fig. 3-29. The relationship between the efficiency of heat transport and streamwise-pitch-length: (a) $Q_f = 1.21 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$ and (b) $Q_f = 1.67 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$

3.2-5-5 Comparisons

In this subsection, some findings were introduced by comparisons of this experimental results and the results of the numerical simulations.

As a comparison of temperature rise distributions with temperature distributions of numerical results, the middle size streamwise-pitch-length of inline hemisphere arrangement was the best for heat transport in case of $N=0.00$. This means the relatively high temperature rise and the temperature was observed in the case of installing the middle length in both studies. According to the previous studies [47, 52], they proposed the middle size streamwise-pitch-length for heat transfer enhancement. The mechanism of this consequence can be described by comparison of the flow velocity of the vertical direction in the numerical simulation result. From Fig. 2-15, optimized velocity makes the highest heat transport. Therefore, this behavior may be affected to this suggestion.

Based on the comparison of temperature rise, heat flux distributions and the efficiency of heat transport, all distributions formed the concentration on the bottom-wall. This behavior makes increasing heat-load on the wall. However, heat transport performance in case of high N was not better than that of low N and $N=0.00$, approximately 20.0% injected heat have not reached on the bottom-wall under high N . It can be considered that remaining heat has been transported by the velocity near the free-surface revealed in the numerical simulation. Therefore, the heat load on the bottom-wall decreased with increasing N .

Based on comparison of heat flux distributions under various N in this experiment and previous experiment, the behavior of peak is different. The moving direction was opposite. In this experiment, the peaks moved to upstream with increasing N . This difference was caused by the effect of installing many hemispheres and flow velocity decreasing as described on next section.

3.2-5-6 Discussions

The main findings from this experiment as summarized below

- (1) The temperature rise/heat flux/efficiency of heat transport decreased with increasing strength of the transverse magnetic field.
- (2) The middle streamwise-pitch-length showed the best heat transport performance in case $N=0.00$.
- (3) The heat flux peaks moved to the upstream with increasing the strength of the transverse magnetic field.
- (4) The heat flux peak of the middle streamwise-pitch-length located on the most upstream in three different arrangements.
- (5) The relatively fast flow rate transported the heat flux peaks to downstream in comparison with low flow rate.
- (6) All configurations converged to the efficiency of heat transport $15.0\sim 20.0\%$ under the relatively high N .

The finding (1) caused by the flow velocity suppression and the vortex damping effect. From the comparison of the vertical flow velocity distribution in the numerical simulation, the velocity was locally suppressed on the upper-side of the bulk and makes velocity gradient between the bulk and near the free-surface in case of $N=10.0$. This gradient increased with increasing N . It can be considered that this relatively fast flow transported the high temperature fluids near the free-surface to the further downstream. In addition, vortexes from hemispheres have damped by the transverse magnetic field. The numerical results showed that the vorticity of flow direction is important for heat transport, however, the vorticity of horseshoe vortex is relatively low. It might be damped quickly under the transverse magnetic field. Therefore, the heat transport performance was degraded with increasing N .

The experiment and numerical results confirmed that the middle streamwise-pitch-length is appropriate for heat transport in case of $N=0.00$. However, it was difficult to

compare in case of MHD because of different N respectively. From the comparison suggests that high heat transport performance can be gained under low N or high N . The reason of this phenomenon may relate to the effect of the flow velocity decrease. It can be hypothesized that the optimized inline arrangement for the enhancement of heat transport efficiency might be different depending on the difference in the magnetic field strength and the flow conditions. In this experiment, the optimized length may be changed as shorter under the transverse magnetic field.

To evaluate which length is appropriate for heat transport enhancement, the heat flux peak locations were investigated. The finding (3) and (4) means that there is a possibility to transport the high temperature fluid to the wall in short time in case of the short distance from the heater to the heat flux peak. Note that, this trend opposite to the previous experimental result in case of the delta-wing. This difference may be caused by the upward and downward flow structure around obstacles under the heating location. The delta-wing generates the suction flow on the center of the downstream of the delta-wing, however, the upward flow is constituted on the downstream of the delta-wing sides. On the other hand, the hemisphere generates upward flow on the upstream and downward flow on the downstream. Based on this behavior, both flow structure was likely to break the local high flow velocity near the free-surface and transport the high temperature fluid to the further upstream by velocity decreasing on the bulk. Therefore, inline hemisphere arrangement induces the heat transport effectively rather than the single delta-wing under the transverse magnetic field.

The convergence of heat transport efficiency was observed under high N . This is to say two estimations can be hypothesized in case of higher N . First, the efficiency of heat transport does not decrease any further despite the rise of the field strength. Second, the efficiency of heat transport decreases with increasing N . From my opinion, the second hypothesis can be considered for physical behavior in high N . The reason for choosing this, the difference between the local flow velocity near the free-surface and that on the bulk should be large under high N . It is because the induced Lorentz force increases with

increasing N and the velocity near the free-surface slips, hence the velocity suppression occurs only on the bulk. Finally, the large velocity gap may be induced. Therefore, the heat transport performance may be decreasing under the higher N condition.

3.3 Vertical parabolic magnetic field experiment

The experiment under the vertical parabolic magnetic field was conducted at LMFREX facility has appeared before. As regard to consider for an actual divertor design, the magnetic field is not the uniform magnetic field. This suggests for requiring the data under the non-uniform magnetic field. Generally, the performance of the vertical heat transfer under the vertical magnetic field tends to be increased caused by the uniform velocity field suppression. Due to this behavior, the temperature stratifies on the vertical direction by localized heated on the free-surface. To prevent the temperature stratification, using obstacles as vortex generators or injecting the most appropriate magnetic field for enhancement of thermal mixing. In this chapter, the experiment of the liquid metal film-flow with using various type of vortex generators under the vertical parabolic magnetic field are described.

3.3-1 LMFREX

LMFREX is an experimental facility of MHD liquid metal film-flow under the vertical/inclined parabolic magnetic field manufactured in Uji Campus of Kyoto University in 2018. The experimental apparatus of LMFREX in Fig. 3-30. LMFREX can generate the strength of magnetic field 0.38T at the maximum, the test channel shape is similar to LMX however it is shorter than the channel of that of 63%. The channel made by completely acrylic resign. The channel length is 0.63m, and the width is 0.10m. LMFREX constitutes the test flow channel, an electromagnetic pump, the heat exchanger, a cooling chiller of the ethylene glycol cooling system, a ceramic heater for localized surface heating, an electromagnetic flow meters, GaInSn storage tanks, argon gas lines, and a vacuum pump. A photo of whole-view of LMFREX in Fig. 3-31.

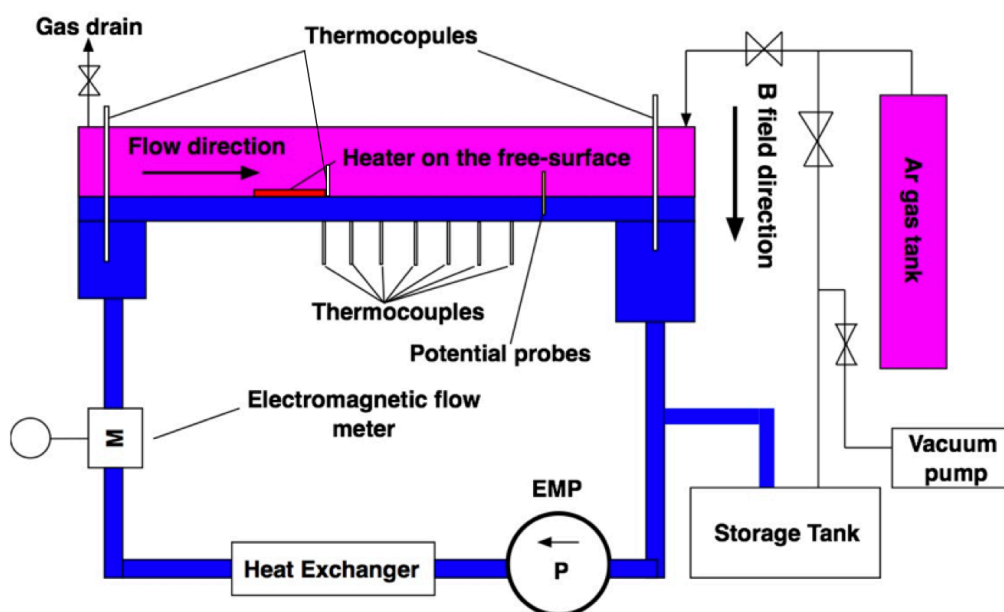


Fig. 3-30. The experimental apparatus of LMFREX.

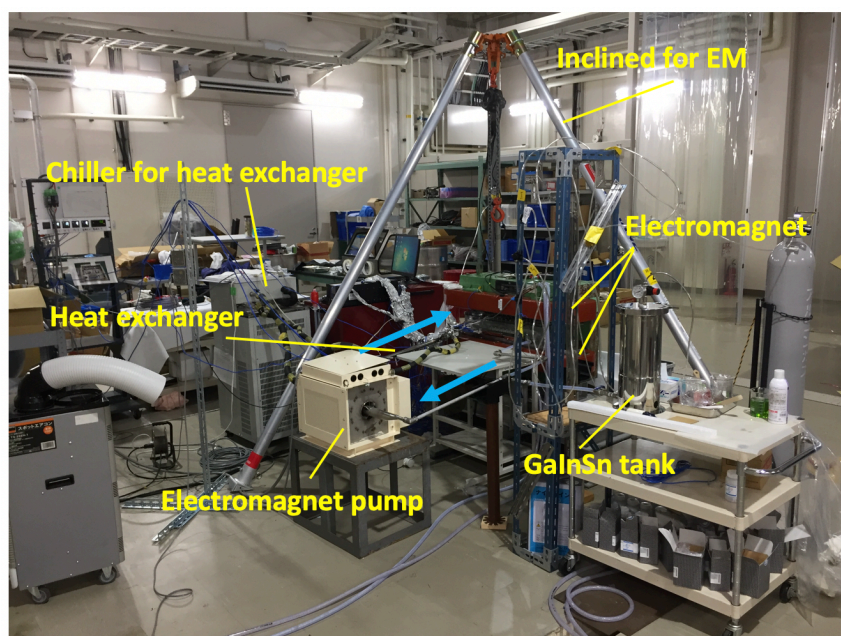


Fig. 3-31. Whole-view of LMFREX (Light-blue arrow indicates the GaInSn flow direction)

- Test channel

The schematic of the test channel was illustrated in Fig. 3-32. Since it gives rise a developed flow quickly and it can be lower the influence of the relatively high flow velocity in the pipe, the liquid reservoir was designed at the inlet and the outlet of the test channel. Due to the transparency of acrylic characteristic, it is possible to measure fluid depth directly by a camera. Some diagnostics were installed in the test channel including temperature measurement and a velocity measurement.

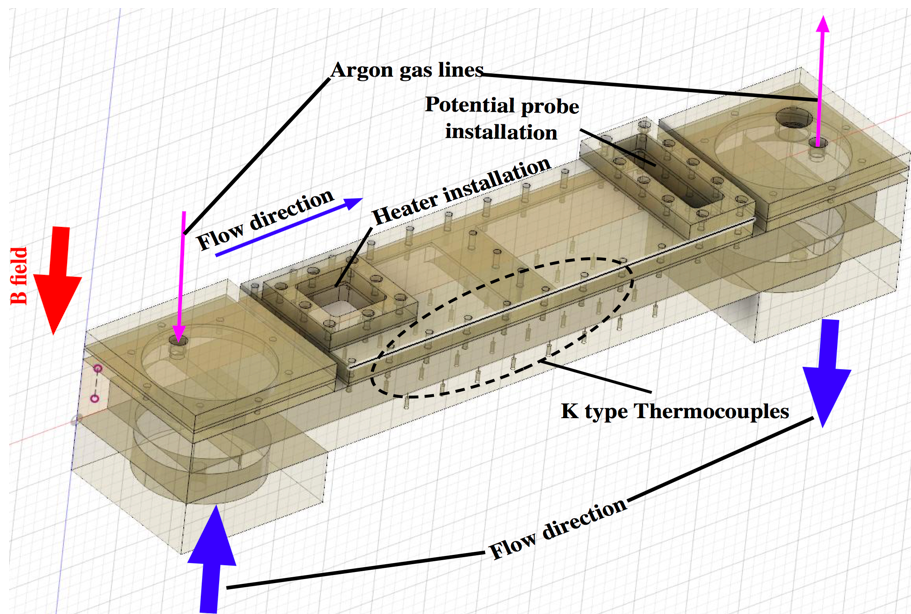


Fig. 3-32. Schematic of the test channel of LMFREX.

- The heater for localized heating free-surface

The ceramic heater was installed at the free-surface for localized heating. The heater and an installing jig were used as same as the LMX experiment in case of installing an inline hemisphere under the transverse magnetic field.

- The control of the electromagnetic pump

The control method of the electromagnetic pump was used by a three-phase DC variable autotransformer “Type S 3P-240-30”. This can be controlled by manually and installed a digital voltmeter at the output of the autotransformer so that every experimental condition for flow rate can be unified in all cases.

- EMP pumping power and thermal influence to the working fluid

The electromagnetic pump was used in this study manufactured by “Sukegawa-electric company”. The pumping principle is used induced Lorentz force by the magnetic field and an injected current inside the pump. The pump constitutes a set of magnets, a pair of electrodes and a circular channel. A pair of electrodes inject the electrical current through inside the liquid metal flow and enhancing electromagnetic force that moves the liquid. Since there is no mechanical structure in the pump, there is no risk of leakage of the working fluid and no high pressure is applied to the inside of the pump, whereby the malfunction is unlikely to occur in the liquid part.

Disadvantageously, a large electrical potential difference is induced by electrodes installed at the wall, resulting in Joule heating. The Joule heating is transferred to the working fluid, thus increases the fluid temperature. In the high flow rate range, high heat generation occurs due to the current limit of the electromagnetic pump and the flow rate becomes constant. The pump-power of the electromagnetic pump used in this study is shown in Fig. 3-33. It is satisfied with this performance in this study as 2.70L min^{-1} at the maximum.

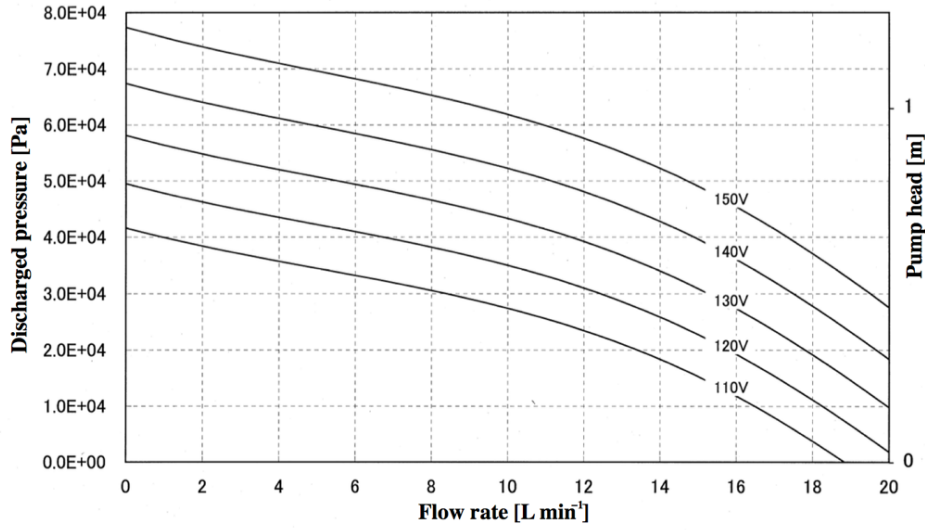


Fig. 3-33. The pump power as a function of input voltage for GaInSn circulation [53].

The Joule heating Q_{joule} is generated by an injected electrical current $Q_{joule} = Q/t = (J^2/\sigma)t/t \sim \sigma E^2$, where, and time t . The amount of joule heating from EMP generates 1.10kW at the maximum. This generated heat is transferred to the working fluid, resulting in an increase the fluid temperature. When the experimental condition requires of higher temperature, this phenomenon can be useful for preventing fluid solidification such as a blast furnace and a metal casting [54], however, GaInSn in this study requires the relatively low temperature because of thermal properties of acrylic reigns. In addition, there are relatively high heat load to GaInSn under high flow rate and makes a constant flow rate. Therefore, the working fluid requires some heat exchange mechanics for keeping the constant room temperature.

To evaluate the heat load to GaInSn, the total heat load in this experiment can be defined as $Q_{Total} \equiv Q_{EMP} + Q_{in} + Q_{Joule}$ where, the heat load by the electromagnetic pump Q_{EMP} , the injected heat power Q_{in} and the Joule heating in the test section Q_{Joule} . The actual values are given as $Q_{EMP} = 1.10\text{kW}$ at the maximum flow rate, $Q_{in} = 91.9\text{W}$ and $Q_{Joule} = 3.18\text{W}$ were induced at the maximum by the electromagnet in the test section. Q_{Total} was 1195W in case of maximum input of the voltage 150V. To

cooling this amount of heat, LMFREX has a heat exchanger and a cooling chiller described below.

- The cooling chiller and the heat exchanger

The cooling chiller was used “EYELA CTP-6000” in this study. The maximum cooling performance is 1.20kW with using an antifreeze solution such as an ethylene glycol. The heat exchanger was constituted double pipes as a copper inner pipe and a SUS304 outer pipe as illustrated in Fig. 3-34. Heated GaInSn passed inside the inner pipe and the cooling medium flows between the inner wall and outer pipe wall. The heat exchanger was also connected to the cooling chiller to inject ethylene glycol.

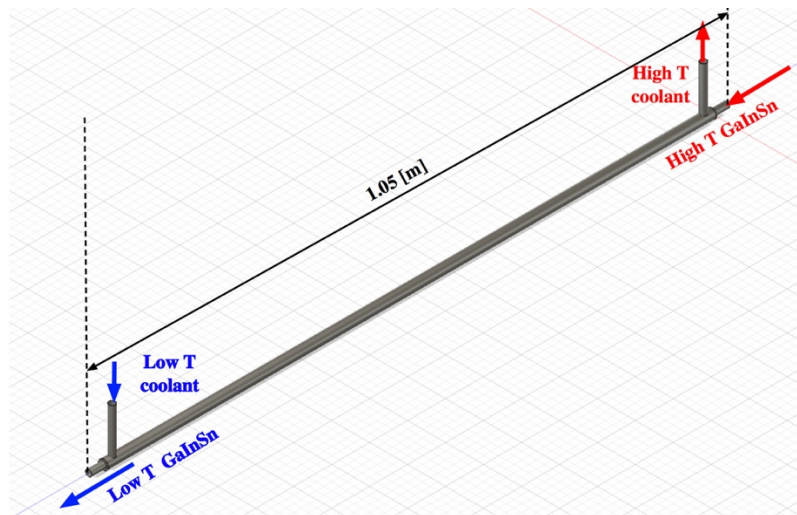


Fig. 3-34. Schematic of the heat exchanger of LMFREX.

- The control of a set of electromagnet and cooling

For the control of the electromagnet, DC power supply was used. It can be controlled manually and, output up to 100V at the maximum. The heat load on the coil inside the electromagnetic was induced by Joule heating, which can be removed using

cooling water. However, since the temperature of the cooling water also relatively increases during the summer season, it must be taken not to exceed the limitation of the coil temperature. Therefore, a pair of electromagnets is equipped with a thermistor that directly measures the coil temperature, making it possible to monitor the temperature. At the temperature of 38°C in room temperature and the maximum voltage in summer hot weather, the coil temperature reached 52°C at the maximum.

- The magnetic field distribution

The generated magnetic field from a set of electromagnet forms the vertical parabolic shape distribution on the spanwise direction as illustrated in Fig. 3-35(a). The magnetic field was at constant at the streamwise line within 0.130m width. In Chapter.2, numerical simulation, this magnetic field was injected into the numerical model. The strength of the magnetic field could be controlled by DC power supply as mentioned on above. The relationship between the input DC voltage and the output magnetic field on the center of the magnetic pole in Fig. 3-35(b).

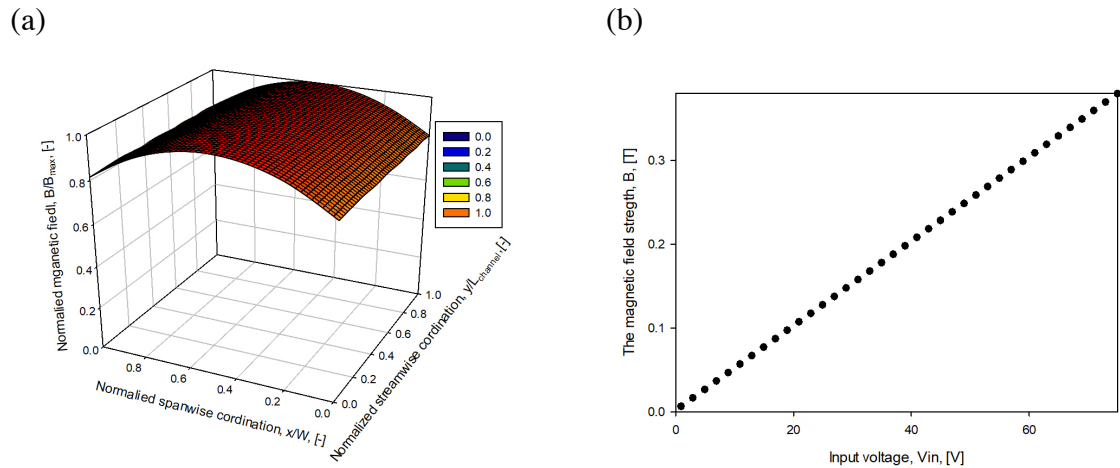


Fig. 3-35. The characteristic of the magnetic field on LMFREX: (a) The normalized magnetic field distribution, (b) The magnetic field strength as a function of input DC voltage.

- The electromagnetic flow meter

The electromagnetic flow meter in this experiment was used Keyence FD-M5AY. This is possible to measure the relatively low flow rate such as 0.25Lmin^{-1} at the minimum. The electromagnetic flow meter was installed on the downstream of the heat exchanger or upstream of the inlet of the test channel.

3.3-2 Diagnostics

To measure the thermal characteristic of localized heated free-surface of liquid metal film-flow, “class 1” 40 K-type TCs were installed at the bottom-wall, and one TC at the free-surface. The schematic of diagnostics at the test section was illustrated in Fig. 3-38. Additionally, the energy balance of the experiment is a key parameter for accuracy validation. To evaluate the energy balance, TCs were installed at the inlet and the outlet of the test channel. Data-Aquisition-system (DAQ system) for correcting the temperature data was used “Graphite DATA PLATFORM GL7000” which can be collecting temperature data on 10ms per 1 sampling data with $\pm 0.02\%$ inaccuracy. For preventing the influence of electromagnetic noise to TCs, an extension lead wire was covered by Aluminum coating wire, the earth wire connected to the Aluminum against for noise interference. An insulating material was coated on the thermocouple wire portion as a countermeasure for circulating electrical current by contact between the strands.

To measure the flow velocity distribution on spanwise line, LMFREX has a potential probe on the downstream of the channel with using a digital multimeter and a fast speed collecting DAQ system. At first, the measurement principle of the potential probes describes below. The potential probes are using the principle with Ohm’s law given by from equation (1.2) $\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B})$. According to the divergence of the electrical current density is zero as $\nabla \cdot \mathbf{J} = 0$ and the electrical field is given by $\mathbf{E} = -\nabla\phi$ with using the electrical potential ϕ , equation (1.2) can be rewritten as

$$\nabla^2 \phi = \nabla \cdot (\mathbf{u} \times \mathbf{B})$$

$$\Delta \phi = |\mathbf{u} \times \mathbf{B}| \Delta x \quad (3.1)$$

where, x is spanwise coordination, Δx means the distance between probes 2.54mm in this study. In case of the vertical magnetic field, the potential gradient tends to be the spanwise direction, the gradient tends to the vertical direction under the transverse magnetic field. From Eq. (1.2), the flow velocity can be given by $u = \Delta \phi / B \Delta x$. Therefore, the electrical potential probe measurement is the method for measure the flow velocity indirectly. For example, $\Delta \phi$ is given as 12.2 μ V calculated based on the constant flow rate 1.70Lmin⁻¹ under the highest magnetic field strength 0.38T in this study. The schematic of the measurement system of potential probes was illustrated in Fig. 3-36. Since the tiny $\Delta \phi$ is induced under the low magnetic field, it should have to be amplified to measure the relatively small voltage via an amplifier circuit. I designed an amplifier circuit that the output voltage is 10⁴ times higher than the input of the voltage theoretically. Each circuit has a characteristic amplification factor; Figure 3-37 shows the relation between the amplified voltage and the input voltage with a certain inclination.

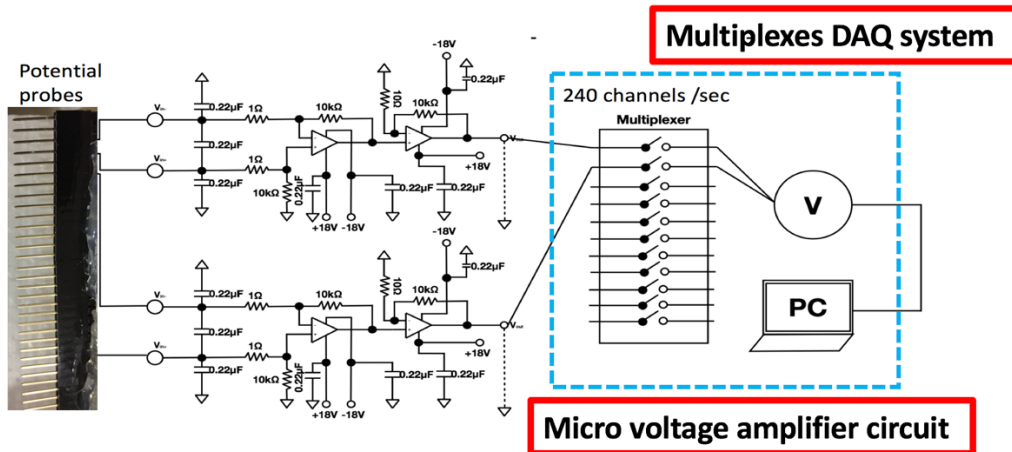


Fig. 3-36. Schematic of flow velocity measurement system.

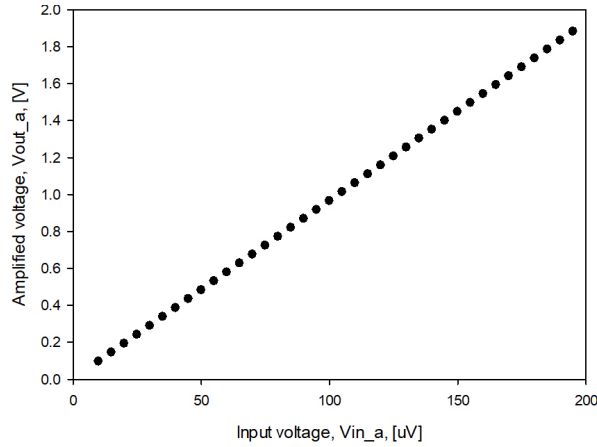


Fig .3-37. The relation between the amplified voltage and the input voltage.

3.3-3 Reference case

The reference case of the experiment under the parabolic vertical magnetic field has been conducted the configuration that the flow in case of an absence of obstacle under the field. To evaluate thermal mixing enhancement under the parabolic vertical magnetic field, the temperature rise, the heat flux, the normalized temperature, the surface temperature, and the efficiency of heat transport were evaluated from the experimental data. Particularly, MHD effect to the flow velocity distribution was measured by using the potential probes. Section 3.4-3-1 describes the experimental conditions and experimental apparatus of the test channel, Section 3.4-3-2 introduces thermal characteristic such as the temperature rise /the normalized temperature/ the heat flux at the bottom-wall and the surface temperature at the free-surface. Section 3.4-3-3 describes heat transport performance using the efficiency of heat transport. Section 3.4-3-4 describes MHD effect to the velocity field under the presence of the magnetic field.

3.3-3-1 Experimental apparatus and conditions

The schematic of diagnostics locations of the test channel in Fig. 3-38. The locations of TCs were installed an inline arrangement. The potential probe was installed

at the 46.0mm further downstream from the most downstream TCs. The heater was installed on the free-surface and the input power was injected 91.9W. The experimental parameters were listed in Table 3-6. The range of Reynolds number was $4.87 \times 10^2 - 1.58 \times 10^3$, Interaction parameter range was 0.00 – 149. All dimensionless numbers in this experiment were based on the half of hydrodynamic perimeter as the characteristic number. The flow depth H are different on each interaction parameters N ; this difference was caused by induced Lorentz force in the liquid metal film flow at the arbitrary constant flow rate. Flow depth H [m] can be measured by using a camera directly due to the transparency of the channel and the heater heights were adjusted on each strength of the parabolic vertical magnetic fields. The relationships between flow depth and interaction parameter are shown in Fig. 3-39.

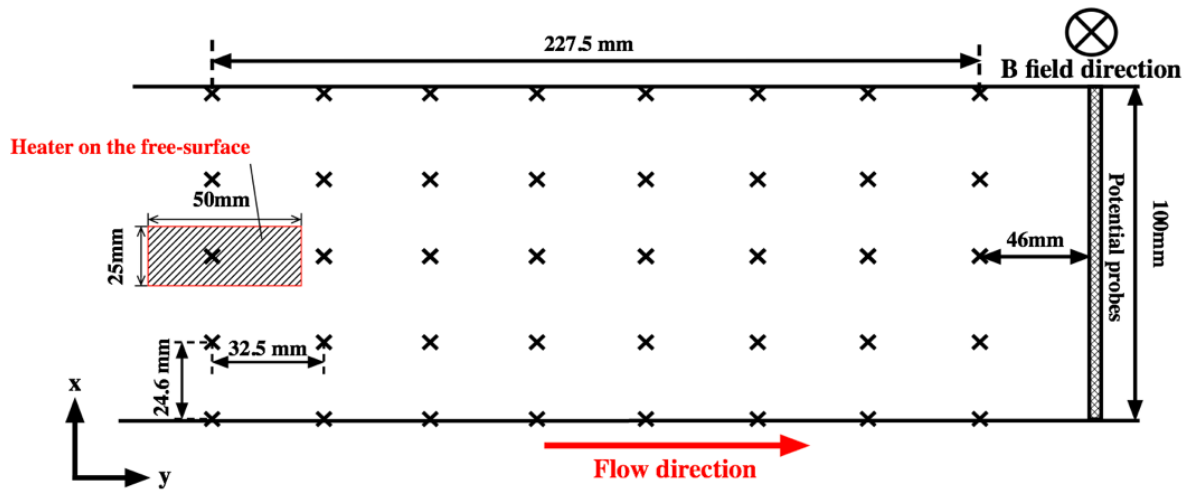


Fig. 3-38. Schematic of diagnostics locations of the channel (x-marks show TCs locations; grid area shows potential probe rake).

Table 3-6. The experimental parameters of the reference case under the vertical magnetic field.

Parameters	Symbols	Value
Reynolds number [-]	Re	487 – 1583
Interaction parameter [-]	N	0.00 – 36.1
Flow rate [L min^{-1}]	Q_f	0.60, 1.70
Injected heater power [W]	Q_{in}	91.9

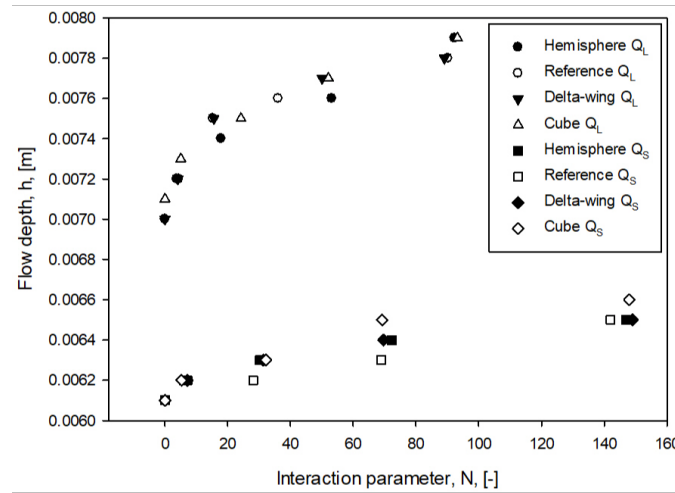


Fig. 3-39. The relationships between flow depth and interaction parameter.

3.3-3-2 Temperature characteristics

Figure 3-40 gives the temperature rise distributions at the bottom-wall in case of an absence of obstacles at $Q_f = 1.70 \text{ Lmin}^{-1}$ under various N respectively. Seen from distributions, the temperature rise increased with increasing N gradually. In terms of an area of high temperature rise, there is approximately 3.50°C difference between $N=0.00$ and $N=90.2$. This tendency was opposite to the results of the transverse magnetic field. It means a large amount of high-temperature fluid was transported to the bottom-wall by

the effect of vertical parabolic magnetic field. This suggested that the performance of fluid transport from the free-surface to the bottom-wall better than that of the transverse magnetic field. At low N , there were approximately 1.50°C difference of the relatively high temperature rise between $N=0.45$ and $N=1.84$. However, there was not large difference in $N=13.9$ and $N=15.2$. This difference can be considered that the magnetic field effect to the behavior of fluid transport in case of comparatively low N is larger than that of high N . The vertical velocity field under the vertical parabolic magnetic field tends to be suppressed uniformly including the velocity near the free-surface as introduced on the numerical result. Thus, the fluid transport behavior has been changed from the fluid mixing.

Figure 3-41 shows the normalized temperature distributions in case of an absence of obstacles at $Q_f = 1.70\text{Lmin}^{-1}$ under various N respectively. One of the characteristics of distributions that the whole distributions moved to the upstream with increased N . This tendency was similar to the case of inline hemisphere arrangement under the transverse magnetic field. The reason for this behavior was the effect of uniform velocity decreasing by the vertical parabolic magnetic field. The fluid transport is largely depending on the flow velocity. If slow velocity transports the heat in short distance compare than the case at high velocity, this means that the high temperature fluid can be concentrated on the bottom-wall locally. In addition, this behavior suggests that the heat inside the liquid metal film flow can be transport quickly in case of the high strength of the magnetic field. The second characteristic was the shape of distributions very similar at all N . This indicates that the flow direction was not affected by the magnetic field. Thus, the localized heated high temperature fluid was transported to the downstream/the bottom-wall of heating position.

Figure 3-42 plots give the interaction number dependency of the surface temperature. The surface temperature increased with increasing N . This means that the high temperature fluid accumulated near the free-surface caused by flow velocity decrease. Comparison of the surface temperature at low N range and high range, the slope

of the surface temperature in case of low N was higher than that of high N case. This means the temperature under comparatively low N increased suddenly by the relatively low strength of the vertical parabolic magnetic field. From the description of temperature rise, the temperature at the bottom-wall at low N is more affected than that of high N . Thus, the behavior may have corresponded to the temperature rise at the bottom-wall. According to Rhoad [49], the surface temperature under the vertical magnetic field was increased with increasing N . Therefore, the result of this experiment tends to the previous study and the high temperature fluid may be accumulated near the free-surface.

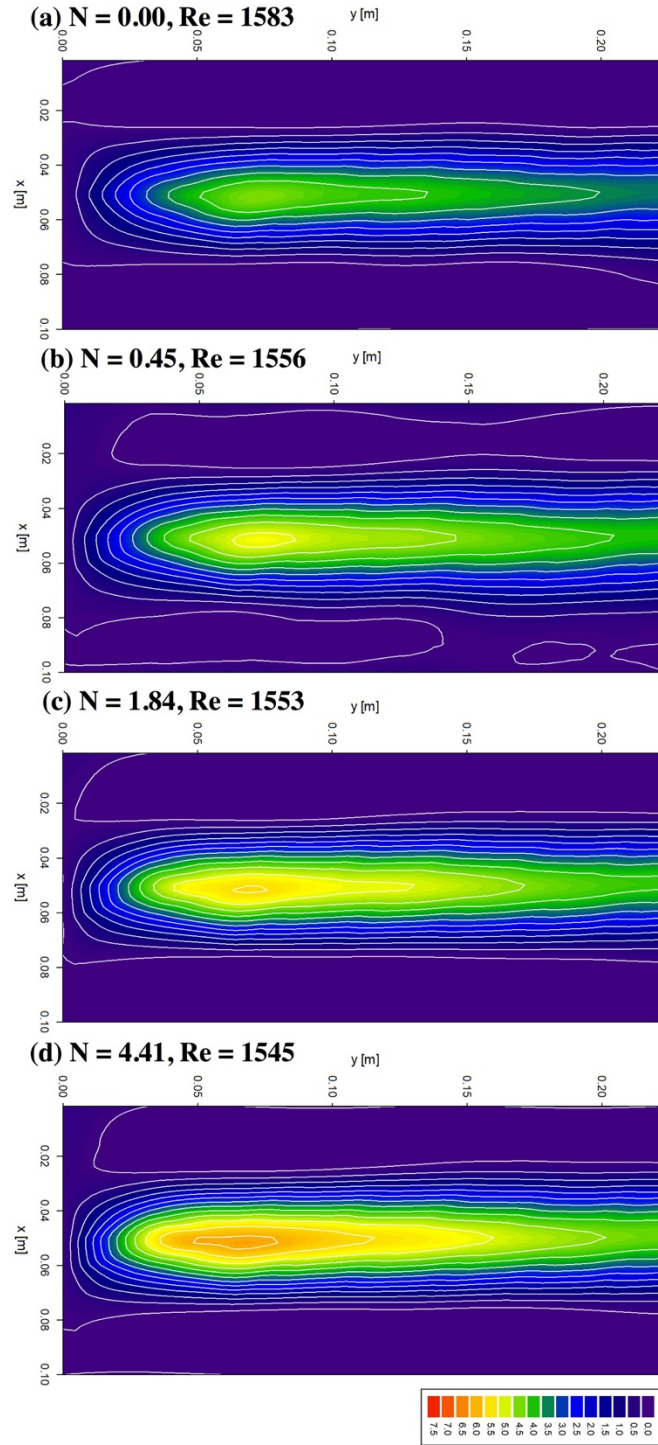


Fig. 3-40. The temperature rise distributions at the bottom-wall in case of an absence of obstacles under various N of the vertical parabolic magnetic field.

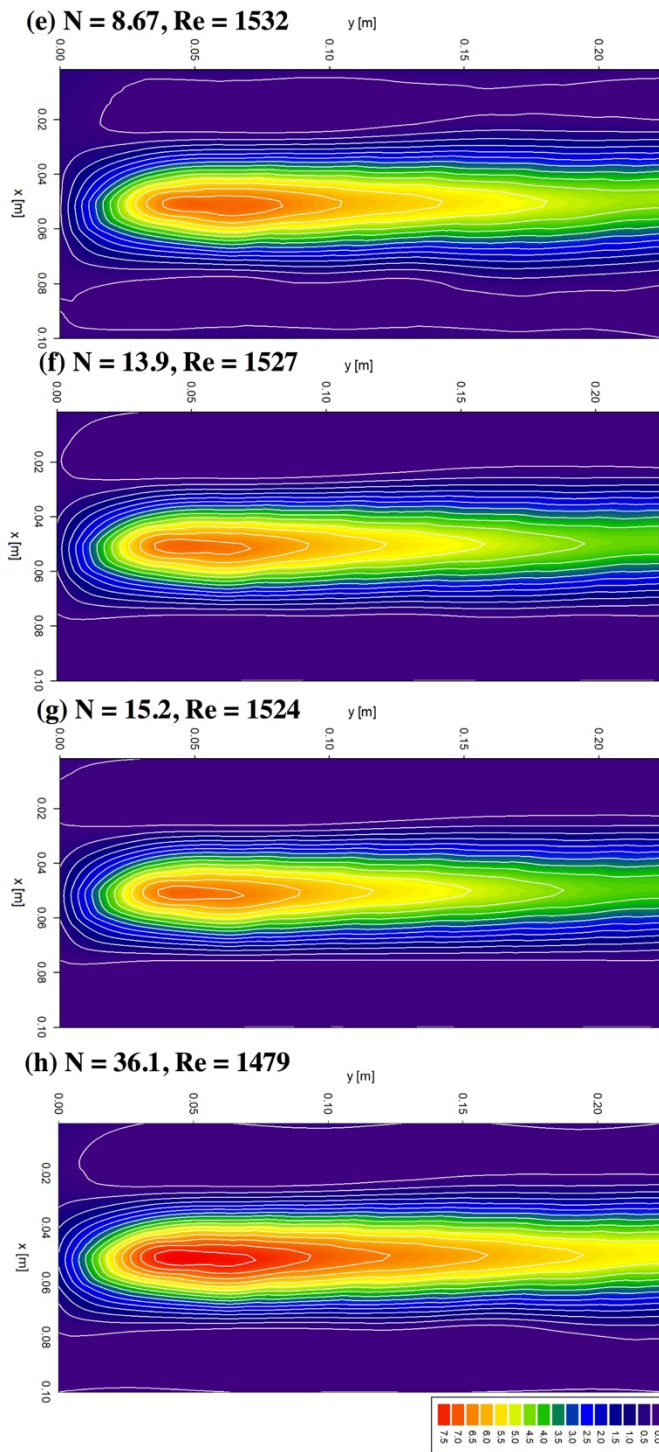


Fig. 3-40 (Cont.)

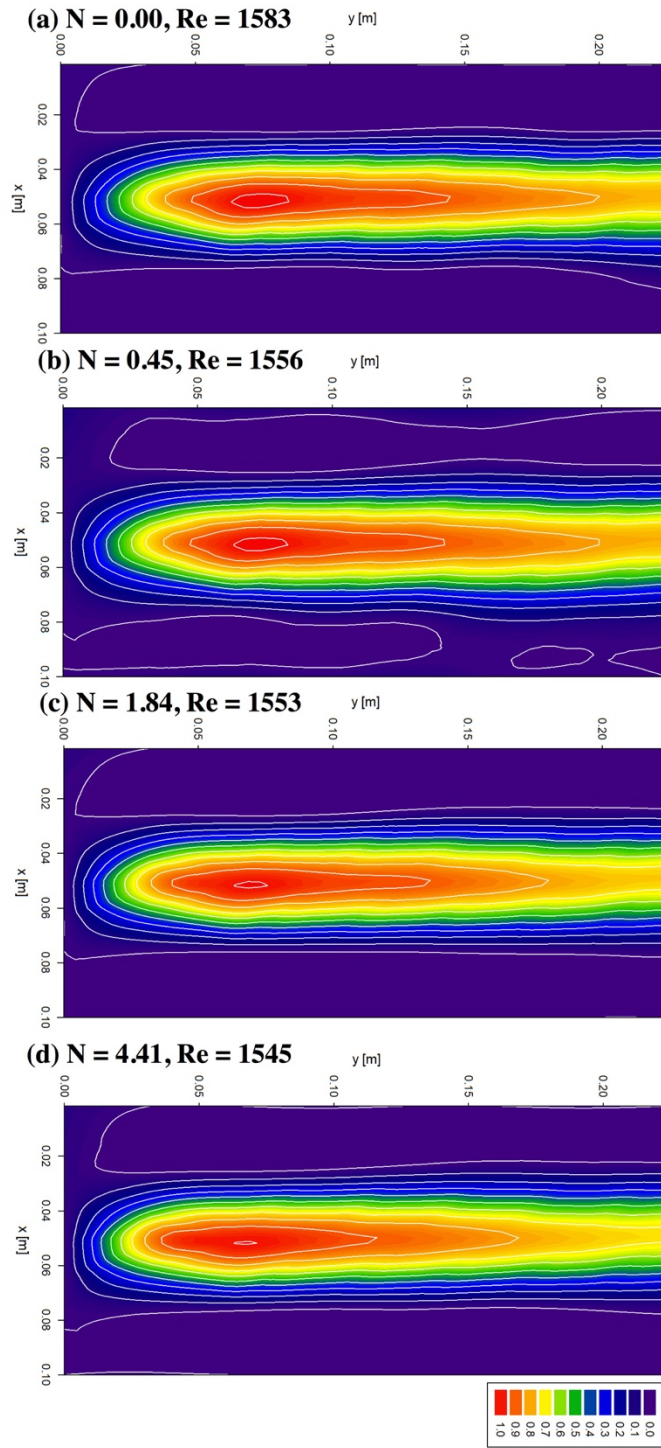


Fig. 3-41. The normalized temperature distributions at the bottom-wall in case of an absence of obstacles under various N of the vertical parabolic magnetic field.

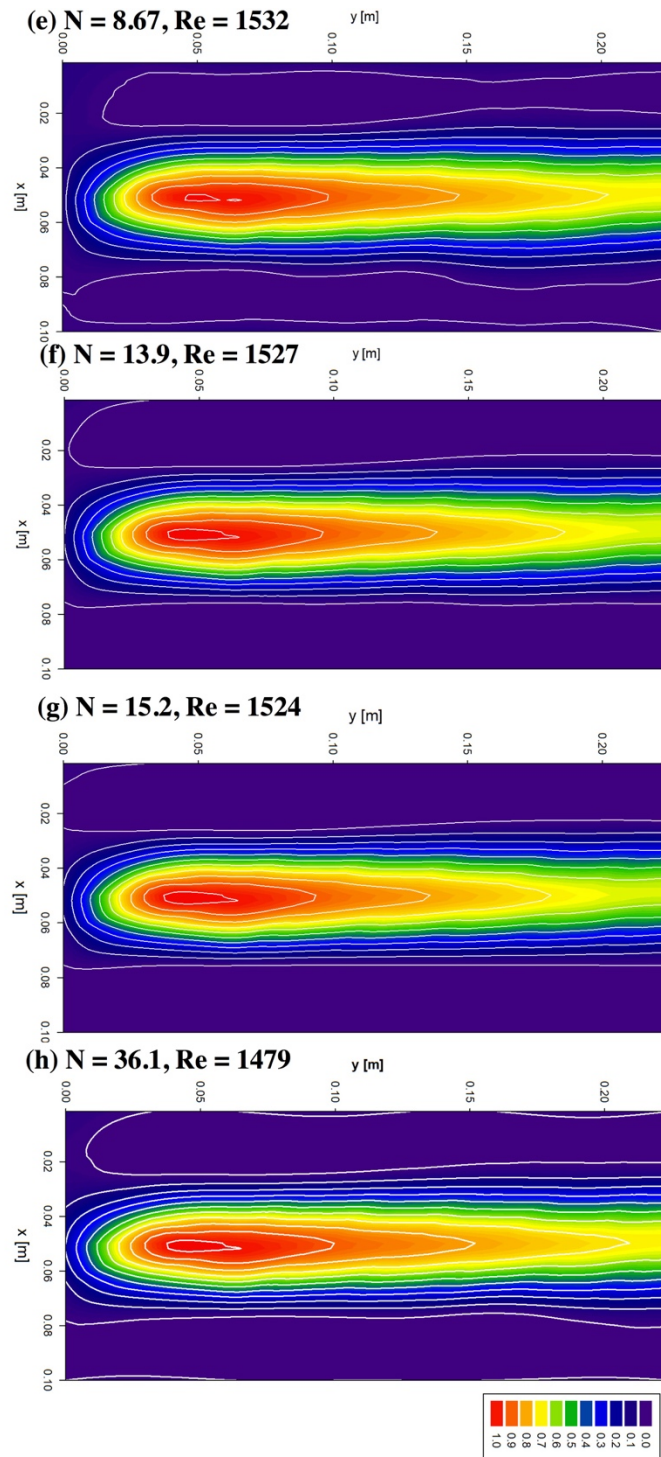


Fig. 3-41 (Cont.)

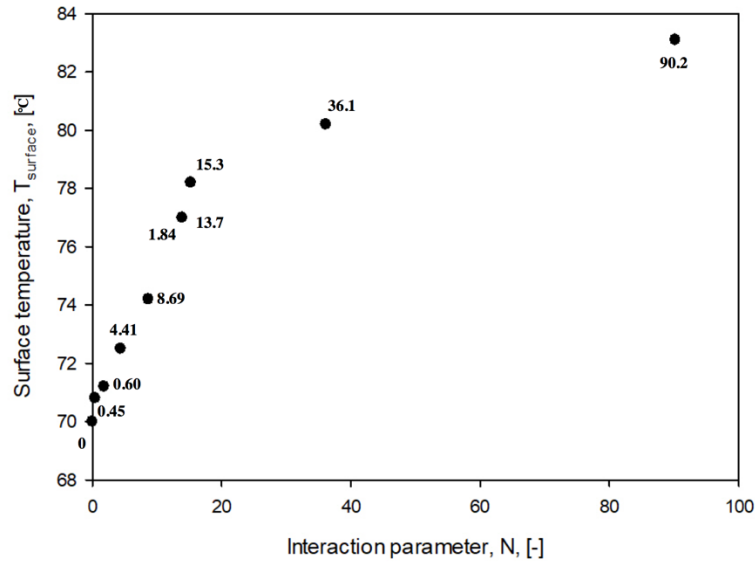


Fig. 3-42. The interaction number dependency of the surface temperature for 1.70Lmin^{-1} (Numbers show interaction parameter).

3.3-3-3 Heat transport performance

The evaluation of heat transport performance was referred to the heat flux analysis, the efficiency of heat transport. Heat flux distributions were based on the temperature at the bottom-wall, inlet/outlet temperature and the fluid depth. The heat flux gives the information of the place which heat load or cooling and how much heat was transported locally. Based on the heat flux distribution, the efficiency of heat transport was evaluated to understand how much the input energy was transported to the bottom-wall.

Figure 3-43 shows heat flux distributions. At comparatively low N , the characteristic of the tendency was similar to temperature rise analysis. However, the heat flux at relatively high N ($N > 8.67$) shows much the same distributions. This is to say; the heat flux is likely to be constant even under higher N . This result was caused by increasing the bulk temperature and the temperature at the bottom-wall. The bulk temperature was depending on the temperature at the inlet and outlet, it means that temperature difference was larger than the case of $N < 8.67$. Due to the effect of flow velocity decreasing, high

temperature fluid tends to accumulate on the test section as mentioned on above. In contrast, the fluid was transported quickly to the further downstream of the test section at the high flow velocity. Thus, a heat accumulation was given rise inside the liquid metal film-flow. Thus, the high heat flux was observed.

Figure 3-44 plots of the relationship between the efficiency of heat transport and various N in case of an absence of obstacles at the flow rate of 1.70L min^{-1} . The tendency was increased with increasing N at low N . At comparatively high N , the efficiency of heat transport plotted almost 74.0%. This means the amount of heat transport in case of high N was larger than that of low N . The result was correlated to the tendency of heat flux as described in above. The reason for this behavior is caused by inducing the heat accumulation at the relatively short distance from the heating location in case of high N . In fact, the previous experiment shows that remaining heat was not identified due to the limitation of the measurement section in case of relatively high strength of the transverse magnetic field. In contrast, the tendency was opposite in this magnetic configuration. Therefore, heat accumulation was induced the high efficiency of heat transport in this result.

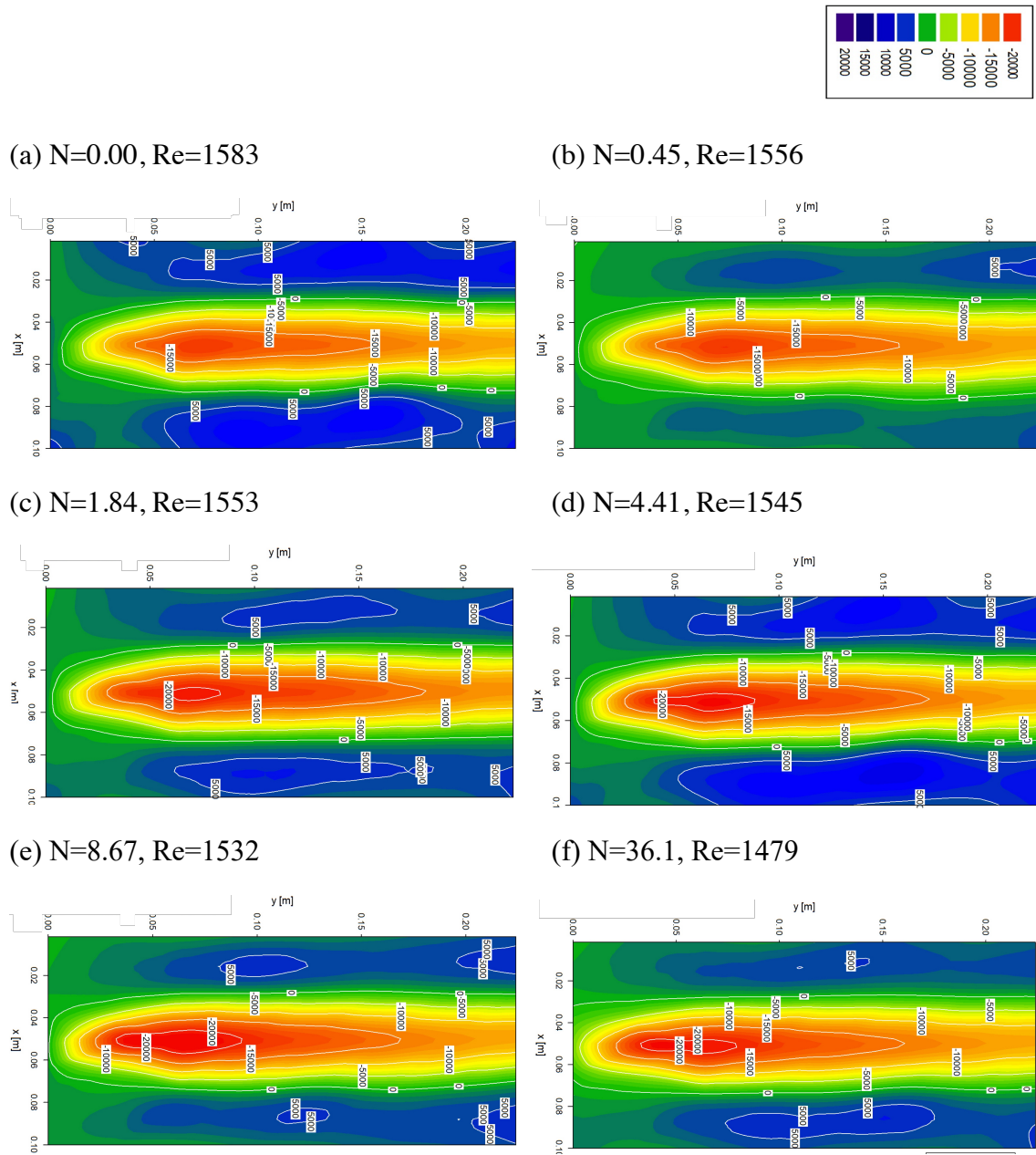


Fig. 3-43. The heat flux distributions at the bottom-wall in case of an absence of obstacles under various N of the vertical parabolic magnetic field.

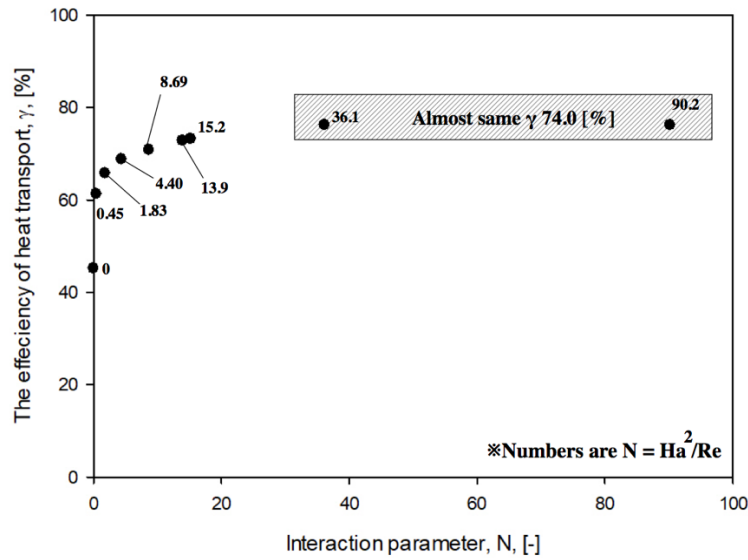


Fig. 3-44. The relationship between the efficiency of heat transport and interaction parameter in case of an absence of obstacle under the vertical parabolic magnetic field at $Q_f = 1.70 \text{ L min}^{-1}$.

3.3-3-4 MHD effect to the velocity field

To certificate for the effect of thermal behavior, the vertical flow velocity distribution measurement is necessary. However, measurement technique was very difficult to because of the thin thickness of liquid metal film-flow. To measure the flow velocity distribution in liquid metal film-flow, I developed the potential probe. Thus, the flow velocity on the cross-sectional direction was measured for the test case. In this subsection, the measurement result of the normalized spanwise flow velocity distribution on 4.00mm height from the bottom-wall was shown in Fig. 3-45.

For maximizing the MHD effect, the flow rate was conducted at $Q_f = 0.60 \text{ L min}^{-1}$ and $N=149$ and $Re = 487$. The white circle indicates the experimental data with error range which means the fluctuation range, the black circle indicates numerical simulation result used by STREAM Package as same as Chapter 2. One of the characteristics of the experimental result is error range which tends to larger at near the

side-wall. This is caused by the effect of the offset voltage by the own characteristic of the amplifier and induced the electrical noise. This effect makes fluctuation of the signals. Another consideration is the effect of boundary-layer of electrical current. The electrical current near the side-wall directed to the bottom-wall rather than the spanwise direction. Due to this, potential probe near the side-wall is difficult to measure correctly. To increase the measurement performance, it requires higher resolution voltage meter and lower offset voltage electrical circuit. However, the distribution was the good agreement to the numerical result.

The characteristic of the distribution was the relatively fast flow near the side-wall and the suppressed the velocity on the bulk. By the effect of vertical parabolic magnetic field, it can be considered that high induced Lorentz force was generated on the center of the bulk because of the comparability of high magnetic field strength. On the other hand, the induced Lorentz force was the relatively low near the side-wall. This force gradient may make this distribution.

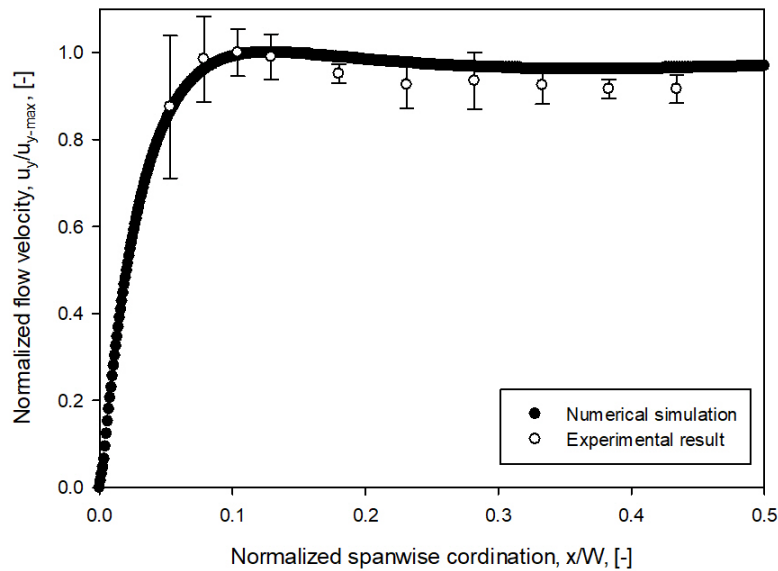


Fig. 3-45. The distribution of streamwise flow velocity on the spanwise coordination on 4.00mm height from the bottom-wall in case of an absence of obstacle at $N=149$, $Re=487$ and $Q_f = 0.60Lmin^{-1}$.

3.3-3-5 Comparisons

Based on the comparison of the efficiency of heat transport in the numerical and experimental result, the efficiency of heat transport was approximately 20.0% increased with increasing N , increased 3.10% in the numerical result. This means that there is a possibility to enhance heat transport more than the numerical simulation. The reason for this difference may be caused by the difference of changing the heat flux. In the experiment, the difference of the heat flux was 1.33 times difference between $N=0.00$ and the maximum N . On the other hand, there was 1.07 times difference in the numerical result. Due to this difference, the heat transport performance has been affected.

From Fig. 3-45, the streamwise flow velocity showed good agreement to the numerical result. In detail of the difference between normalized flow velocity on the bulk, there was slightly different. However, their difference was only 4.00% difference at the maximum. In addition, the error bar of the almost measured points covered the numerical results. This means the numerical simulation performance has high accuracy to the velocity field.

3.3-3-6 Discussions

The main findings from this experiment configuration as summarized below

- (1) The temperature rise distributions were given a constant increasing with increases N .
- (2) The surface temperature increased with increasing N .
- (3) The performance of heat transport from the free-surface to the bottom-wall increased with increasing N .
- (4) The heat transport performance showed approximately constant heat flux and the efficiency of heat transport at the relatively high N .
- (5) The spanwise velocity distribution was affected by the vertical parabolic magnetic field.

In terms of temperature rise analysis on the bottom-wall, the temperature rise behaved as finding (1). This tendency was opposite to the result in case of the transverse magnetic field. The reason for this behavior was depending on the streamwise flow velocity on the vertical line. From the numerical result, the flow velocity on the bulk and the free-surface was uniformly suppressed by Lorentz force. By this phenomenon, the thickness of the thermal boundary layer has been increased. Thus, the high heat load was induced near the heating location locally. Due to this effect, the high temperature fluid has been accumulated near the heating position. Therefore, the surface temperature increased (finding (2)). These results indicate that the temperature of the fluid may be increased under the vertical parabolic magnetic field.

On the contrary, heat flux at comparatively high N showed similar heat flux and the distribution shape. This is caused by the increasing the bulk temperature. From the temperature analysis, the temperature at the bottom-wall was increased with increasing N . Based on this, it can be considered that the bulk temperature was also increased. The increased bulk temperature was depended on the behavior of heat accumulation and flow velocity. When it was given rise on the test section, the flow velocity decreasing occurred and bulk temperature should be increased. In addition, the constant heat flux means that the heat transport mechanism may be changed as heat conduction from the thermal mixing. This gives the possibility to increase the fluid temperature at the relatively high N . Therefore, the result suggests for liquid divertor that the cooling technique must be required under the vertical parabolic magnetic field.

Because of heat flux behavior, the efficiency of heat transport correlates to the heat flux values as increased at comparatively low N and approximately constant at high N . This can be considered that high heat transport performance can be gained under the relatively high N . This result may be induced by heat accumulation. Therefore, some impingement cooling jet from the back-side of the bottom-wall should be installed for heat removal.

The spanwise flow velocity distribution showed the non-uniformly velocity distribution due to the vertical parabolic magnetic field. The characteristic of the distribution is relatively higher velocity near the side-wall. The reason for this distribution shape was caused by the induced electrical current gradient as mentioned in Chapter 2. In terms of heat transport performance, the relatively high flow velocity is appropriate for the high performance of heat transport. Based on this, it can be considered that the velocity difference by non-uniform magnetic field could be enhanced turbulent for heat transport effectively.

3.3-4 Effect of a single obstacle

3.3-4-1 Experimental apparatus and conditions

The schematic of diagnostics locations of the test channel in case of installed a single obstacle in Fig. 3-46. The schematic of the blockage ratio of obstacles was chosen as 8.00% obstacle size. It is because that this blockage ratio appropriate for the inline and staggered obstacles arrangement and makes possible to normalize all results. The obstacle was installed at the center of the channel line and below the heater. Whole diagnostics and test section were as same as the previous. The experimental conditions were listed in Table 3-7. Note that, the characteristic number was used the half of the hydrodynamic perimeter. This condition was the same as the reference case. Fig. 3-47 gives the relationship between the flow depth and interaction parameter. The flow height was increased with increasing N due to the constant pump head. For this pump condition, the total amount of liquid metal in the channel should be increased because that the flow was suppressed by MHD effect. However, the depth changing was observed about $9.00 \times 10^{-4}\text{m}$ difference in case of 1.70Lmin^{-1} , $9.0 \times 10^{-5}\text{m}$ difference in case of 0.60Lmin^{-1} at the maximum. Therefore, there were not a large difference between the case at $N=0.00$ and the maximum N .

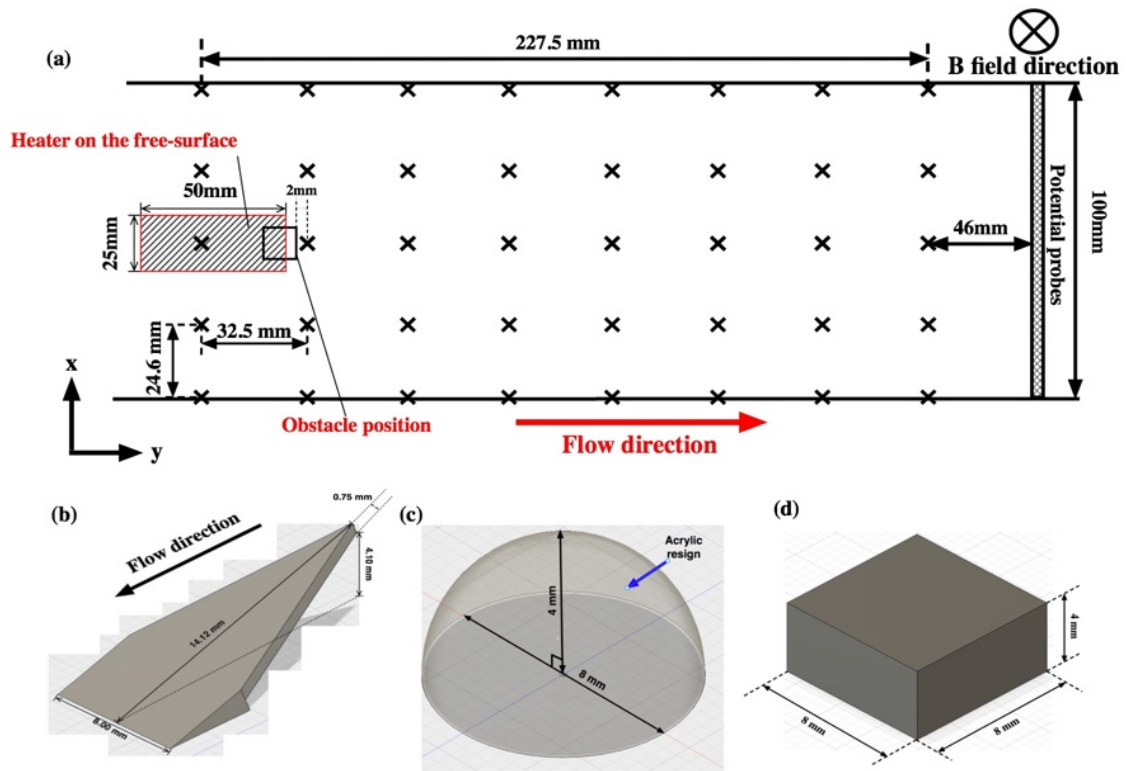


Fig. 3-46. Schematic of diagnostics locations of the channel and obstacles (x-marks show TCs locations; grid area shows potential probe rake): (a) Schematic of heater location, obstacle location, TCs locations and potential probe rake location, (b) Delta-wing, (c) Hemisphere, (d) Cube.

Table 3-7. The experimental parameters for the case of installed a single obstacle under the vertical parabolic magnetic field.

Parameters	Symbols	Value
Reynolds number [-]	Re	428 – 1583
Interaction parameter [-]	N	0.00 – 238
Flow rate [L min ⁻¹]	Q_f	0.50, 1.70
Injected heater power [W]	Q_{in}	91.9

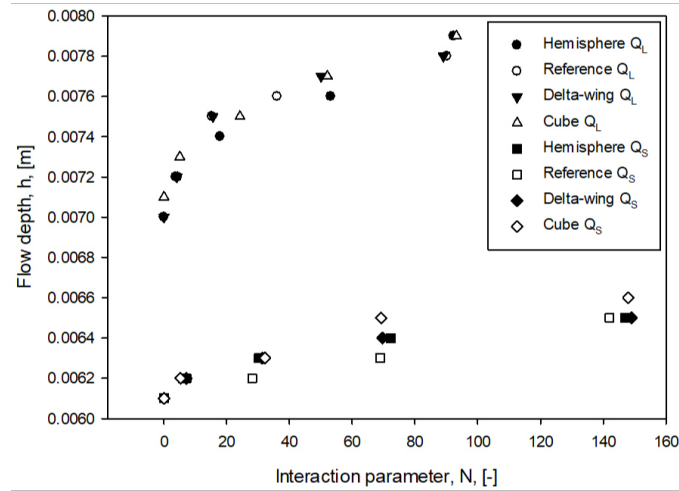


Fig. 3-47. The relationship between the flow depth and interaction parameter in case of installed various single obstacle under the vertical parabolic magnetic field ($Q_s = 0.60L \text{ min}^{-1}$, $Q_L = 1.70L \text{ min}^{-1}$).

3.3-4-2 The effect of obstacle height

The effect of the different height of the obstacle is important for finding an optimized obstacle. To enhance thermal mixing liquid metal film-flow, the obstacle height should be large due to inducing the fluctuations near the free-surface. However, there are likely to expose of the obstacle top by the relatively high liquid metal surface tension. Thus, it is required to detect the maximum allowance height for thermal mixing. In this subsection, the heat transport performance of the different height of the cubes was described.

To find the optimum height of obstacle, I have conducted the experiment using different height cubes at $Q_L = 1.70L \text{ min}^{-1}$ at $N = 0.00$. The size of the cube used in this experiment and experimental conditions were listed in Table 3-8. The relationship between the efficiency of heat transport and the height of the cube at $N = 0.00$ shows 44.2% for 3.00mm and 51.2% for 4.00mm. Note that, the height of the cube over 5.00mm were exposed on the free-surface. Thus, the optimum height of the obstacle was 57.2% of the fluid depth.

Table 3-8. The size of cubes for the experiment of different height under the vertical parabolic magnetic field.

Parameters	Values
The area of the bottom [mm ²]	8.00 × 8.00
Height, H [mm]	3.00, 4.00, 5.00, 6.00
Fluid depth [mm]	7.00

3.3-4-3 Temperature characteristics

Figure 3-48 shows the temperature rise distributions in case of installed the delta-wing under various N . The tendency was same as the result in case of the reference, the increasing the temperature rise with increasing N . In terms of the value of temperature rise, there are 5.50°C difference at the maximum N . The reason of this temperature difference may be considered as the vortex behavior and decreasing the flow velocity. From the numerical results, the delta-wing generates a pair of vortexes on the wake, this vortex survived even the relatively high N . Hence, it can be considered that the vortex might be survived over $N=90.0$.

To understand the characteristic of temperature, the normalized temperature distributions were analyzed in Fig. 3-49. As seen from figures, the distribution has been moved from the downstream to the upstream with increasing N . This is caused by the velocity decreases. Almost the same behavior was observed in case of an absence of obstacle on previous. On the other hand, the area of high normalized temperature in case of $N=95.1$ was located on further upstream than that of $N=90.1$ in the reference case. This means the delta-wing is likely to transport high temperature fluid more quickly than the reference. In addition, distributions over $N=10.2$ were similar shape and contours. Thus, it can be considered that the mechanism of fluid transport was changed at surround $N=10.2$. This changing mechanism may be related to the vortexes behavior. In case of the fast flow velocity, a pair of vortexes should be elongated to the streamwise direction. In contrast, the slow velocity, it should be shorter. Based on this, the mechanism of fluid

transport was changed by vortex behavior. Therefore, the vortex suppression may have occurred at comparatively high N .

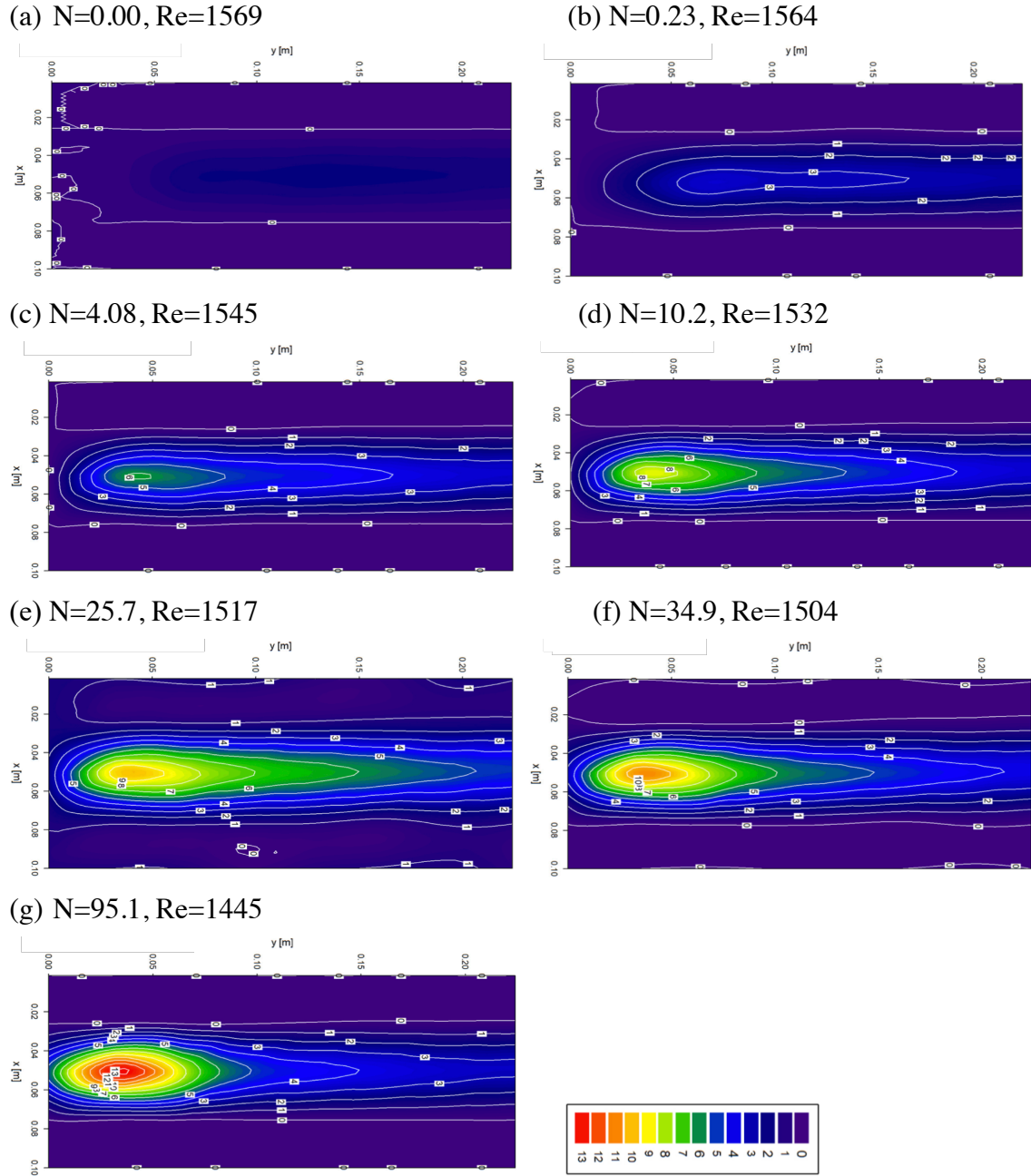


Fig. 3-48. The temperature rise distribution at the bottom-wall in case of installed the delta-wing at various N and $Q_f = 1.70 \text{ Lmin}^{-1}$ of the vertical parabolic magnetic field.

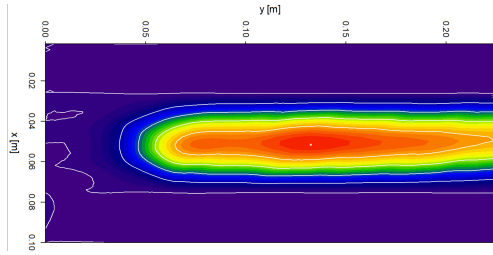
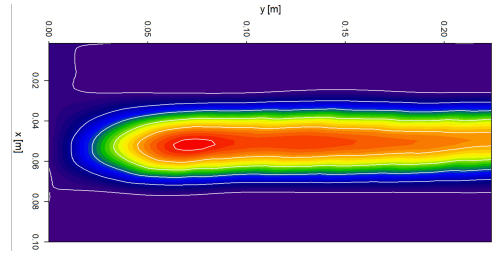
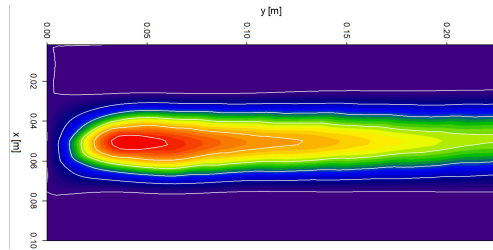
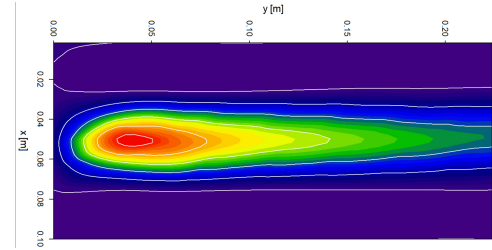
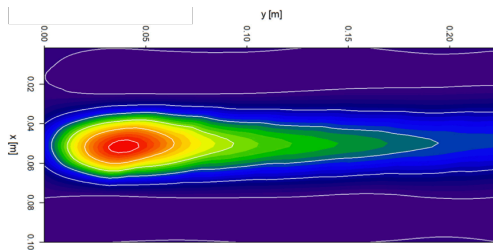
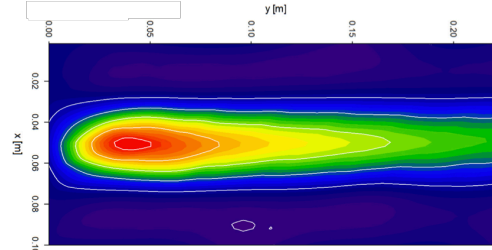
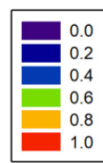
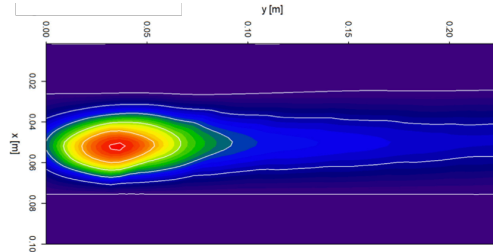
(a) $N=0.00$, $Re=1569$ (b) $N=0.23$, $Re=1564$ (c) $N=4.08$, $Re=1545$ (d) $N=10.2$, $Re=1532$ (e) $N=25.7$, $Re=1517$ (f) $N=34.9$, $Re=1504$ (g) $N=95.1$, $Re=1445$ 

Fig. 3-49. The normalized temperature rise distribution at the bottom-wall in case of installed the delta-wing at various N and $Q_f = 1.70 \text{ Lmin}^{-1}$ of the vertical parabolic magnetic field.

Figure 3-50 shows the relationships between the surface temperature and interaction parameter in case of installing three type obstacles. The surface temperature rapidly increased on low N and gradually increased in relatively high N in all cases. The

reason for the increase of $T_{surface}$ is that temperature stratification is formed then increase the temperature on the free-surface. Based on the comparison, there is variation in terms of the relationship between $T_{surface}$ and N even on relatively high N and it became the results of Reference, Hemisphere, Cube, Delta-wing in descending order of the surface temperature $T_{surface}$. It is found that the obstacle has a possibility to decrease $T_{surface}$. The results in case of installed the delta-wing were the lowest and it was 8.00°C lower than the reference case. Thus, the delta-wing can be decreasing the surface temperature effectively.

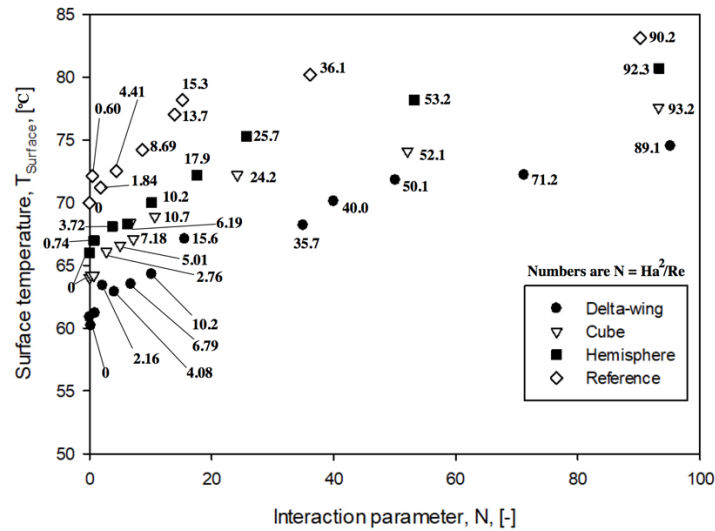


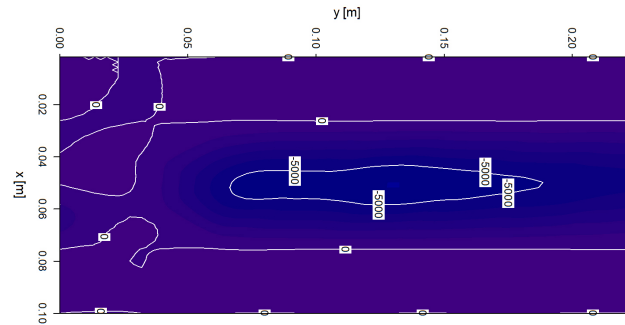
Fig. 3-50. The relationship between the surface temperature and interaction parameter in case of installing three type obstacles at $Q_f = 1.70\text{Lmin}^{-1}$.

3.3-4-4 Heat transport performance

The heat transport performance was evaluated by the heat flux distribution and the originally defined the efficiency of heat transport. Figure 3-51 shows the heat flux distributions in case of the delta-wing. The characteristic of the heat flux behavior is gradually decreasing at the comparatively low N and the same distributions under high N . The distributions over $N > 25.7$ were almost same heat flux and shape. This is caused

by the characteristic of the definition of heat flux and the velocity decreases. At the constant flow rate, the fluid depth of the liquid metal film-flow should be increased with increasing the strength of the magnetic field because of velocity decreasing. Due to this, the heat flux has been affected as constant even increasing temperature at the wall at the high N range. Based on the aspects pointed out thus far, it can be considered that the heat flux in case of thin film flow may be increased and increasing the heat load to the wall. However, the delta-wing and other obstacles can prevent the reaming high temperature fluid near the free-surface. In addition, the delta-wing shows the higher heat flux on the wall by comparison of the reference case. It is 1.50 times higher than that of the reference case at high N range. Therefore, the delta-wing can enhance heat transport even under high strength of the vertical parabolic magnetic field.

(a) $N=0.00$, $Re=1569$



(b) $N=0.23$, $Re=1564$

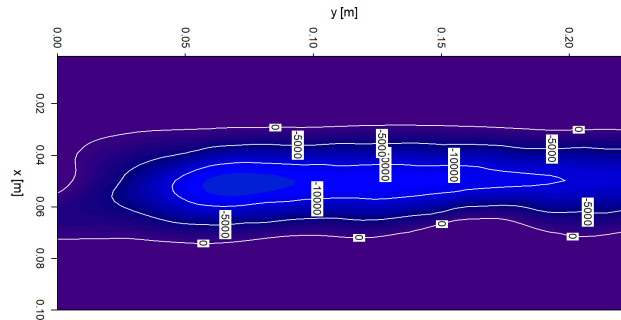
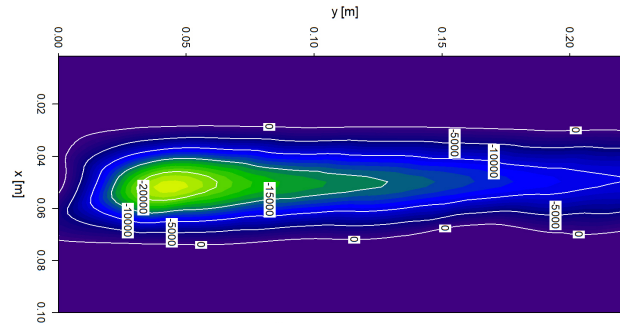
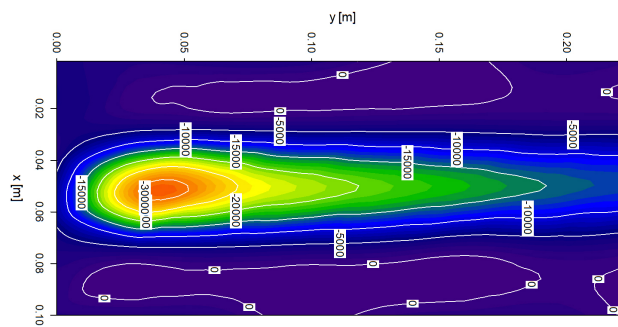


Fig. 3-51. The heat flux distribution at the bottom-wall in case of installed the delta-wing at various N and $Q_f = 1.70 \text{ Lmin}^{-1}$ of the vertical parabolic magnetic field.

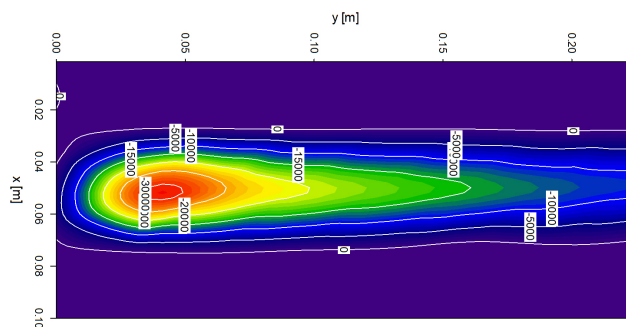
(c) $N=4.08$, $Re=1545$



(d) $N=10.2$, $Re=1532$



(e) $N=25.7$, $Re=1517$



(f) $N=34.9$, $Re=1504$

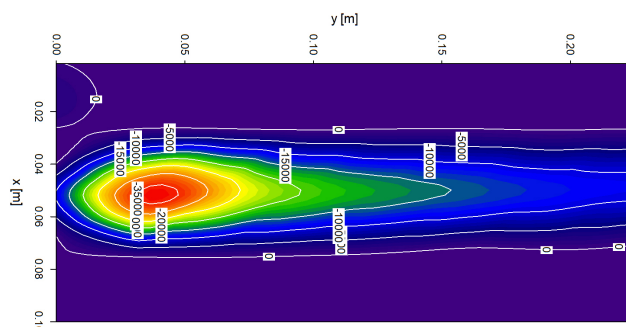


Fig. 3-51 (Cont.)

(g) $N=95.1$, $Re=1445$

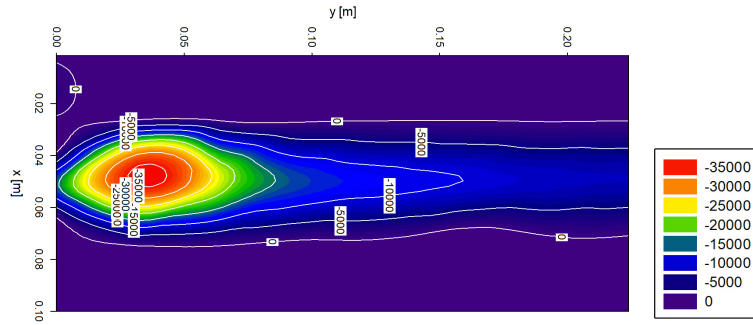


Fig. 3-51 (Cont.)

To evaluate the heat transport performance in case of the delta-wing and other obstacles, the efficiency of heat transport was shown in Fig. 3-52. At the comparatively low N , the efficiency of heat transport rapidly increased and, gradually increased on high N . Based on the comparison of each case, the delta-wing shows the highest γ on all N . This is to say, the delta-wing can transport heat near the free-surface to the wall effectively. On the other hand, the heat transport performance in case of the hemisphere and cube was similar to the reference case. This means that there is a possibility to not enhance heat transport by the vortex from the hemisphere and cube. From Chapter 1, the vortex characteristic of the cube and hemisphere has an axis of the vortex parallel to the vertical magnetic field in this experiment. That said, the vortex size may be developed. However, the rotational plane was located on the free-surface. Therefore, the thermal mixing was enhanced on the spanwise plane. Due to this effect, the vertical heat transport has not much stronger than the delta-wing case under the vertical magnetic field.

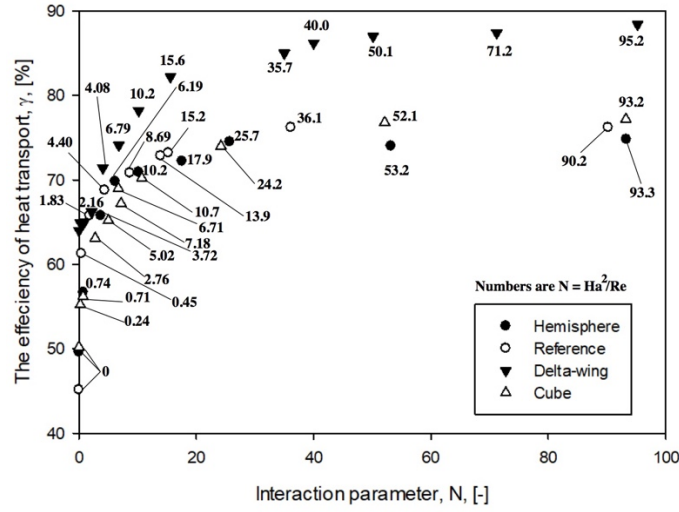
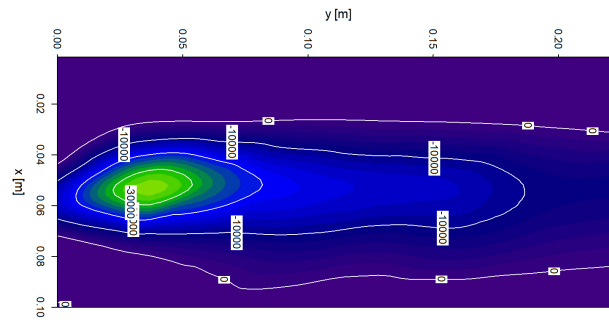


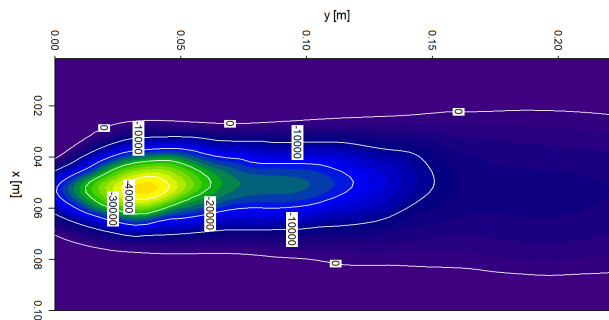
Fig. 3-52. The relationship between the efficiency of heat transport and interaction parameter in case of the single obstacle under the vertical parabolic magnetic field and $Q_f=1.70\text{Lmin}^{-1}$.

The above descriptions were in case of the relatively high flow rate $Q_f = 1.70\text{Lmin}^{-1}$. I had conducted the experiment under the $Q_f = 0.50\text{Lmin}^{-1}$. This could be performed under higher interaction parameter. The maximum N was 153. Figure 3-53 shows the heat flux distributions in case of the cube, delta-wing, hemisphere and the reference case at $N=0.00$ and the highest N. Based on the comparison $N=0.00$ cases and the maximum N cases, the locations and the shape were almost same. This is caused by the effect of laminar flow. The comparatively low flow velocity cannot transport the high temperature fluid to the downstream, it transports heat to the near the heating location. Due to this, the high temperature fluids are likely to accumulate inside the fluid near the heater and the heat transport mechanism was likely to change as heat conduction rather than the heat transport. This high local high heat flux on the upstream. The high heat flux was observed in case of delta-wing, hemisphere, cube, reference in descending order. This behavior indicates that the delta-wing is effective for heat transport even in the relatively low flow velocity.

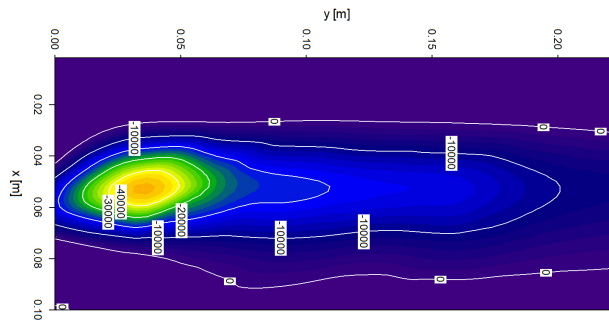
(a) Reference, $N=0.00$, $Re=518$



(b) Reference, $N=139$, $Re=464$



(c) Cube, $N=0.00$, $Re=492$



(d) Cube, $N=137$, $Re=457$

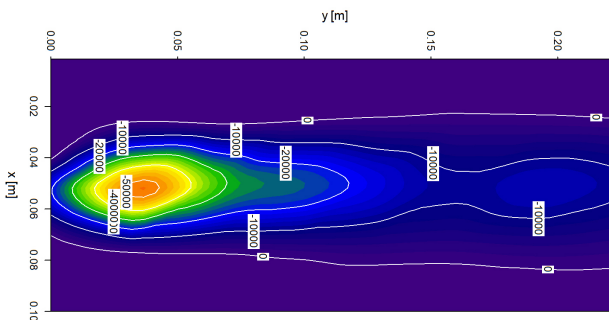
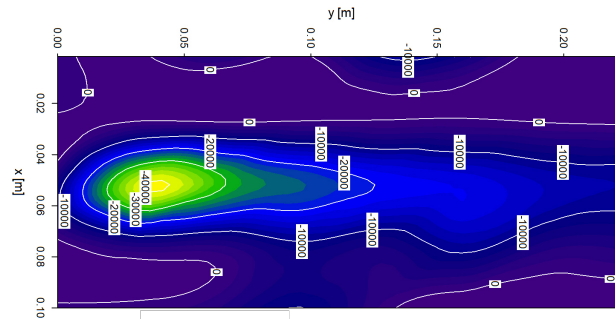
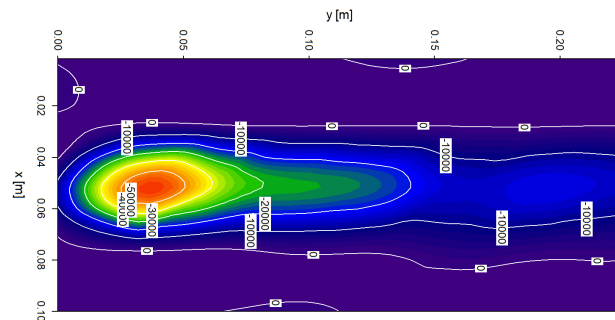


Fig. 3-53. The heat flux distribution at the bottom-wall at $Q_f = 0.50 \text{ Lmin}^{-1}$ in case of $N=0.00$ and the highest N of the vertical parabolic magnetic field.

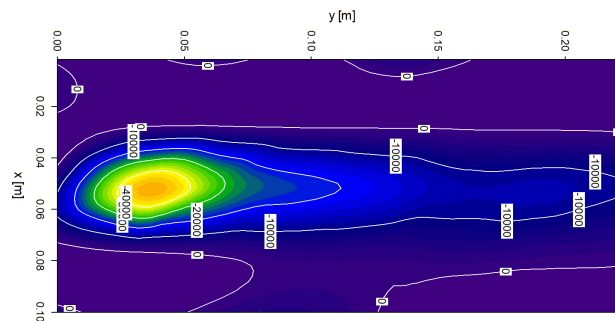
(e) Hemisphere, $N=0.00$, $Re = 495$



(f) Hemisphere, $N=147$, $Re=477$



(g) Delta-wing, $N=0.00$, $Re=512$



(d) Delta-wing, $N=153$, $Re=479$

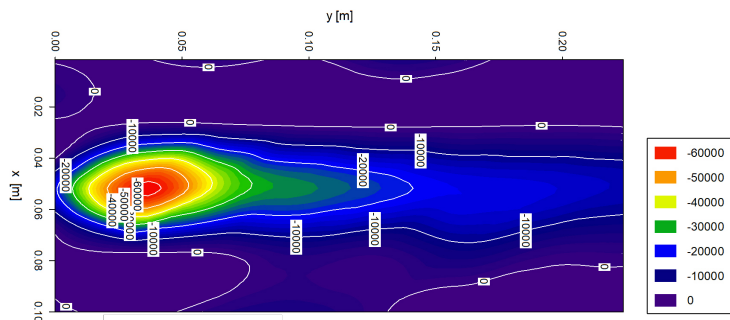


Fig. 3-53 (Cont.)

3.3-4-5 Comparisons

To understand the heat transport mechanism in case of installing the obstacle under the vertical parabolic field, these results should be compared to the numerical results. In this subsection, some comparisons are described.

Based on the comparison of experimental/numerical results of the relationship between the efficiency of heat transport and N , the converging point was different. In case of the numerical result, γ converged over $N = 10.0$. On the other hand, the γ has been became almost constant value over $N=20.0$. Thus, there was 10.0 difference. This is caused by the effect of changing the fluid depth and the different characteristic of the temperature behavior. From the numerical result, the temperature at the wall has been a constant at the relatively low N . However, the experimental results showed the increasing temperature rise with increasing N . In addition, the fluid depth also increased because of constant flow rate and Lorentz force. This difference makes the difference of heat flux. Due to this, the efficiency of heat transport was affected.

Effect of the obstacle was the same tendency in both experimental and numerical result. This suggested that the delta-wing is the most appropriate for heat transport enhancement of the liquid metal film-flow under the vertical parabolic magnetic field. It is a possibility to use many delta-wings for thermal mixing efficiently. Therefore, the next section will be introduced practical configurations for finding the optimized arrangement with using delta-wings.

3.3-4-5 Discussions

In this section, the experiment using various shape obstacle installed at the center of the wall has conducted under the vertical parabolic magnetic field. The main findings are listed followings:

- (1) The experimental results in case of the delta-wing showed the highest heat transport performance.
- (2) The normalized distributions moved to the upstream from the downstream of the

channel.

- (3) Obstacles can make decreasing the surface temperature.
- (4) The cube and hemisphere were not appropriate for vertical heat transport.
- (5) The relatively low flow rate makes the heat accumulation on the bottom-wall even under the non-magnetic field.

For (1), all numerical and experimental results suggested the delta-wing can transport the heat from the free-surface to the wall efficiently. This is caused by the vortex characteristic from the delta-wing enhances heat transport even under the vertical parabolic magnetic field. A pair of vortexes has been diminished on the short distance from the delta-wing at the comparatively high N . However, this suction flow has only existed on the delta-wing. Therefore, the delta-wing is likely to heat transport enhancement under high strength of the vertical parabolic magnetic field.

For (2), the reason for this behavior was affected by the velocity decrease. This means the heat accumulation has occurred on the relatively upstream of the channel. In addition, this behavior suggested that the possibility of heat removal from the liquid metal film-flow as quickly. This was also overserved in case of installed inline hemisphere arrangement under the transverse magnetic field. Thus, this behavior is appropriate for increasing heat transport performance. In terms of the distribution shapes and locations, there was similar at relatively high N . It can be considered that they may not be changed under higher N . In fact, the finding (5) showed this hypothesis. Based on the comparison of $N=0.00$ and maximum N at $Q_f=0.50\text{Lmin}^{-1}$, the location/shape of heat flux has not been largely changed. This means that the MHD effect becomes limited in case of low flow velocity, just increasing heat load and the efficiency of heat transport on the bottom-wall. However, the surface temperature is also increased, it is required for decreasing the surface temperature using obstacles. To get high heat transport performance and the relatively low surface temperature, the obstacle can be an effective method by finding (3).

Table 3-9. The experimental parameters of the experiment using the inline/staggered obstacles under the vertical parabolic magnetic field.

Parameters	Symbols	Value
Reynolds number [-]	Re	1489 – 1583
Interaction parameter [-]	N	0.00 – 91.3
Flow rate [L min^{-1}]	Q_f	1.70
Injected heater power [W]	Q_{in}	91.9
Streamwise-pitch-length [mm]	L_p	15.0, 30.0, 60.0
Spanwise-pitch-length [mm]	L_w	12.0
Obstacles		Delta-wing, Hemisphere

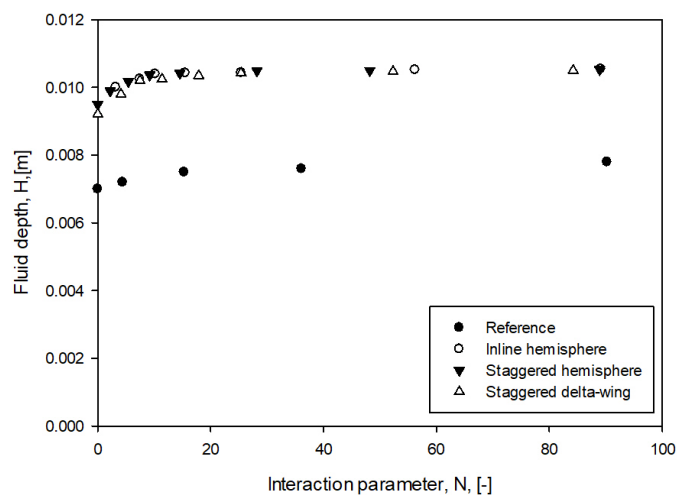


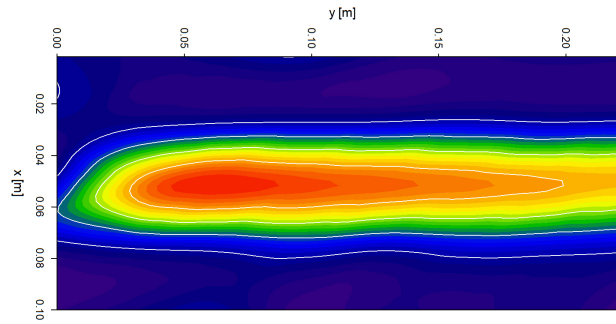
Fig. 3-55. The relationship between the fluid depth and interaction parameter in case of installing inline-hemisphere and the staggered delta-wing.

3.3-5-2 Temperature characteristic

Figure 3-56 shows the normalized temperature distributions in case of installed the inline and staggered hemisphere arrangement of the 30.0mm streamwise-pitch-length. One of the characteristics of the distributions was moved from the downstream to the upstream with increasing N. This tendency has been observed in previous. Another

characteristic was the area of the relatively high temperature in case the inline hemisphere arrangement was wider than that of the staggered arrangement. This means that the inline arrangement can be rise fluid temperature near the wall rather than the staggered. This characteristic was also observed in case of high N . Based on this, the inline hemisphere arrangement can be made wide the temperature distribution on the wall, the staggered arrangement can concentrate the high temperature fluid on the wall locally even in MHD condition. However, the total amount of the transported heat was not considered on here. Thus, the analysis of heat transport performance should be analyzed to evaluate the heat transport performance.

(a) Inline arrangement, $N=0.00$, $Re=1583$



(b) Inline arrangement, $N=87.2$, $Re=1489$

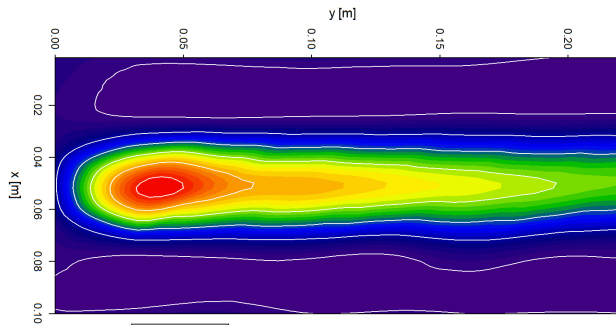
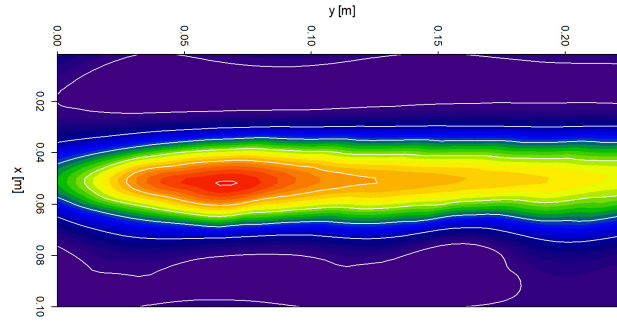


Fig. 3-56. The normalized temperature distributions in case of 30.0mm streamwise-pitch-length of the inline and staggered hemisphere arrangement under non-magnetic field.

(c) Staggered arrangement, $N=0.00$, $Re = 1581$



(d) Staggered arrangement, $N= 78.4$, $Re=1503$

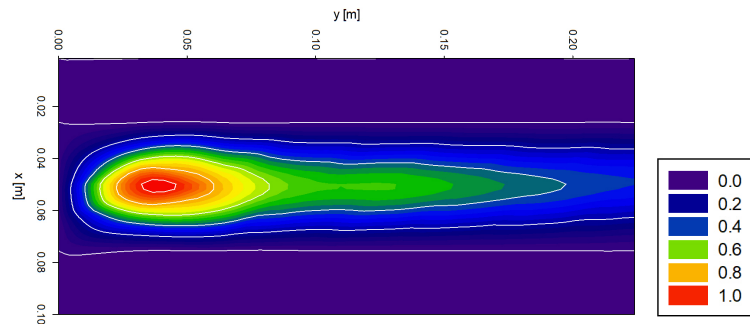


Fig. 3-56 (Cont.)

One of the advantages of the installing obstacle is decreasing the surface temperature as introduced in previous. The surface temperature decreasing has been also observed in this hemisphere arrangements in Fig. 3-57. In the case of the staggered hemisphere arrangement, the surface temperature was the lowest. On the other hand, the inline arrangement was approximately averaged 6.20°C difference than staggered and averaged 0.20°C lower than the reference case. This suggested that the staggered arrangement can decrease the surface temperature, however, the inline arrangement has less effect to the surface temperature decreasing compared than the staggered arrangement. The behavior is caused by the heat accumulation between hemispheres on the streamwise line and the effect of upward/downward flow velocity. From the numerical results, the vertical velocity in case of installing the staggered arrangement was larger than the inline arrangement. This can be enhanced fluid mixing for vertical heat

transport. In addition, the area of the downward velocity was divided due to the spanwise fluctuation. This makes less area of vertical flow direction. Due to this effect, the high temperature fluid fluctuated to the spanwise direction in case of inline arrangement. Therefore, the staggered arrangement was appropriate for vertical heat transport enhancement.

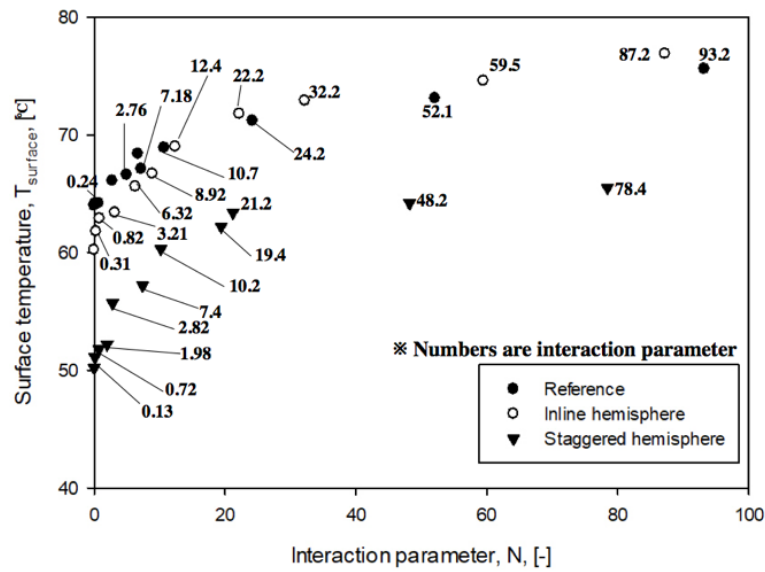


Fig. 3-57. The relationship between the surface temperature and interaction parameter in case of the inline and staggered hemisphere arrangement under the vertical parabolic magnetic field.

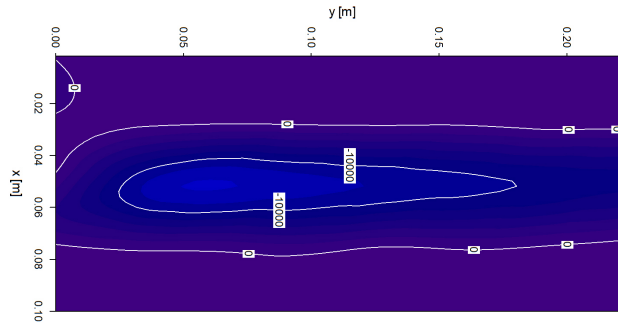
3.3-5-3 Heat transport performance

Based on results so far, it can be considered that the combination of the staggered arrangement with the delta-wing likely to more enhance heat transport. The heat transport performance of the different streamwise-pitch-length of the staggered delta-wing arrangement was evaluated. Firstly, Figure 3-58 shows the heat flux distributions of the staggered delta-wing arrangement and staggered/inline hemisphere of 30mm streamwise-pitch-length at $N=0.00$ and the maximum N . As seen from figures, the heat flux of the staggered delta-wing arrangement at the maximum N was the highest. This result

suggested that the staggered delta-wing can enhance heat transport more than the inline and staggered hemisphere arrangement.

To finding the high-performance arrangement, the experiment of three different streamwise-pitch-length was conducted. The heat flux of three different streamwise-pitch-length in case of the staggered delta-wing was shown in Fig. 3-59. The results were shown that the relatively long streamwise-pitch-length was the highest heat flux. It is suggested that the long streamwise-pitch-length transports the heat from the free-surface to the bottom-wall in most effectively. Heat flux over $5.00 \times 10^4 \text{ Wm}^{-2}$ was the largest heat flux as I have observed in this study. By the evaluation of the efficiency of heat transport, $\gamma=89.7\%$ was measured in case of the staggered delta-wing arrangement of long streamwise-pitch-length under $N=81.2$. Therefore, this arrangement was the most appropriate arrangement by directly measured in this study.

(a) Inline hemisphere, $N=0.00$, $Re=1583$



(b) Inline hemisphere, $N=87.2$, $Re=1489$

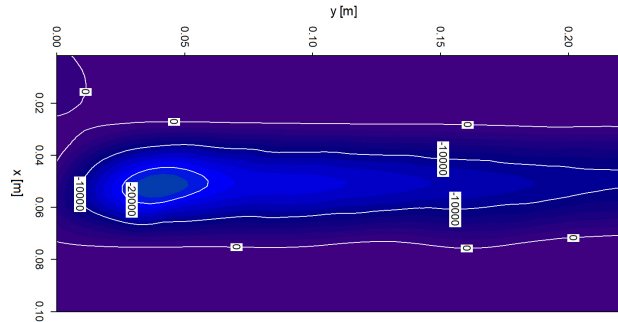
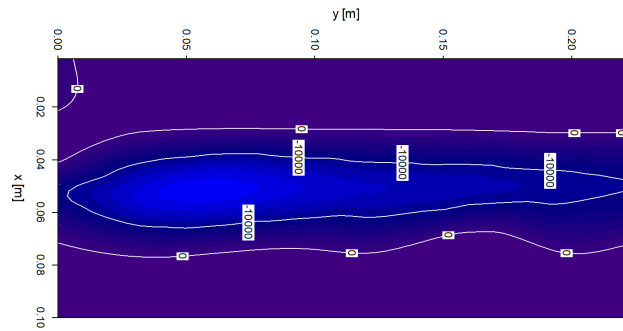
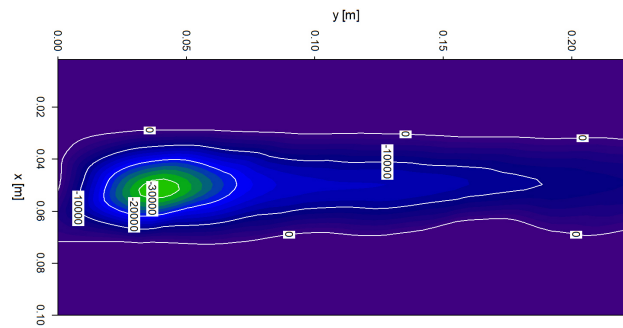


Fig. 3-58. The heat flux distributions at the wall in case the staggered delta-wing/hemisphere and inline hemisphere arrangement of 30.0mm streamwise-pitch-length.

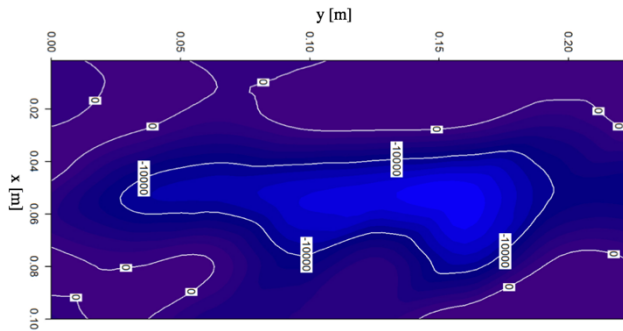
(c) Staggered hemisphere, $N=0.00$, $Re=1581$



(d) Staggered hemisphere, $N=78.4$, $Re=1503$



(e) Staggered delta-wing, $N=0.00$, $Re=1584$



(f) Staggered delta-wing, $N=79.2$, $Re=1498$

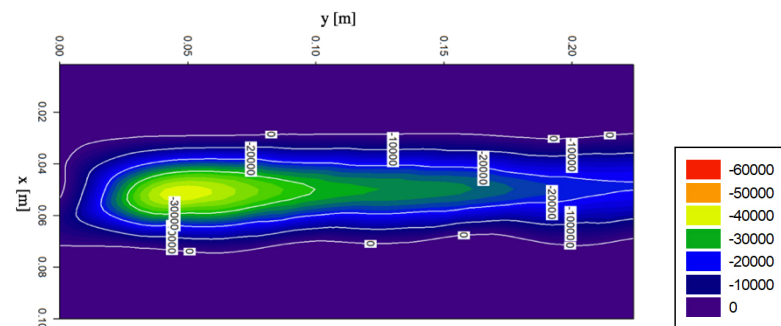
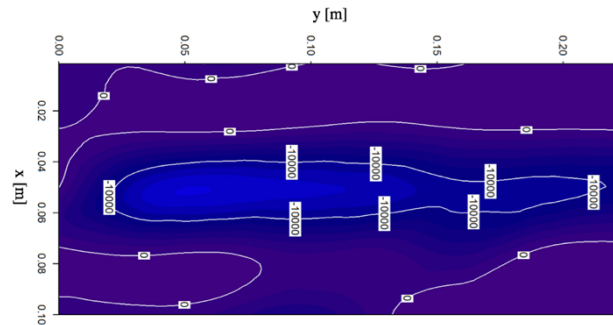
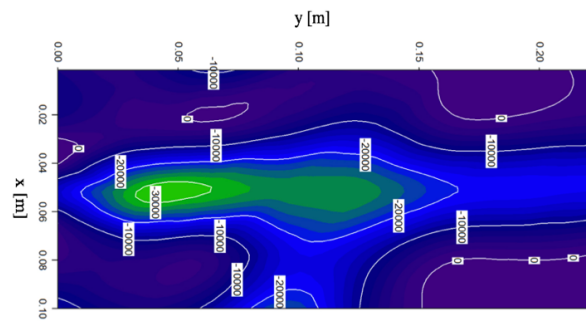


Fig. 3-58 (Cont.)

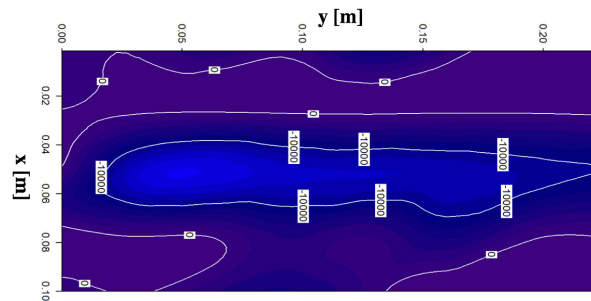
(a) $L_p=15.0\text{mm}$, $N=0.00$, $\text{Re}=1583$



(b) $L_p=15.0\text{mm}$, $N=77.4$, $\text{Re}=1496$



(c) $L_p=60.0\text{mm}$, $N=0.00$, $\text{Re}=1587$



(d) $L_p=60.0\text{mm}$, $N=81.2$, $\text{Re}=1488$

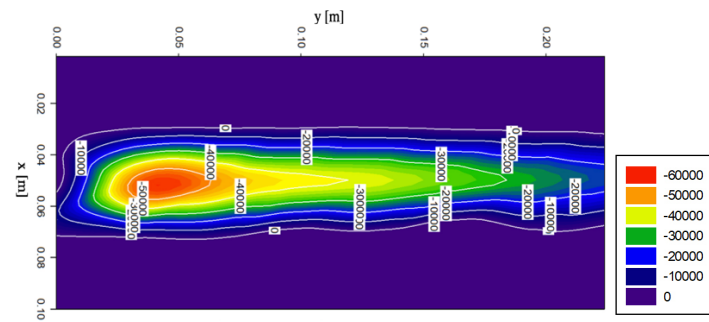


Fig. 3-59. The heat flux distributions at the wall in case the staggered delta-wing arrangement of three different streamwise-pitch-length.

3.3-5-4 Comparisons

Based on the comparisons of the numerical and the experimental results, both results suggested that the longest streamwise-pitch-length of the staggered delta-wing arrangement is appropriate for vertical heat transport enhancement. Particularly, the heat transport mechanism for the highest heat transport performance was the combination of the heat conduction and heat transport. As mentioned above, the heat conduction is a danger of temperature rise. To prevent this and enhance higher heat transport, the height of the delta-wings should be taller to prevent increasing the surface temperature and transport the high temperature fluid by thermal mixing behavior instead of the heat conduction. The concept of this delta-wing shape was effectively using the vortex for keeping low surface temperature. Generally, the vortex from the delta-wing generated on the bottom-wall and the bulk, it was identified that less performance of thermal mixing near the free-surface. If the delta-wing edge located near the free-surface, it may be generated the vortex near the free-surface. This vortex has a possibility to enhance thermal mixing near the free-surface and decreasing the surface temperature.

3.3-5-5 Discussions

The experiment using the inline/staggered arrangement of the hemisphere and the delta-wing was conducted under the vertical parabolic magnetic field. The phenomenon common to all results was increasing the heat load on the bottom-wall with increasing the strength of the magnetic field and the heat transport performance converged to the constant under the comparatively high N . This tendency was also observed in other configurations. Due to this behavior, the surface temperature was increased with increasing high N . However, the installing obstacles can make lose the temperature increasing. Especially, the staggered delta-wing arrangement of the relatively long streamwise-pitch-length was the highest heat transport performance in this study. This result was also observed in numerical result in Chapter 2. The shortest streamwise-pitch-length makes high suction flow directed to the bottom-wall from the center of the bulk.

However, the relatively high flow velocity was induced near the free-surface. This behavior transports the heat to the further downstream. In contrast, the relatively slow and high flow velocity appeared in case of long streamwise-pitch-length, this local slow velocity makes heat accumulation and heat was conducted on this area and transported by the suction flow. Hence, the heat transport mechanism of the relatively long streamwise-pitch-length of the staggered delta-wing arrangement was two steps: (1) The heat was conducted on the relatively slow streamwise velocity area. (2) The conducted heat was transported to the bottom-wall by a pair of vortexes from the delta-wing. Since the heat was conducted on heat accumulation area, the fluid temperature on that area is likely to increase. Therefore, it is required to prevent this by other methods. This method was introduced in Chapter 5.

In case of the inline arrangement, there were likely to induce the shedding behavior to the spanwise direction, this makes that the high temperature fluid accumulated in the liquid metal. By this effect, there is a high possibility that the temperature of the liquid metal will increase under higher N . Therefore, I concluded that the staggered delta-wing arrangement was the most appropriate for thermal mixing enhancement for vertical heat transport.

Based on the surface temperature analysis and comparisons, the staggered delta-wing showed the lowest surface temperature. The temperature was the reference case and inline hemisphere arrangement case in descending order. From the numerical result, upward and downward flow velocity in case of inline hemisphere arrangement were lower than other cases. In addition, the high temperature fluids tend to accumulate near the free-surface due to the spanwise fluctuation. Based on these results, inline hemisphere arrangement was not appropriate for vertical heat transport under the vertical parabolic magnetic field. In contrast, the staggered delta-wing was the lowest temperature. However, the surface temperature likely to increase in the wake of delta-wing because of inducing the heat accumulation or relatively high streamwise flow velocity near the free-

surface by the numerical result. To prevent the surface temperature increases, some techniques are proposed using the staggered delta-wing arrangement as below:

- (1) Installing the delta-wing of two different height alternately. For the purpose of not occurring heat accumulation, the high-height delta-wing should be installed below locally heated area. This makes the vortex near the heating location and it can be enhanced thermal mixing.
- (2) From the result of the streamwise-pitch-length, the many suction flow was induced between the delta-wings. It has a possibility to enhance heat transport using the combination (1) and this.

Chapter 4 Discussions

Based on the results in Chapters 2 and 3 on the thermal mixing characteristics of the MHD liquid metal liquid film-flow, the optimum obstacle shape and arrangement were studied from the viewpoint of the efficiency of heat transport originally defined in this study.

All numerical and experimental results showed that the localized heated area on the free-surface has been expanded at the bottom-wall by comparisons of distributions. This tendency is very helpful for preventing the heat accumulation near the heating location. Also, the behavior was observed even under the magnetic field. For keeping the fluid temperature at the relatively low region, dispersing the heat is the significant strategy. Due to this, the liquid metal film-flow has a possibility to protect the wall without reaching the evaporation point of the fluid. This can be considered that the thermal mixing of MHD liquid metal film-flow is superior to heat conduction for the heat transport mechanism of divertor.

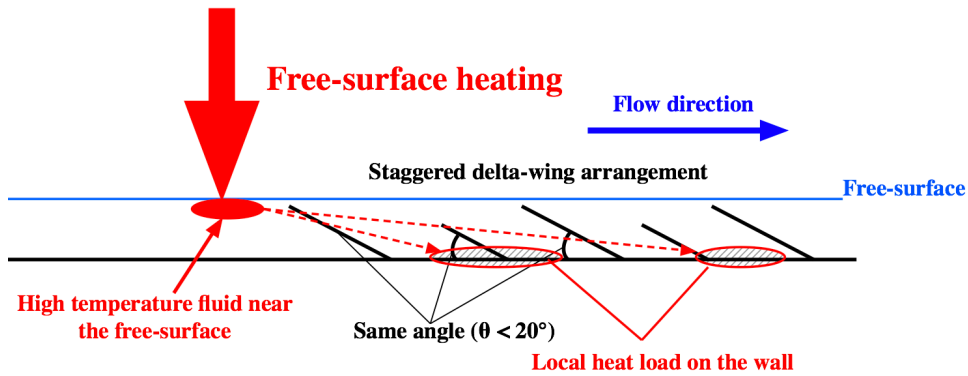
From numerical and experimental results of the obstacles arrangement, the delta-wing arrangement has been shown the highest heat transport performance. In terms of the obstacle shape, the highest heat transport performance was observed in case of the delta-wing. One of the characteristics of the delta-wing is generating the relatively strong upward and downward flow, it is appropriated for vertical heat transport enhancement. Despite in MHD condition, this vortex structure was available. Therefore, it can be concluded that the delta-wing obstacle is the most appropriate for heat transport enhancement.

Based on the engineering aspect, two kinds of arrangement of the hemisphere were considered for installing in liquid divertor. The staggered arrangement was superior to vertical heat transport rather than the inline arrangement. In the case of the inline arrangement, it was enhanced spanwise thermal mixing rather than vertical heat transport because of that spanwise fluctuation. Since the spanwise fluctuation have not occurred,

in case of streamwise-pitch-length of the inline arrangement except for 30.0mm, the fluctuation can be suppressed depending on the arrangement characteristics. In fact, the streamwise-pitch-length 36.0mm has not occurred in numerical simulation. In addition, the streamwise-pitch-length surrounded 36.0mm has been shown the high efficiency of heat transport in case of the transverse magnetic field in the experiment and numerical simulation. Hence, it takes into consideration that the transverse magnetic field effects to suppress the spanwise fluctuation. On the other hand, it can be considered that the effect for heat diffusion. If the heat diffusion was induced, the temperature of whole liquid metal may be increased gradually. Therefore, this method could be difficult to use alone for heat transport of the liquid divertor.

In case of the staggered arrangement, all results showed that the local heating occurs under magnetic/non-magnetic field and the heat transport performance was higher than the inline arrangement case. From the evaluation of the efficiency of heat transport, the long streamwise-pitch-length of the staggered delta-wing arrangement was the highest heat load on the bottom-wall in case of the vertical parabolic magnetic field. This suggested that this arrangement is appropriate for liquid divertor cooling in case of local heating on the wall. However, this arrangement is likely to increase the surface temperature due to the relatively slow flow velocity on the wake of the delta-wing. Thus, this phenomenon may cause evaporation of the liquid metal film-flow and it must be solved this problem. The solution against the prevent for surface temperature increasing requires to enhance the fluid mixing near the free-surface. The delta-wing generates a pair of vortexes on the area between the bulk center and the wall. To enhance fluid mixing near the free-surface, this vortex should be moved to near the free-surface. Therefore, I propose that using the delta-wing of two different height alternately as the staggered arrangement. Figure 4-1(a) shows the proposed arrangement for liquid divertor. In this figure, the streamwise-pitch-length was chosen the short length due to the comparatively high vertical flow velocity. Ideally, this arrangement can be considered of one of the high performances of heat transport.

(a) Alternated changing the height arrangement of the delta-wing



(b) Gradually height decreasing arrangement of the delta-wing

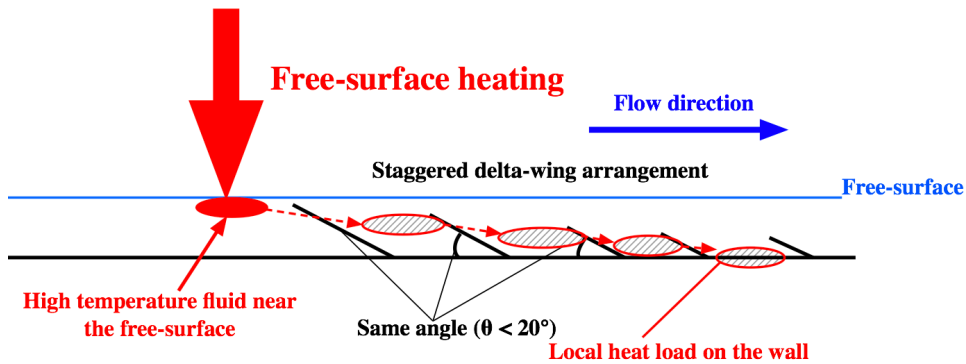


Fig. 4-1. Proposing arrangement for liquid divertor concept.

Another possible arrangement is to gradually reduce the height of the delta-wing along the downstream for lowering the position of the generated vortex. This arrangement has a possibility to enhance thermal mixing of the high temperature fluid on each height. Figure 4-1(b) shows the illustration of this arrangement. To enhance thermal mixing in case of this arrangement, it can be considered that the streamwise-pitch-length should be short due to the inducing the relatively high upward and downward flow.

Based on the comparison of the proposed arrangement, the alternated changing the height arrangement of the delta-wing may be higher heat load on the wall than another case. This is because that there is a possibility that heat accumulates between the tall

height delta-wings and decrease the surface temperature due to the tall height of the delta-wing. The behavior can be useful for local heating on the wall. In another arrangement, it can be considered that the relatively wide heat load may appear on the wall. These characteristics give choices for the cooling strategy of the heat transport system of liquid divertor. Therefore, I concluded that the alternated changing the height arrangement is appropriate for concentrating the heat locally on the wall and, the gradually height decreasing arrangement can be enhanced heat transport as the relatively wide heat load.

Chapter 5 Implementation

The best obstacle arrangement for heat transport enhancement has been proposed in the previous chapter. For the application to actual equipment, I proposed a new divertor cooling method based on the results of this study.

To consider the heat removal technique from the liquid divertor, it must be known the transported heat characteristics. Based on the comparison of experimental result in case of the reference at the highest interaction parameter ($N = 139$) and $N=0.00$, the vertical parabolic magnetic field affected that the heat flux was 1.30 times higher than the $N=0.00$ case. Under the higher N than this, the shape of the distribution can be considered to become similar and it can be estimated that the wall is locally heated. Based on this estimation, the heat removal method can be proposed by using an impingement jet cooling system [55, 56]. Figure 5-1 shows the concept of the impingement jet cooling for liquid divertor. The advantage of this system is the quick heat removal from the liquid metal film-flow, it can prevent the fluid temperature increases. Furthermore, it is possible to reduce economic costs by grasping the position of local heating. However, a thermal stress load is applied to the wall material due to a large temperature gradient. This could be avoided by using proposing obstacle arrangement below.

In case of wall heating area is wide (called diffusion heating), the economic cost also increases due to the installing many cooling types of equipment. From the viewpoint of thermal stress, a large thermal stress load is applied on the wall material, so it is necessary to consider dispersing thermal stress by broadening the heating area instead of an extremely localized heated using the optimized obstacle arrangement. Therefore, the balance between local heating and diffusion heating should be considered. For the purpose of the local heating on the wall, the described staggered delta-wing arrangement in Chapter 4 can be used for vertical heat transport from the free-surface to the wall. Additionally, this arrangement can make expansion of the heating area of the wall. This is likely to be decrease localized heat load near the heating location. Figure 5-2 shows the

proposed heat removal technique by using the suggested obstacle arrangement and the impingement jet cooling system. In the figure, L_p' is depending on the delta-wing arrangement proposed in the previous chapter. From results of this study, the heat load on the wall forms the symmetrical distribution and high loaded area located near the heating location. Thus, the proposed cooling system should be installed near the local high-heat-loaded wall. If the remaining heat which is streamed to the downstream is relatively higher than the heat capacity of the working fluid, the area of impinging jet cooling system must be expanded. Therefore, this insight gives a possibility to choose the number of impinging jet cooling systems for heat removal efficiency.

For choosing optimum the proposed delta-wing arrangement in Chapter 4 for implementation, some considerations except heat transport should be considered. It is general that the large volume obstacle makes high drag force. The tall height delta-wing corresponds to this factor. On the other hand, another arrangement is the relatively low drag force because that the low height of the delta-wings. Thus, the gradually height decreasing arrangement is superior from the viewpoint of the drag force. Regarding to MHD effect, the area of the localized heated on the wall has been moved from the downstream to the upstream. This suggested that the alternated changing the height arrangement makes it practically feasible rather than another arrangement in case of making heat concentration on the wall. It is the hypothesis that the alternated changing the height arrangement can accumulate the high temperature fluid between tall delta-wings. This makes an extremely high local heat load on the wall may be archived. Based on these considerations, both arrangements depend on the thermal resistance performance of the wall material and can give thermal design choices.

To summarize the discussion, I concluded that the optimized devised the staggered delta-wing arrangement has a possibility to enhance heat transport and, high heat removal performance can be satisfied with using impingement jet cooling system installing at the back-front of the bottom-wall.

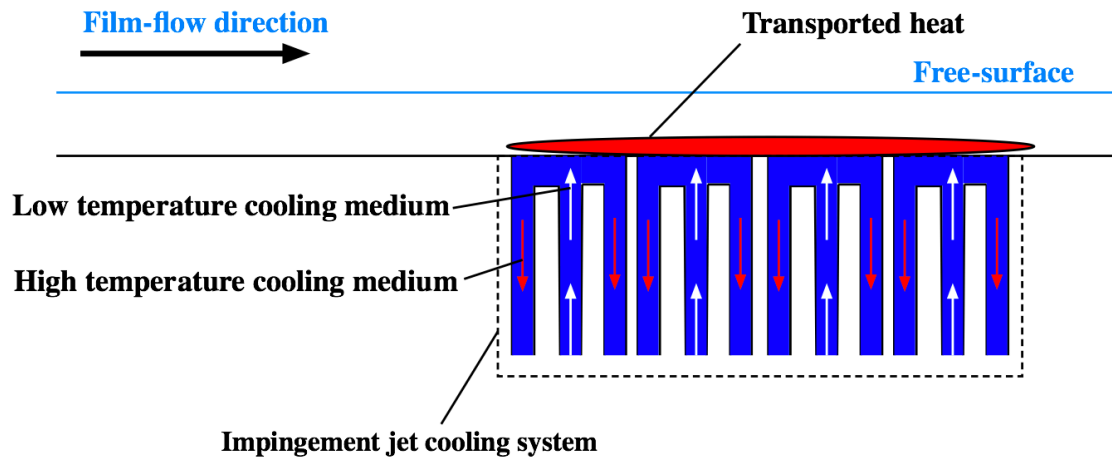


Fig. 5-1. The impingement jet cooling system for liquid divertor.

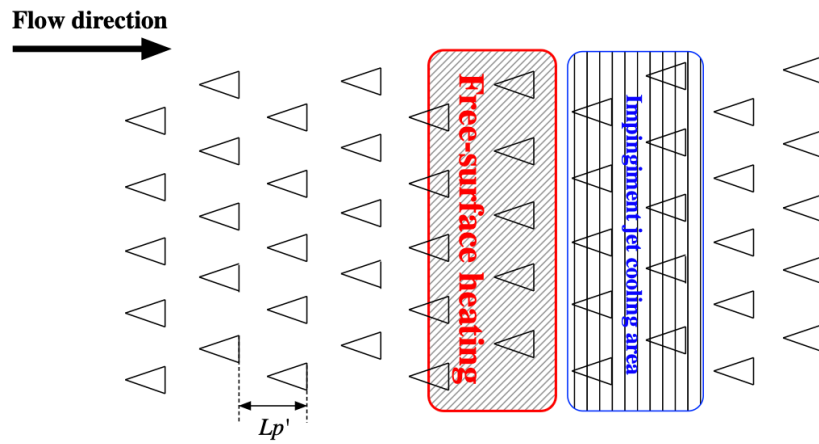


Fig. 5-2. Schematic of proposed obstacle arrangement for thermal mixing enhancement of the liquid divertor.

Chapter 6 Conclusions

In this study, thermal mixing enhancement of MHD liquid metal film-flow was investigated by numerically and experimentally for proposing to liquid divertor heat removal method. The localized heated film-flow stratifies the temperature, this induces the surface temperature increases. To prevent the temperature rising, I have been conceived that installing the cube, delta-wing, and hemisphere as a vortex generator. The following findings were revealed in this study.

1. The vortex from the delta-wing constitutes the suction flow on the behind the delta-wing, and spring outflow on the downstream of the delta-wing edge. This flow structure includes the upward and downward flow even in MHD/no-MHD condition.
2. All experimental and numerical results showed that high thermal mixing performance can be performed in case of the delta-wing.
3. In case of the transverse magnetic field, the heat transport performance was decreased with increasing N . In contrast, the heat transport performance increased in case of the vertical parabolic magnetic field.
4. The temperature rise distribution in case of the delta-wing under the transverse magnetic field moved to downstream with increasing N .
5. The middle streamwise-pitch-length of the inline hemisphere arrangement showed the high heat transport performance under the transverse magnetic field. Particularly, the location of the heat flux peak has been moved to upstream with increasing N . This behavior suggested to remove heat quickly and avoiding temperature rising.
6. The difference of finding 4 and 5 depended on the flow structure surround the delta-wing and the hemisphere. The upward and downward flow structure existed under the heating location in case of installing inline hemisphere arrangement. This flow was likely to break the relatively fast flow near the free-surface and transport heat to the bottom-wall effectively.

7. The vertical heat transport under the magnetic field was strongly affected by the flow streamwise velocity distribution on the vertical coordination.
8. The streamwise flow velocity distribution on the spanwise coordination was affected by 10.0% difference vertical parabolic magnetic field. The relatively high flow velocity appeared near the side-wall.
9. The staggered arrangement has been shown the high heat transport performance rather than inline arrangement under the vertical parabolic magnetic field.
10. The specific inline hemisphere arrangement induces the spanwise fluctuation. This is not appropriated for vertical heat transport. However, the arrangement has a possibility to avoid extremely high heat load on the wall due to the spanwise fluctuation.
11. The delta-wing staggered arrangement has given rise the highest heat transport performance in this study. Especially, the short streamwise-pitch-length showed the highest vertical flow velocity, and upward and downward flow was enhanced alternately. However, the heat transport performance was lower than other cases due to the comparatively high flow velocity near the free-surface. This flow transports the high temperature fluid to the further downstream.
12. Based on the experimental and numerical results, the high heat load on the bottom-wall distributed as symmetrical. This makes local heat concentration on the wall. To remove heat effectively, I proposed that installing the impingement jet cooling system on the back side of the wall.
13. For dispersing thermal stress of the wall, the combination of the optimized inline hemisphere and the delta-wing staggered arrangement can be helpful for the possibility to the balance thermal mixing enhancement and avoiding the extremely high heat load on the wall. The optimized inline hemisphere should be chosen that induces spanwise fluctuation. For optimized staggered delta-wing arrays as the changing the height of the delta-wing along to the streamwise direction for the purpose of thermal mixing near the free-surface.

14. In terms of thermal resistance performance of the wall material, the proposed obstacle arrangements give choices that extremely high local heat load or an overall heat load on an arbitrary area.

Due to these findings, the performance of thermal mixing is depending on the vortex behavior, the effect of the magnetic field suppressed the strength of the vortex rotation. However, the results suggested that the localized heated free-surface of liquid metal film-flow under the magnetic field has a possibility to enhance heat transport performance using proposed obstacle arrangement. Additionally, the combination of the impingement jet cooling technique and the proposed obstacle arrangement is appropriate for heat removal from the liquid divertor. Therefore, I concluded that this study gives one of the solutions of thermal design for liquid divertor.

Appendix

The analytical method for experimental and numerical data is introduced in this Appendix. The following contents were used in the experiments.

• Time averaged

The data analysis of a temperature/ a heat flux and a normalized temperature data were applied to a time averaged. A time averaged formula can be given as

$$A(x, y) = \frac{\sum_{n=0}^M A(n\Delta t, x, y)}{T} \quad (1)$$

where, $A(n\Delta t, x, y)$ is a physical parameter and T is a measuring time. Hereafter, the symbolic form of time averaged data is assumed as A . The temperature distributions in numerical simulations has used the temperature on an arbitrary time, this time defined by enough time for numerical convergence. Due to the this, the temperature distribution in numerical results used at the time converged. Note that, the measuring time was over 100(seconds) in the experiment in order to converge to the steady state.

• High order interpolation

The temperature data was outputted as discretized location data. It should have to be interpolated for continuously by some specific mathematical analysis solutions; The bilinear/bicubic interpolation solutions gives the continuous solutions. This study has been used the bicubic interpolation solutions as same as the study [57]. The temperature / heat flux / normalized temperature distributions were analyzed using this analytical technique.

• Temperature rise distribution

The temperature rise distributions in the experiment were used as the difference between the data measurement by TCs on the bottom wall of the test channel $T_m(t, x, y)$ and the inlet temperature $T_{in}(t)$ by a TC installed on the inlet. Thus, the temperature distributions can be given by

$$T_w(t, x, y) = T_m(t, x, y) - T_{in}(t). \quad (2)$$

This equation means how much temperature rise compare than the fluid temperature on the inlet of the test channel. If Equation (1) shows high $T_w(t, x, y)$, it means the localized high temperature fluids near the free-surface touched on the bottom wall by heat transport/thermal mixing. On the contrary, $T_w(t, x, y) = 0$ means that the temperature of the fluids as same as the temperature at the inlet. However, the temperature distributions in the results were using a time averaged temperature distribution $T_w(x, y)$.

• Heat flux distribution

The definition of a heat flux distribution in this study referred to the temperature data $T_m(x, y)$. The general definition of heat flux is defined by heat flux $q_w = h(T_b - T_w)$ where h is overall heat transfer coefficient, T_b is a bulk temperature of the fluid. The bulk temperature in this study was defined as linear approximation, it is defined as

$$T_b(y) \equiv \frac{T_{out} - T_{in}}{L}y + T_{in} \quad (3)$$

where T_{out} is temperature on the outlet of the test channel, T_{in} is the temperature on the inlet and L is the channel length. The bulk temperature is increased with increasing the streamwise coordination. Note that the heat transfer coefficient h in this study could not measure. It is because that TCs measured liquid temperature near the bottom wall

directly then, the analysis of local heat flux $q_w(x, y)$ requires as Fourier's law as follows:

$$q_w(x, y) \equiv -k \frac{(T_b(y) - T(x, y))}{H/2} \quad (4)$$

where H is fluid depth. The negative heat flux $q_w(x, y)$ means $T_b > T_w$, positive means $T_w > T_b$. The defined heat flux towards the bulk from the bottom wall. If high heat loaded area on the bottom wall shows large absolute value $|q_w(x, y)|$ of negative heat flux. In case of the experiment under normalized fluid depth, this heat flux can lead as the comparison of heat transport performance for the various experimental condition. Therefore, it can be normalized results.

• Normalized temperature distribution

For comparisons of the shape and locations of the temperature distribution, it should have to be normalized. The characteristic of this distribution is key point for understanding the place which area is loaded the heat. A normalized temperature distribution $T_n(x, y)$ is defined as

$$T_n(x, y) \equiv \frac{T_w(x, y) - T_{w-min}}{T_{w-max} - T_{w-min}} \quad (5)$$

in which T_{w-max} is the maximum temperature on the bottom wall and T_{w-min} is the minimum temperature so that each $T_n(x, y)$ lie 0 to 1.

• The efficiency of heat transport

To evaluate the heat transport performance, it can be use localized heater power near the free-surface and the total thermal energy received by the bottom wall. An efficiency of heat transport was defined in this study as

$$\gamma = \frac{q'_w S}{Q_{in} - Q_{loss}} \times 100 \quad (6)$$

where Q_{in} is the heater power, Q_{loss} is a heat loss which has a relation as $Q_{in} = Q_{loss} + Q$, q'_w is defined as $q'_w \equiv (|q_w| - q_w)/2$ and S is an area of negative $q_w < 0$. This equation means how much heat near the free-surface is transported to the bottom wall as ratio of input energy and received energy. The range of Q_{loss} in this experiment was $Q_{loss} < 15\%$ because that the thermal characteristic of test channel walls was used thermal insulation material. In this study, the relations between the efficiency of heat transport and interaction parameter, the location of heat flux peak are shown in experimental results. These relations describe the heat transport performance and the dependency of each physical parameters.

• Spectral analysis of temperature

The temperature fluctuation was primarily induced by vortex shedding from obstacles, and the turbulence of the flow. Vortexes are affected by the magnetic field and identified by the spectral analysis of temperature fluctuation data based on the Fast Fourier Transformation (FFT) as follows:

$$\mathcal{F}\{T_m(t, x, y)\} = \sum_{n=0}^{M-1} T_m(n\Delta t, x, y) e^{-i2\pi n f / M} \quad (7)$$

The amplitudes were obtained by the taking the absolute value of T_m . The reason for doing the spectral analysis is due to understanding heat transport characteristics and the strength of vortex rotations in each strength of the magnetic field.

• The flow velocity distribution

The flow velocity distributions in the liquid metal film-flow under the magnetic field was strongly affected by magnetic field directions. The measuring technique was using a potential probe for measuring tiny induced electrical potential difference inside the liquid metal film flow between probes. In this subsection, I introduce the analytical method for the corrected date of the electrical potential difference.

From equation (1.2) $\Delta\phi = (u \times B)\Delta x$, induced voltage is strongly depending on the distance of probes Δx and $\Delta x = 2.54 \times 10^{-3}\text{m}$ in this study. For example, the maximum $\Delta\phi$ in case of highest strength of the vertical magnetic field and the flow under $Re = 500$ on LMFREX can be calculated as $\Delta\phi = 32.0\mu\text{V}$. This tiny induced voltage should be through an amplifier for measured described on Section-2. The equation (1.2) can be formed as

$$u = \frac{\Delta\phi}{B\Delta x} \quad (8)$$

under the perpendicular relation between u and B . Note that it can be measured $4.30\mu\text{V}$ at the minimum caused by an offset of the voltage meter. Therefore, it should have to be amplified as 10^4 times through a house make amplifier described in Chapter 3.

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