Title
Natural convection heat transfer from horizontal rod bundles in liquid sodium. Part 2: Correlations for horizontal rod bundles based on theoretical results

Author(s)
Hata, Koichi; Takeuchi, Yuto; Hama, Katsuhiko; Shiotsu, Masahiro

Citation

Issue Date
2014-08-13

URL
http://hdl.handle.net/2433/198283

The Version of Record of this manuscript has been published and is available in Journal of Nuclear Science and Technology (2014)
http://www.tandfonline.com/10.1080/00223131.2014.947347.; This is not the published version. Please cite only the published version. この論文は出版社版でありません。引用の際には出版社版をご確認ご利用ください。

Type
Journal Article

Textversion
author
Kyoto University
Natural convection heat transfer from horizontal rod bundles in liquid sodium

Part 2: Correlations for horizontal rod bundles based on theoretical results

Koichi Hata\textsuperscript{a,*}, Yuto Takeuchi\textsuperscript{a}, Katsuhiko Hama\textsuperscript{b} and Masahiro Shiotsu\textsuperscript{b}

\textsuperscript{a} Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
\textsuperscript{b} Dept. of Energy Science and Technology, Kyoto University, Sakyoku, Kyoto 606-8501, Japan

Natural convection heat transfer from horizontal rod bundles in $N_{xm}\times N_{ym}$ arrays ($N_{xm}$, $N_{ym}=5$--9) in liquid sodium was numerically analyzed for three types of the bundle geometry (in-line rows, staggered rows I and II). The unsteady laminar two-dimensional basic equations for natural convection heat transfer caused by a step heat flux were numerically solved until the solution reaches a steady-state. The PHOENICS code was used for the calculation considering the temperature dependence of thermo-physical properties concerned. The surface heat fluxes for each cylinder were equally given for a modified Rayleigh number, $R_f$, ranging from 0.0637 to 63.1 ($q=1\times10^4$--$7\times10^6$ W/m$^2$). $S_x/D$ and $S_y/D$ for the rod bundle, which are ratio of the distance between center axes on the abscissa and the ordinate to the rod diameter, were ranged from 1.6 to 2.5 on each bundle geometry. The spatial distribution of Nusselt numbers, $Nu$, on horizontal rods of a bundle was clarified. The average value of Nusselt number, $Nu_{av}$, for three types of the bundle geometry with various values of $S_x/D$ and $S_y/D$ were calculated to examine the effect of the array size, $S/D$ and $R_f$ on heat transfer. The bundle geometry for the higher $Nu_{av}$ value under the condition of $S_x/D\times S_y/D=4$ was examined by changing the ratio of $S_x/S_y$. A correlation for $Nu_{av}$ for three types of bundle geometry above mentioned including the effects of $S_x/D$ and $S_y/D$ was developed. The correlation can describe the theoretical values of $Nu_{av}$ for three types of the bundle geometry in $N_{xm}\times N_{ym}$ arrays ($N_{xm}$,
$N_{m}=5-9$) for $S_r/D$ and $S_y/D$ ranging from 1.6 to 2.5 within 10% difference.

*Corresponding author. Email: hata@iae.kyoto-u.ac.jp
1. Introduction

Knowledge of natural convection heat transfer from a horizontal rod bundle in liquid sodium is important as a database for the design of a heat exchanger in a fast breeder reactor for decay heat removal at a loss of flow accident. However, there have been little fundamental experimental work in liquid sodium and little is known on the effects of bundle geometry and value of $S/D$ (ratio of the distance between center axes, $S$, to the rod diameter, $D$) on heat transfer.

There have been a few works on interactions between two or more horizontal cylinders in natural convection. Marsters [1] carried out a study of three, five and nine horizontal cylinders in a vertical array in air. They have found that for closely spaced arrays, individual tube Nusselt numbers are smaller than for a single cylinder, and for wide spacing individual tube Nusselt numbers are higher than for a single cylinder. Lieberman and Gebhard [2] have conducted experiments in air on the interactions of heated wires arranged in a plane array. The array could be oriented so that its plane made angles of 0°, 30°, 60° and 90° with the vertical. Their data were for the wire spacing ranging from 37.5 diameters to 225 diameters.

Correlations for natural convection heat transfer from 4 to 16 horizontal cylinders to cubical enclosures were represented by Warrington and Weaver [3], but the effect of cylinder geometry on heat transfer and the heat transfer coefficients on each cylinder were not discussed. Natural convection heat transfer experiments on horizontal rod bundle for design of casks for transportation, storage, and permanent disposal of spent nuclear assemblies have been conducted with air and helium in enclosing cask by Fedorovitch [4], Irino et al. [5], and Vdovets et al. [6].

Keyhani and Luo [7] carried out numerical simulations with air and helium in 3×3 to 9×9 arrays, predicted the average Nusselt number of each rod for a modified Rayleigh number, $Ra_d^*$, of 1 to $3.16\times10^2$ and obtained pure conduction results for rod bundles ranging 3×3 to 13×13 arrays.
Keyhani and Dalton [8] experimentally investigated natural convection heat transfer in enclosed $N \times N$ arrays ($N=3, 5$ and $7$) of electrically heated rods and correlated a generalized enclosure Nusselt number as a function of enclosure modified Rayleigh number and the array size ($N$).

In Part 1 of this paper, the natural convection heat transfer coefficients on two parallel horizontal cylinders have already been obtained experimentally and theoretically for various setting angles, $\gamma$, between the vertical direction and the plane including both of these center axes, over the range of zero to $90^\circ$ in liquid sodium and the correlations for two cylinders were presented as a function of $R_f [=Gr^3 Pr^2/(4+9Pr^{1/2}+10Pr)]$, $S/D$ and $\gamma$ based on theoretical solutions. The theoretical values of average Nusselt number, $Nu$, on each of these two cylinders are in agreement with the corresponding experimental data with the deviations less than $15 \%$. A combined correlation for multi-cylinders in a vertical array was presented based on the correlations for two cylinders. The average Nusselt numbers on each of the cylinders predicted by the correlation were in agreement with the corresponding theoretical solutions for $R_f$ ranging from 4.7 to 63 within $10 \%$ difference.

The objectives of present study are: (1) to obtain the numerical solutions of the average Nusselt number from theoretical laminar natural convection equations for a wide range of the array size ($N_{xm} \times N_{ym}$), $S/D$ and $R_f$ on three bundle geometries (in-line rows, staggered rows I and II), (2) to clarify the effect of the array size, $S/D$, $R_f$ and the bundle geometry on heat transfer, (3) to obtain the bundle geometry accompanied with a higher heat transfer coefficient, and (4) to present a correlation to describe the effect of the array size, $S/D$, $R_f$ and the bundle geometry on natural convection heat transfer.

2. Theoretical Solution of Laminar Natural Convection Equations

2.1 Fundamental Equations

Considering the one-half symmetry of the problem, the unsteady laminar two
dimensional basic equations in boundary fitted coordinates as shown in Figures 1 (a) and (b) for a 5×5 array are described as follows.

(Continuity Equation)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0
\]  

(1)

(Momentum Equation)

\[
\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho uu) + \frac{\partial}{\partial y}(\rho uv) = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \tau_{xx} + \frac{\partial}{\partial y} \tau_{xy}
\]  

(2)

\[
\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial y}(\rho vv) = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \tau_{yx} + \frac{\partial}{\partial y} \tau_{yy} - \rho g
\]  

(3)

(Energy Equation)

\[
\frac{\partial}{\partial t}(\rho c_p T) + \frac{\partial}{\partial x}(\rho c_p u T) + \frac{\partial}{\partial y}(\rho c_p v T) = \frac{\partial}{\partial x}\left(\frac{\lambda}{c_p} \frac{\partial}{\partial x}(c_p T)\right) + \frac{\partial}{\partial y}\left(\frac{\lambda}{c_p} \frac{\partial}{\partial y}(c_p T)\right)
\]  

(4)

where

\[
\tau_{xx} = 2\rho v \frac{\partial u}{\partial x}, \quad \tau_{yy} = 2\rho v \frac{\partial v}{\partial y}, \quad \tau_{xy} = \tau_{yx} = \rho v \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)
\]  

(5)

\( u, v \) are the \( x, y \) components of a velocity vector, respectively.

< Figure 1 (a) and (b) >

2.2 Boundary Conditions

The fundamental equations are numerically analyzed together with the following boundary conditions.

On the surfaces of cylinders: constant heat flux, and non-slip condition.

At the right outer boundary: constant heat flux, and non-slip condition.

\[
T = T_0, \quad \frac{\partial u}{\partial x} = 0 \text{ for in-flow,}
\]
\[ \frac{\partial T}{\partial x} = 0, \quad \frac{\partial u}{\partial x} = 0 \] for out-flow.

At the lower and upper boundary:

\[ T = T_0, \quad \frac{\partial v}{\partial y} = 0 \] for in-flow,

\[ \frac{\partial T}{\partial y} = 0, \quad \frac{\partial v}{\partial y} = 0 \] for out-flow.

where \( T_0 \) is a bulk liquid temperature.

### 2.3 Method of Solution

The control volume discretization equations were derived from these fundamental equations by using the hybrid scheme [9]. The thermo-physical properties for each control volume are given as those at each volume temperature. The procedure for the calculation of the flow field is the SIMPLE algorithm which stands for Semi-Implicit Method for Pressure-Linked Equations.

The surface heat fluxes, \( q \), for each cylinder were equally given in the range of \( 1 \times 10^4 \) W/m\(^2\) to \( 7 \times 10^6 \) W/m\(^2\) as an initial condition, and numerical calculation was continued until the steady-state was obtained. The surface temperature on the cylinder was calculated from the analyzed temperature of the first control volume on the cylinder surface, \( TEM \), which is supposed to be located on the center of the control volume, by solving the thermal conduction equation in liquid sodium as follows [10-14].

\[ T_s = \frac{q}{\lambda} \left( \frac{\Delta r}{2} \right)_{\text{out}} + TEM \]  \hspace{1cm} (6)

where, \((\Delta r)_{\text{out}}\) is the outer control volume width for the \( r \)-component. The liquid temperatures on the test tube surface in the conductive sub-layer [15, 16] will become linearly lower with
an increase in the radius by the heat conduction from the surface temperature on the test tube,
\[ T_f = T_s - \Delta q/\lambda\ ]. And let those, \( T_f \), equal the analyzed liquid temperature of the outer control volume on the test tube surface, \( TEM \), as given in Eq. (6). Half the outer control volume width for the r-component, \((\Delta r)_{\text{out}}/2\), would become the thickness of the conductive sub-layer for the local heat transfer in a horizontal cylinder under two-phase model classified into laminar sub-layer and transition region of the buoyancy-driven flow. Average heat transfer coefficient on the cylinder surface was obtained by averaging the calculated local surface temperatures at every 10° in \( \theta \). All the calculations were made by using the PHOENICS code [17].

3. Results and Discussion

In this section, correlations of natural convection heat transfer for a single horizontal cylinder and two horizontal cylinders, and a combined correlation for multi-cylinders in a vertical array previously obtained are firstly explained. The correlation from horizontal rod bundles of in-line rows and staggered rows I and II in \( N_{nx} \times N_{ny} \) arrays is presented by use of these correlations.

3.1 The Correlations Previously Obtained

3.1.1 For a Single Horizontal Cylinder

The following correlation for \( Nu \) was given as a function of \( R_f \) by least square fitting within ± 4%.

\[
Nu = 10^z
\]

where

\[
z = 0.193385 + 0.145037 \log R_f + 0.664323 \times 10^{-2} (\log R_f)^2 \\
- 0.232432 \times 10^{-3} (\log R_f)^3 - 0.238613 \times 10^{-4} (\log R_f)^4
\]

In this work, Nusselt numbers on horizontal rods of a bundle and their average value obtained theoretically for a wide range of surface heat flux are compared with those given by
Equation (7) at the same condition.

3.1.2 For Two Horizontal Cylinders

The calculated values of $\frac{Nu}{Nu_{SC}}$ for the upper and lower cylinders were approximately expressed by the following correlations.

For the upper cylinder:

$$\frac{Nu}{Nu_{SC}} = 1 - 0.60 \exp[-AR_f^m (S / D)]$$  \hspace{1cm} (8)

where $A = 0.29 + 6.8 \times 10^{-3} \gamma$, $m = 0.12 + 1.67 \times 10^{-3} \gamma$

For the lower cylinder:

$$\frac{Nu}{Nu_{SC}} = 1 - C \exp[-KR_f^n (S / D)]$$  \hspace{1cm} (9)

where

$$C = 0.4 + 2.2 \times 10^{-3} \gamma,$$

$$K = 0.56 + 0.34(S / D) \sin \gamma : 0 \leq \gamma \leq \arcsin(D / S),$$

$$K = 0.9 : \gamma > \arcsin(D / S),$$

$$n = 0.16 + 1.2 \times 10^{-3} \gamma.$$

The values of $\frac{Nu}{Nu_{SC}}$ derived from these correlations were in agreement with the numerical solutions for the upper and lower cylinders within -5 and +9 % error.

3.1.3 For Multi-cylinders in a Vertical Array

A combined correlation for multi-cylinders in a vertical array with a constant $S/D$ was given based on the correlations for two cylinders in Part 1 of this work. Each horizontal cylinder consisting the vertical array were numbered sequentially from $i=1$ (lowermost cylinder) to $i=N_m$ (uppermost one). The combined correlation was as follows:

$$\left[ \frac{Nu}{Nu_{SC}} \right]_{i=a} = \prod_{i=1}^{a-1} \left[1 - 0.60 \exp[-AR_f^m (a - i)S / D]\right]$$ \hspace{1cm} (10)

$$\times \prod_{i=a}^{N_m-1} \left[1 - C \exp[-KR_f^n (N_m - i)S / D]\right]$$

where the $\frac{Nu}{Nu_{SC}}$ value for a cylinder with $i=a$ was given by multiplying the mutual effects between the cylinder and other lower and upper cylinders.
3.2 Calculated Results for Horizontal Rod Bundles of In-line Rows for $S_x=S_y$

Natural convection heat transfer from horizontal rod bundles in $N_{x,m} \times N_{y,m}$ arrays was numerically analyzed for the bundle geometry of in-line rows (IR) as shown in Figure 2 (a). $S_x/D$ and $S_y/D$ for the rod bundle which are ratios of the distance between center axes on the abscissa and the ordinate to the rod diameter were ranged from 1.6 to 2.5 in $5 \times 5$, $7 \times 7$ and $9 \times 9$ arrays. The surface heat fluxes for each cylinder were equally given at $1 \times 10^4$, $2 \times 10^4$, $7 \times 10^4$, $2 \times 10^5$, $7 \times 10^5$, $1 \times 10^6$, $2 \times 10^6$ and $7 \times 10^6$ W/m$^2$. The parameters used for the calculation are tabulated in Table 1.

The numerical results of $Nu$ on a rod bundle of a $5 \times 5$ array with $S_x/D=S_y/D=2$ for $R_f=1.30$ and 6.79 ($q=2 \times 10^5$, $1 \times 10^6$ W/m$^2$) were shown in Figures 3 and 4 as typical examples. They are shown as the ratio of $Nu$ to those for a single cylinder given by Equation (7) for the same condition, $Nu/Nu_{SC}$, versus $N_x$ graph with $N_y$ as a parameter, where $N_x$ is the column number and $N_y$ is the row number ($N_x=1$, $5$ are the edge columns; $N_x=3$ is the center column; $N_y=1$ is the lowest row; $N_y=5$ is the uppermost row). The values of $Nu/Nu_{SC}$ are symmetrical on the graph. The value of $Nu/Nu_{SC}$ on each column for $N_y=1$ (the lowest row) is higher than those for other rows. The value at $N_x=3$ for $N_y=1$ is the maximum. The values of $Nu/Nu_{SC}$ for each column become smaller with the increase in the row number. The $Nu/Nu_{SC}$ value at $N_x=3$ for $N_y=5$ is the minimum. The values of $Nu/Nu_{SC}$ at $N_x=1$, $5$ (edge column) are higher than those for other columns on the same row number except those for $N_y=1$.

The contour of liquid temperature and the distribution of velocity vectors on a rod bundle of a $5 \times 5$ array for $R_f=6.79$ were plotted in Figures 5 and 6, respectively. It is recognized that a flow of liquid sodium turns to the center column and ascends along it. The liquid temperature on the edge column and the lowest row is lower and that on the center column
becomes higher with the increase in the row number as mentioned above.

< Figure 5 and 6 >

The values of $\frac{Nu}{Nu_{SC}}$ are also shown versus $N_y$ with $N_x$ as a parameter in Figures 7 and 8. The values of $\frac{Nu}{Nu_{SC}}$ for $N_x=1,5$ (edge column) are far higher than those for other column except the lowest row ($N_y=1$). The edge column are not affected by the thermal boundary layer from the lower cylinder, because of being a in-flow plane. The values of $\frac{Nu}{Nu_{SC}}$ for $N_x=2,4$ are almost in agreement with those for $N_x=3$ (center column), the values for $N_x=3$ are about 8 % higher and about 13 % lower than those for $N_x=2,4$ at the lowest row and the uppermost row, respectively. The values of $\frac{Nu}{Nu_{SC}}$ for each rod derived from the combined correlation in a vertical array, Equation (10), are shown as a solid curve in each figure for comparison. The value at $N_y=1$ for $N_x=3$ is higher than the curve of the combined correlation, because of the contribution of the fluid flow caused by the buoyancy force, and the value at $N_y=5$ for $N_x=3$ is lower than the curve, because of the development of the thermal boundary layer by the mutual effects between the center rod and other surrounding rods. It is shown from these figures that the values of $\frac{Nu}{Nu_{SC}}$ on the same column and row numbers become smaller with the decrease in $R_f$.

< Figure 7 and 8 >

As shown in Figures 7 and 8, the value of $Nu$ on the center column shows the same trend of dependence as predicted by the combined correlation in a vertical array, but that on the edge column is far higher than the corresponding value. The average value of the Nusselt numbers for the rods in the bundle was obtained to develop the correlation for the rod bundle and to discuss the effect of the array size and the bundle geometry on the heat transfer. The average Nusselt number, $Nu_{av}$, for a rod bundle in $N_{xm} \times N_{ym}$ array was obtained as follows,

$$Nu_{av} = \frac{\sum_{i=1}^{N_{xm}} \sum_{j=1}^{N_{ym}} Nu_{ij}}{(N_{xm} \times N_{ym})}$$

where $Nu_{ij}$ is the Nusselt number for $i$-th column and $j$-th row.
The ratios of $Nu_{av}$ to those for a single cylinder given by Equation (7) at the same condition, $Nu_{av}/Nu_{SC}$, for the rod bundle in a 5x5 array with $S_x/D=S_y/D=2$ are plotted on the $Nu_{av}/Nu_{SC}$ versus $R_f$ graph in Figure 9 for $R_f$ ranging from 0.064 to 63.1 ($q=1\times10^4-7\times10^6$ W/m²). The $Nu_{av}/Nu_{SC}$ values are 34% of a single cylinder at $R_f=0.0637$ ($q=1\times10^4$ W/m²), 80% at $R_f=14.2$ ($q=2\times10^6$ W/m²) and 87% at $R_f=63.1$ ($q=7\times10^6$ W/m²); they increase with the increase in $R_f$ and approach asymptotically the value of a single cylinder. It is suggested that the $Nu_{av}$ values for the rod bundle are smaller than those for a single cylinder in the lower heat flux region because convection heat transfer is small and the thermal boundary layer becomes thicker for interactions between one rod and the others due to the effect of thermal conduction.

It is assumed that the $Nu_{av}$ may be proportional to the average value of the Nusselt numbers on the center column, $(Nu_{CC})_{av}$. The values of $Nu_{av}/Nu_{SC}$ in a 5x5 array are shown versus $(Nu_{CC})_{av}/Nu_{SC}$ in Figure 10, where $(Nu_{CC})_{av} = \sum_{j=1}^{N_{ym}} Nu_{center-column,j}/N_{ym}$. The theoretical values of $Nu_{av}/Nu_{SC}$ on the center column for rod bundles in 7x7 and 9x9 arrays with $S_x/D=S_y/D=2$ are also shown in this figure. They are approximately expressed by a single curve given by the following equation.

$$Nu_{av}/Nu_{SC} = 1.18 (Nu_{CC})_{av}/Nu_{SC}$$

Equation (12)

It is further assumed that $(Nu_{CC})_{av}$ may be expressed as a function of the average value of the Nusselt numbers on a single vertical array, $(Nu_{SB})_{av}$. The $(Nu_{CC})_{av}/Nu_{SC}$ values on the center column for the rod bundles in 5x5, 7x7 and 9x9 arrays are shown versus the corresponding values of $(Nu_{SB})_{av}/Nu_{SC}$ in Figure 11, where

$$(Nu_{SB})_{av}/Nu_{SC} = \sum_{i=1}^{N_{mf}} [Nu/Nu_{SC}] / N_m$$

derived from Equation (10), $N_m = N_{ym}$ and
\( S = S_y \). As shown in the figure, they are approximately expressed by the following equation.

\[
\frac{(Nu_{CC})_{av}}{Nu_{SC}} = 1.5 \left( \frac{(Nu_{SB})_{av}}{Nu_{SC}} \right) - 0.738 \left( \frac{N_x \times N_y}{N_x \times N_y} \right)^{1/4}
\]  \hspace{1cm} (13)

Combining Equations (12) and (13) leads to,

\[
Nu_{av} / Nu_{SC} = 1.77 \left( \frac{Nu_{SB}}{Nu_{SC}} \right) - 0.871 \left( \frac{N_x \times N_y}{N_x \times N_y} \right)^{1/4}
\]  \hspace{1cm} (14)

The values of \( Nu_{av}/Nu_{SC} \) derived from Equation (14) for rod bundles in 5×5, 7×7 and 9×9 arrays with \( S_x/D=S_y/D=2 \) are compared with the corresponding numerical solutions in Figures 9, 12 and 13, respectively. The theoretical solutions of \( Nu_{av}/Nu_{SC} \) for \( R_f \) ranging from 0.0637 to 63.1 are expressed by Equation (14) within a few % difference.

< Figure 11, 12 and 13 >

### 3.3 Effect of the Bundle Geometry on Heat Transfer

Natural convection heat transfer for rod bundles in 5×5 and 5(6)×5 arrays was numerically analyzed on two types of staggered rows I and II (SRI and SRII) for \( S_x/D=S_y/D=2 \) at \( R_f=4.67, 6.78 \) and 14.2 \( (q=7 \times 10^5, 1 \times 10^6, 2 \times 10^6 \text{ W/m}^2) \). Schematics for the bundle geometry of staggered rows I and II are shown in Figures 2 (b) and (c). In case of staggered rows, unit volume is a triangle and \( S_x \) and \( S_y \) are defined as shown in these figures. The rod bundle of staggered rows II in a 5(6)×5 array shown in Figure 2 (c) has 6 rods at an even number of rows in the array because the entire rod bundle is symmetric with respect to the \( y \) axis, and has 27 rods (5×5+2) in all. \( S_x \) and \( S_y \) are the distance between center axes on the abscissa and the ordinate as shown in the figures. The values of \( Nu_{av}/Nu_{SC} \) for two types of staggered rows I and II with \( S_x/D=S_y/D=2 \) are shown versus the rod bundle geometries with \( R_f \) as a parameter in Figure 14 with those for in-line rows (IR). The \( Nu_{av}/Nu_{SC} \) values for each bundle geometry are higher for higher \( R_f \). The values of \( Nu_{av}/Nu_{SC} \) for two types of staggered rows I and II are in good agreement with those of in-line rows.

And, the values of \( Nu_{av}/Nu_{SC} \) for staggered rows I and II at \( S_x/D=1.6, S_y/D=2.5 \) and \( S_x/D=2.5, S_y/D=1.6 \) almost agree with the corresponding values for in-line rows, as shown in
Figures 15 and 16. It is expected from this comparison that natural convection heat transfer for the rod bundles with the same values of $S_x/D$ and $S_y/D$ does not depend on the bundle geometry.

\[ <\text{Figure 14, 15 and 16}> \]

3.4 Effect of $S_x/D$ and $S_y/D$ on Heat Transfer

Natural convection heat transfer for the bundle geometry of in-line rows in a 5×5 array was numerically analyzed to examine the effect of $S_x/D$ and $S_y/D$ on heat transfer, at the constant heat flux conditions of $R_f=6.78$ and 14.2 ($q=1\times10^6, 2\times10^6$ W/m$^2$) for $S_x/D$ and $S_y/D$ ranging from 1.6 to 2.5.

3.4.1 Effect of $S_x/D$

The theoretical values of $Nu_{av}/Nu_{SC}$ are plotted on $Nu_{av}/Nu_{SC}$ versus $S_x/D$ graph in Figure 17. The $Nu_{av}/Nu_{SC}$ value for $R_f=6.78$ and $S_x/D=1.6$ is 68 % of that for a single cylinder at $S_x/D=1.8$, becomes higher with the increase in $S_x/D$ and is 80 % at $S_x/D=2.5$. The $Nu_{av}$ becomes 21 % larger with the increase in $S_x/D$ from 1.8 to 2.5. The values of $Nu_{av}/Nu_{SC}$ for $R_f=14.2$ and $S_x/D=1.6$ show nearly the same trend of dependence on $S_x/D$, although they are almost 9 % higher than the corresponding values for $R_f=6.78$ and $S_x/D=1.6$. The values of $Nu_{av}/Nu_{SC}$ for $R_f=6.78$ and 14.2, and $S_x/D=2$ almost agree with the corresponding values for $S_x/D=1.6$, although they are slightly higher than the latter.

\[ <\text{Figure 17}> \]

3.4.2 Effect of $S_y/D$

The $Nu_{av}/Nu_{SC}$ values are shown versus $S_y/D$ in Figure 18. The $Nu_{av}/Nu_{SC}$ value for $R_f=6.78$ is 63 % of that for a single cylinder at $S_y/D=1.8$, becomes higher for the higher value of $S_y/D$ and is 66 % at $S_y/D=2.5$. The average Nusselt number becomes 5 % larger with the increase in $S_y/D$ from 1.8 to 2.5. The values of $Nu_{av}/Nu_{SC}$ for $R_f=14.2$ show nearly the same
trend of dependence on $S_x/D$ and are almost 9 % higher than the corresponding values for $R_f=6.78$ as mentioned above.

The values of $Nu_{av}$ become higher with the increase in the values of $S_x/D$ and $S_y/D$. It should be noted that natural convection heat transfer from a horizontal rod bundle is far more influenced by the distance between the center axes on the column, $S_x$, than be done by that on the row, $S_y$. It is considered from this fact that the optimum combination of $S_x/D$ and $S_y/D$ may exist under the condition of a constant value of $S_x/D \times S_y/D$.

< Figure 18 >

### 3.5 Effect of $S_x/S_y$ with the Same Rod Density on Heat Transfer

The higher $Nu_{av}$ under the condition of $S_x/D \times S_y/D=4$ was examined by changing the ratio of $S_y/D$ to $S_x/D$. The values of the average Nusselt number, $Nu$, for the bundle geometry of in-line rows in 5×5 and 7×7 arrays are numerically analyzed for two ratios of $S_x/S_y$ to $S_y/S_x$ ranging from 0.128 to 14.2 ($q=2 \times 10^4 \sim 2 \times 10^6$ W/m²) ; $S_x/S_y=1.6/2.5$ and $S_y/S_x=2.5/1.6$. The values of $Nu_{av}/Nu_{SC}$ for $S_y/D=1.6$, $S_x/D=2.5$ and $S_y/D=2.5$, $S_x/D=1.6$ are plotted in Figures 9, 12 and 13 with those for $S_y/D=2$, $S_x/D=2$. The values of $Nu_{av}/Nu_{SC}$ for $S_x/D=2.5$, $S_y/D=1.6$ are almost 10 % higher than those for $S_y/D=2$, $S_x/D=2$ for the whole range of $R_f$ numerically analyzed here and the values of $Nu_{av}/Nu_{SC}$ for $S_x/D=1.6$, $S_y/D=2.5$ are almost 10 % lower than those for $S_y/D=2$, $S_x/D=2$.

The theoretical values of $Nu_{av}/Nu_{SC}$ for the bundle geometry of in-line rows in a 5×5 array are shown versus $S_x/S_y$ in Figure 19 with $R_f$ as a parameter. As shown in the figure, the $Nu_{av}/Nu_{SC}$ value at $S_x/S_y=1.6/2.5$ for $R_f=4.67$ are 63 % of that for a single cylinder, that at $S_x/S_y=2/2$ are 70 % and that at $S_x/S_y=2.5/1.6$ are 76 %. The $Nu_{av}/Nu_{SC}$ value becomes 20 % higher with the increase in $S_x/S_y$ from 1.6/2.5 to 2.5/1.6. The values of $Nu_{av}/Nu_{SC}$ for $R_f=6.78$ and 14.2 show nearly the same trends of dependence on $S_x/S_y$, although they are far higher than the corresponding values for $R_f=4.67$. The theoretical values of $Nu_{av}/Nu_{SC}$ for the bundle
geometry of in-line rows in a 7\times7 array are shown in \textbf{Figure 20} and those for staggered rows I and II in 5\times5, 5(6)\times5 arrays are shown in \textbf{Figures 21} and \textbf{22}, respectively. The trends of dependence of $Nu/Nu_{SC}$ on $S_x/S_y$ are almost in agreement with that in \textbf{Figure 19}. It is suggested that the higher heat transfer from a horizontal rod bundle will be realized for the bundle geometry whose value of $S_x/D$ is larger than that of $S_y/D$ under the condition of $S_x/D \times S_y/D$ constant.

< Figure 19, 20, 21 and 22 >

4. Correlation for Horizontal Rod Bundles of In-Line Rows, Staggered Rows I and II with Various $S_x/S_y$

It was recognized that the theoretical values of $Nu_{av}$ for rod bundles do not depend on the bundle geometry and become higher for higher value of $S_x/S_y$. A correlation for $Nu_{av}$ from horizontal rod bundle of in-line rows, staggered rows I and II with various $S_x/S_y$ was given as follows based on Equation (14) and the calculated results for the values of $S_x/S_y$ other than unity.

\[
Nu_{av}/Nu_{SC} = [1.77(Nu_{SB})_{av}/Nu_{SC} - 0.871/(N_{xm} \times N_{ym})^{1/4}] (S_x/S_y)^{1/4} \quad (15)
\]

In the case of $S_x/S_y \neq 1$, the $(Nu_{SB}/Nu_{SC}$ value can be calculated from Equation (10) by introducing an effective value $S_{eff}$ given by $S_{eff} = (S_x \times S_y)^{1/2}$ instead of $S$, and $Nu_{SC}$ value from Equation (7). The curves of $Nu_{av}/Nu_{SC}$ for each value of $R_f$ derived from this correlation are shown as an individual curve for comparison in \textbf{Figures 9} and \textbf{12 to 22}. As shown in these figures, the correlation can describe the theoretical solutions of $Nu_{av}$ for the bundle geometry of in-line rows, staggered rows I and II in 5\times5, 5(6)\times5, 7\times7 and 9\times9 arrays for $S_x/D$ and $S_y/D$ ranging from 1.6 to 2.5 within 10 \% difference.

It is expected from these comparisons that this correlation can be used for the design and the safety evaluation of a heat exchanger for a sodium cooled fast breeder reactor in the region of low Grashof numbers, $Gr \leq 10^8$. However, rod diameter of a heat exchanger for a
power plant may be 3 or 4 times larger than that used in this work, \( D = 7.6 \text{ mm} \). In such a case, the values of \( Gr \) become larger than \( 10^8 \) in higher heat flux range of this analysis. Turbulence effects may play an important role on heat transfer for rod arrays at \( Gr > 10^8 \) [18]. The study of rod arrays for higher Grashof numbers will appear in the near future.

5. Summary and Conclusions

Natural convection heat transfer from horizontal rod bundles for three types of the bundle geometry of in-line rows, staggered rows I and II in \( 5 \times 5, 5(6) \times 5, 7 \times 7, 9 \times 9 \) arrays with \( S_x/D \) and \( S_y/D \) ranging from 1.6 to 2.5 was numerically analyzed in liquid sodium.

The spatial distribution of average Nusselt numbers, \( Nu \), which is symmetrical with respect to the \( y \) axis are clarified. The values of \( Nu \) for each column become smaller with the increase in the row number. The value of \( Nu \) at the center rod for the lowest row is the maximum and the \( Nu \) value at the center rod for the uppermost row is the minimum. The values of \( Nu \) for the edge column are higher than those for other column on the same row number except those for the lowest row.

The average Nusselt number for a rod bundle, \( Nu_{av} \), becomes lower with the decrease in the value of \( R_f \) and higher with the increase in the value of \( S_x/D \) and \( S_y/D \).

The values of \( Nu_{av} \) on various bundle geometries with the same values of \( S_x/D \) and \( S_y/D \) are almost in agreement independent of the bundle geometry.

The higher \( Nu_{av} \) value under the condition of \( S_x/D \times S_y/D = 4 \) was examined by changing \( S_x/D \) from 1.6 to 2.5. They are higher for the larger value of \( S_x/D \). It is suggested that the higher heat transfer from a horizontal rod bundle will be realized for the bundle geometries with higher values of \( S_x/S_y \) under the condition of \( S_x/D \times S_y/D = \text{constant} \).

A generalized correlation for \( Nu_{av} \) including the effects of \( S_x/D \) and \( S_y/D \) for various types of bundle geometry was developed. The correlation can describe the theoretical values of \( Nu_{av} \) for three types of the bundle geometry of in-line rows, staggered rows I and II in \( 5 \times 5, \)
5(6)×5, 7×7, 9×9 arrays with S_y/D and S_y/D ranging from 1.6 to 2.5 within 10 % difference.

Nomenclature

\( A \) = non-dimensional quantity in Equation (8)

\( C \) = non-dimensional quantity in Equation (9)

\( c_p \) = isobaric specific heat, J/kg K

\( D \) = rod diameter, m

\( Gr^* = \gamma \beta q D^4 / \nu^2 \), Grashof number for constant heat flux

\( g \) = acceleration of gravity, m/s²

\( K \) = non-dimensional quantity in Equation (9)

\( m \) = exponent in Equation (8)

\( N \) = cylinder number

\( N_m \) = total number of cylinder

\( N_x \) = column number

\( N_{sm} \) = total number of rod in a column

\( N_y \) = row number

\( N_{sm} \) = total number of rod in a row

\( Nu \) = Nusselt number

\( Nu_{av} \) = average Nusselt number for a rod bundle

\( Nu_{CC} \) = average Nusselt number for rods of a center column

\( Nu_{SB} \) = average Nusselt number for rods of single vertical array

\( Nu_{SC} \) = Nusselt number for single cylinder

\( n \) = exponent in Equation (9)

\( P \) = pressure, N/m²

\( Pr \) = Prandtl number

\( q \) = heat flux, W/m²
\( Ra = Gr \ Pr \), Rayleigh number

\( Ra^* = Gr^* Pr \), Rayleigh number for constant heat flux

\( Ra_d^* = Gr_d^* Pr \), modified Rayleigh number

\( R_f = Gr^* Pr^2/(4+9Pr^{1/2}+10Pr) \), modified Rayleigh number

\( r \) radius of a cylinder, m

\((Ar)_{out}\) outer control volume width for r-component, m

\( S \) = distance between the center axis of two parallel horizontal cylinders, m

\( S_{\text{eff}} = (S_x \times S_y)^{1/2} \), effective distance, m

\( S_x \) = distance between the center axes on abscissa, m

\( S_y \) = distance between the center axes on ordinate, m

\( T \) = temperature, K

\( T_0 \) = bulk liquid temperature, K

\( TEM \) analyzed liquid temperature of the outer control volume, K

\( T_f \) = liquid temperature, K

\( T_h \) = heater surface temperature, K

\( t \) = time, s

\( u, v \) = velocity components in x and y directions, m/s

\( x, y \) = Cartesian coordinates, m

Greek Symbols

\( \gamma \) = setting angle of the two horizontal cylinders, deg

\( \theta \) = peripheral angle from the bottom of the cylinder, deg

\( \lambda \) = thermal conductivity, W/(m K)

\( \nu \) = kinematic viscosity, m²/s

\( \rho \) = density, kg/m³

\( \tau \) = viscous stress tensor, kg/s² m
Acknowledgments

This research was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan.

References


List of figure captions

Table 1. Parameters for calculation.
Figure 1 (a). Boundary fitted coordinates for a 5×5 array.
Figure 1 (b). Details of boundary fitted coordinates for a 5×5 array.
Figure 2. Bundle geometry: (a) In-line rows (IR); (b) Staggered rows I (SRI); (c) Staggered rows II (SRII).
Figure 3. \( \frac{Nu}{Nu_{SC}} \) versus \( N_x \) for a 5×5 array with \( N_y \) as a parameter at \( R_f=1.30 \).
Figure 4. \( \frac{Nu}{Nu_{SC}} \) versus \( N_x \) for a 5×5 array with \( N_y \) as a parameter at \( R_f=6.79 \).
Figure 5. Contour of liquid temperature for a 5×5 array at \( R_f=6.79 \).
Figure 6. Distribution of velocity vectors for a 5×5 array at \( R_f=6.79 \).
Figure 7. \( \frac{Nu}{Nu_{SC}} \) versus \( N_y \) for a 5×5 array with \( N_x \) as a parameter at \( R_f=1.30 \).
Figure 8. \( \frac{Nu}{Nu_{SC}} \) versus \( N_y \) for a 5×5 array with \( N_x \) as a parameter at \( R_f=6.79 \).
Figure 9. \( \frac{Nu_{av}}{Nu_{SC}} \) versus \( R_f \) for a 5×5 array with \( S_x/D \) and \( S_y/D \) as a parameter.
Comparison with the predicted curves, Equations (14) and (15).
Figure 10. \( \frac{Nu_{av}}{Nu_{SC}} \) versus (\( Nu_{CC} \)) \( av \)/\( Nu_{SC} \) for 5×5, 7×7 and 9×9 arrays. Comparison with the predicted curve, Equation (12).
Figure 11. (\( Nu_{CC} \)) \( av \)/\( Nu_{SC} \) versus (\( Nu_{SB} \)) \( av \)/\( Nu_{SC} \) for 5×5, 7×7 and 9×9 arrays. Comparison with the predicted curve, Equation (13).
Figure 12. \( \frac{Nu_{av}}{Nu_{SC}} \) versus \( R_f \) for a 7×7 array with \( S_x/D \) and \( S_y/D \) as a parameter.
Comparison with the predicted curves, Equations (14) and (15).
Figure 13. \( \frac{Nu_{av}}{Nu_{SC}} \) versus \( R_f \) for a 9×9 array with \( S_x/D \) and \( S_y/D \) as a parameter.
Comparison with the predicted curves, Equations (14) and (15).
Figure 14. \( \frac{Nu_{av}}{Nu_{SC}} \) versus bundle geometry for \( S_x/D=S_y/D=2 \) with \( R_f \) as a parameter.
Figure 15. \( \frac{Nu_{av}}{Nu_{SC}} \) versus bundle geometry for \( S_x/D=1.6, S_y/D=2.5 \) with \( R_f \) as a parameter.
Figure 16. \( \frac{Nu_{av}}{Nu_{SC}} \) versus bundle geometry for \( S_x/D=2.5, S_y/D=1.6 \) with \( R_f \) as a
parameter.

Figure 17. $\frac{Nu_{av}}{Nu_{SC}}$ versus $S_y/D$ with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).

Figure 18. $\frac{Nu_{av}}{Nu_{SC}}$ versus $S_y/D$ with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).

Figure 19. $\frac{Nu_{av}}{Nu_{SC}}$ versus $S_y/S_y$ for in-line rows in a $5\times5$ array with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).

Figure 20. $\frac{Nu_{av}}{Nu_{SC}}$ versus $S_y/S_y$ for in-line rows in a $7\times7$ array with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).

Figure 21. $\frac{Nu_{av}}{Nu_{SC}}$ versus $S_y/S_y$ for staggered rows I in a $5\times5$ array with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).

Figure 22. $\frac{Nu_{av}}{Nu_{SC}}$ versus $S_y/S_y$ for staggered rows II in a $5(6)\times5$ array with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Pressure</strong></td>
<td>101.3 kPa</td>
</tr>
<tr>
<td><strong>Diameter of Rod (D)</strong></td>
<td>7.6 mm</td>
</tr>
<tr>
<td><strong>Outer Control Volume Width for r-component ((\Delta r)_{out})</strong></td>
<td>0.4 mm</td>
</tr>
<tr>
<td><strong>Array Size ((N_x \times N_y))</strong></td>
<td>5 \times 5, 5(6) \times 5, 7 \times 7, 9 \times 9</td>
</tr>
<tr>
<td><strong>Bundle Geometry</strong></td>
<td>In-line Rows, Staggered Rows I, Staggered Rows II</td>
</tr>
<tr>
<td><strong>(S_x/D, S_y/D) (S=Rod Pitch)</strong></td>
<td>1.6, 1.8, 2, 2.2, 2.4, 2.5</td>
</tr>
<tr>
<td><strong>Liquid Temperature</strong></td>
<td>673 K</td>
</tr>
<tr>
<td><strong>Heat Flux (q)</strong></td>
<td>1 \times 10^4, 2 \times 10^4, 7 \times 10^4, 2 \times 10^5, 7 \times 10^5, 1 \times 10^6, 2 \times 10^6, 7 \times 10^6 W/m^2</td>
</tr>
<tr>
<td><strong>(Gr^*)</strong></td>
<td>1.20 \times 10^4, 2.41 \times 10^4, 8.54 \times 10^4, 2.49 \times 10^5, 9.33 \times 10^5, 1.38 \times 10^6, 3.06 \times 10^6, 1.43 \times 10^7</td>
</tr>
<tr>
<td><em><em>(Ra^</em> (=Gr^<em>Pr))</em></em></td>
<td>5.98 \times 10^4, 1.20 \times 10^2, 4.24 \times 10^2, 1.23 \times 10^3, 4.50 \times 10^3, 6.59 \times 10^3, 1.42 \times 10^4, 6.17 \times 10^4</td>
</tr>
<tr>
<td>*<em>(R_f (=Gr^<em>Pr^2/(4+9Pr^{1/2}+10Pr)))</em></em></td>
<td>0.0637, 0.128, 0.449, 1.29, 4.67, 6.78, 14.2, 63.1</td>
</tr>
</tbody>
</table>
Figure 1 (a). Boundary fitted coordinates for a 5×5 array.

Figure 1 (b). Details of boundary fitted coordinates for a 5×5 array.
Figure 2. Bundle geometry: (a) In-line rows (IR); (b) Staggered rows I (SRI); (c) Staggered rows II (SRII).
Figure 3. \( \frac{Nu}{Nu_{SC}} \) versus \( N_x \) for a 5×5 array with \( N_y \) as a parameter at \( R_f = 1.30 \).
Figure 4. \( \frac{Nu}{Nu_{Sc}} \) versus \( N_x \) for a 5×5 array with \( N_y \) as a parameter at \( R_f = 6.79 \).
Figure 5. Contour of liquid temperature for a 5×5 array at $R_f=6.79$. 

Natural Convection from 5x5 H-Rod Bundle
Figure 6. Distribution of velocity vectors for a 5×5 array at $R_f=6.79$. 

Natural Convection from 5x5 H-Rod Bundle
Figure 7. \( \frac{Nu}{Nu_{SC}} \) versus \( N_y \) for a 5×5 array with \( N_x \) as a parameter at \( R_f = 1.30 \).
Figure 8. $\frac{Nu}{Nu_{SC}}$ versus $N_y$ for a 5×5 array with $N_x$ as a parameter at $R_f=6.79$. 

$S_x/D = 2$
$S_y/D = 2$
$R_f = 6.79$

$N_x$
- $1.5$
- $2.4$
- $3$

Eq. (10)
Figure 9. \( \frac{Nu_{av}}{Nu_{sc}} \) versus \( R_f \) for a 5×5 array with \( S_x/D \) and \( S_y/D \) as a parameter. Comparison with the predicted curves, Equations (14) and (15).
Figure 10. $\frac{Nu_a}{Nu_{SC}}$ versus $(Nu_{CC})_a/Nu_{SC}$ for 5×5, 7×7 and 9×9 arrays. Comparison with the predicted curve, Equation (12).
Figure 11. \( \frac{(Nu_{CC})_{av}}{Nu_{SC}} \) versus \( \frac{(Nu_{SB})_{av}}{Nu_{SC}} \) for 5×5, 7×7 and 9×9 arrays. Comparison with the predicted curve, Equation (13).
Figure 12. $\frac{Nu_{av}}{Nu_{SC}}$ versus $R_f$ for a $7 \times 7$ array with $S_x/D$ and $S_y/D$ as a parameter. Comparison with the predicted curves, Equations (14) and (15).
Figure 13. $Nu_{av}/Nu_{sc}$ versus $R_f$ for a 9×9 array with $S_x/D$ and $S_y/D$ as a parameter. Comparison with the predicted curves, Equations (14) and (15).
Figure 14. $\frac{Nu_{av}}{Nu_{sc}}$ versus bundle geometry for $S_x/D = S_y/D = 2$ with $R_f$ as a parameter.
Figure 15. \( \frac{Nu_a}{Nu_{SC}} \) versus bundle geometry for \( S_x/D = 1.6, S_y/D = 2.5 \) with \( R_f \) as a parameter.
Figure 16. $Nu_{av}/Nu_{sc}$ versus bundle geometry for $S_x/D=2.5$, $S_y/D=1.6$ with $R_f$ as a parameter.
Figure 17. $Nu_{av}/Nu_{SC}$ versus $S_y/D$ with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).
Figure 18. $\frac{Nu_a}{Nu_{SC}}$ versus $S_y/D$ with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).
Figure 19.  \( \frac{Nu_{av}}{Nu_{sc}} \) versus \( S_x/S_y \) for in-line rows in a 5×5 array with \( R_f \) as a parameter. Comparison with the predicted curve, Equation (15).
Figure 20. $Nu_{av}/Nu_{sc}$ versus $S_x/S_y$ for in-line rows in a $7 \times 7$ array with $R_f$ as a parameter. Comparison with the predicted curve, Equation (15).
Figure 21. \( \frac{Nu_v}{Nu_{SC}} \) versus \( S_x/S_y \) for staggered rows I in a 5×5 array with \( R_f \) as a parameter. Comparison with the predicted curve, Equation (15).
Figure 22. \( \frac{N_{u_x}}{N_{u_y}} \) versus \( S_x/S_y \) for staggered rows II in a 5(6)\( \times \)5 array with \( R_f \) as a parameter. Comparison with the predicted curve, Equation (15).