Experimental Study on Subcooled Boiling-induced Vibration of a Heater Rod near Walls

Title

Author(s)

Takano, Kenji

Citation

Kyoto University (京都大学)

Issue Date

2016-09-23

URL

https://doi.org/10.14989/doctor.k19994

Type

Thesis or Dissertation

Textversion

ETD
Experimental Study on Subcooled Boiling-induced Vibration of a Heater Rod near Walls

Kenji TAKANO
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF CONTENTS</td>
<td>i</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Review of the Literature</td>
<td>5</td>
</tr>
<tr>
<td>1.2.1 Flow-induced Vibration of Nuclear Fuel Rods</td>
<td>5</td>
</tr>
<tr>
<td>1.2.2 Subcooled Boiling-induced Vibration under Flow Boiling</td>
<td>5</td>
</tr>
<tr>
<td>1.2.3 Previous Experiment for a Single Heater Rod</td>
<td>6</td>
</tr>
<tr>
<td>1.3 Objectives and Scope of This Study</td>
<td>8</td>
</tr>
<tr>
<td>1.4 Structure of Thesis</td>
<td>10</td>
</tr>
<tr>
<td>2. EXPERIMENTAL METHODOLOGY</td>
<td>11</td>
</tr>
<tr>
<td>2.1 Experimental Apparatus</td>
<td>11</td>
</tr>
<tr>
<td>2.2 Experimental Conditions</td>
<td>13</td>
</tr>
<tr>
<td>2.2.1 Exp.1: Influences of Wall Existence</td>
<td>13</td>
</tr>
<tr>
<td>2.2.2 Exp.2: Influences of Wall Configuration</td>
<td>15</td>
</tr>
<tr>
<td>2.3 Data Processing</td>
<td>17</td>
</tr>
<tr>
<td>3. EXPERIMENT AND RESULTS</td>
<td>18</td>
</tr>
<tr>
<td>3.1 Exp.1: Influences of Wall Existence</td>
<td>18</td>
</tr>
<tr>
<td>3.1.1 Procedure of measurement</td>
<td>18</td>
</tr>
</tbody>
</table>
3.1.2 Case of 5mm-gap distance to wall and case of no wall ................. 19
3.2 Exp.2: Influences of Wall Configuration ........................................ 25
  3.2.1 Procedure of measurement ...................................................... 25
  3.2.2 Single wall configuration ......................................................... 27
    3.2.2.1 Case of 3mm-gap distance to wall .................................... 27
    3.2.2.2 Case of 1mm-gap distance to wall .................................... 39
  3.2.3 Parallel walls configuration .................................................... 58
    3.2.3.1 Case of 3mm-gap distance to wall .................................... 58
    3.2.3.2 Case of 1mm-gap distance to wall .................................... 72
  3.2.4 Corner walls configuration ..................................................... 90
    3.2.4.1 Case of 3mm-gap distance to wall .................................... 90
    3.2.4.2 Case of 1mm-gap distance to wall .................................... 102

4. DISCUSSION .................................................................................. 114
  4.1 Encouraged Acceleration due to Existence of a Wall (Exp.1) ............. 114
  4.2 Behavior of vapor bubbles (Exp.2) .............................................. 118
    4.2.1 Case of 3mm-gap distance to wall ....................................... 118
    4.2.2 Case of 1mm-gap distance to wall ....................................... 119
  4.3 Thermal conditions for growth of large bubbles ............................. 125
  4.4 Velocity of large bubbles ............................................................ 127
    4.4.1 Case of 3mm-gap distance to wall ....................................... 127
    4.4.2 Case of 1mm-gap distance to wall ....................................... 128
  4.5 Number of generated large bubbles ............................................. 134
  4.6 Acceleration due to Behavior of Bubbles .................................... 136
  4.7 Acceleration RMS of Vibration ................................ .................. 141
  4.8 Acceleration PSD of Vibration .................................................... 143
  4.9 Excitation Force due to Behavior of Bubbles under Subcooled Boiling-- 154
5. IMPLEMENTATION .................................................. 160

6. CONCLUDING REMARKS AND FUTURE WORKS ........ 164

REFERENCES ................................................................. 167

ACKNOWLEDGMENT
NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Equivalent diameter of a circle to area of effective microlayer</td>
<td>m</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient</td>
<td>–</td>
</tr>
<tr>
<td>$C_{pL}$</td>
<td>Specific heat of liquid</td>
<td>J/kg/K</td>
</tr>
<tr>
<td>$D_B$</td>
<td>Diameter of a large bubble as a vertical ellipse</td>
<td>m</td>
</tr>
<tr>
<td>$D_e$</td>
<td>Representative diameter of a large bubble</td>
<td>m</td>
</tr>
<tr>
<td>$E_S$</td>
<td>Stiffness of stainless steel</td>
<td>MN/mm²</td>
</tr>
<tr>
<td>$E_{UO2}$</td>
<td>Stiffness of uranium oxide</td>
<td>MN/mm²</td>
</tr>
<tr>
<td>$F_N$</td>
<td>Force normal to the heater rod surface</td>
<td>N</td>
</tr>
<tr>
<td>$F_P$</td>
<td>Force due to vapor pressure in a large bubble to the heater rod surface</td>
<td>N</td>
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<tr>
<td>$F_S$</td>
<td>Force due to surface tension of a large bubble</td>
<td>N</td>
</tr>
<tr>
<td>$H_B$</td>
<td>Horizontal height of a large bubble</td>
<td>m</td>
</tr>
<tr>
<td>$h_{LV}$</td>
<td>Enthalpy of vaporization</td>
<td>J/kg</td>
</tr>
<tr>
<td>$p_{v,100}$</td>
<td>Vaper pressure at 100 deg-C</td>
<td>Pa</td>
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<tr>
<td>$Q'$</td>
<td>Amount of heat value per unit length</td>
<td>W/m</td>
</tr>
<tr>
<td>$q$</td>
<td>Thermal flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>$q_{cond}^{'}$</td>
<td>Amount of heat reduced from a large bubble in condensation</td>
<td>W</td>
</tr>
<tr>
<td>$q_{vap}^{'}$</td>
<td>Amount of heat into a large bubble as vapor</td>
<td>W</td>
</tr>
<tr>
<td>$r_c$</td>
<td>Distance from the center of the column in radial direction</td>
<td>m</td>
</tr>
<tr>
<td>$r(t)$</td>
<td>Radius of a bubble</td>
<td>m</td>
</tr>
<tr>
<td>$S_{ht}$</td>
<td>Area of effective microlayer</td>
<td>m²</td>
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<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>$T_{sat}$</td>
<td>Saturation temperature</td>
<td>K</td>
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<tr>
<td>$V_B$</td>
<td>Volume of a large bubble</td>
<td>m³</td>
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<tr>
<td>$v_\theta$</td>
<td>Velocity of a bubble in horizontal direction</td>
<td>m/s</td>
</tr>
<tr>
<td>$v_z$</td>
<td>Velocity of a bubble in vertical direction</td>
<td>m/s</td>
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</tbody>
</table>
**Greek Symbols:**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_L$</td>
<td>Thermal diffusivity of liquid</td>
<td>m²/s</td>
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<td>$\delta_m$</td>
<td>Thickness of microlayer</td>
<td>m</td>
</tr>
<tr>
<td>$\delta_w$</td>
<td>Gap distance between the heater rod and a wall</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature increase around the bubble from the saturated temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\Delta T_{sub}$</td>
<td>Degree of subcooling</td>
<td>K</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Thermal conductivity</td>
<td>W/m/K</td>
</tr>
<tr>
<td>$\mu_L$</td>
<td>Viscosity</td>
<td>Pa·s</td>
</tr>
<tr>
<td>$\theta_a$</td>
<td>Contact angle of a large bubble at the bottom end to a wall</td>
<td>rad</td>
</tr>
<tr>
<td>$\rho_L$</td>
<td>Density of liquid</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\rho_S$</td>
<td>Density of stainless steel</td>
<td>g/cm³</td>
</tr>
<tr>
<td>$\rho_{UO2}$</td>
<td>Density of uranium oxide</td>
<td>g/cm³</td>
</tr>
<tr>
<td>$\rho_V$</td>
<td>Density of vapor</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Surface tension of a large bubble</td>
<td>N/m</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1.1-1 Nuclear fuel assembly for PWR and BWR
Figure 1.3-1 Vibration of a heating structure in water with vapor bubbles
Figure 2.1-1 Experimental apparatus for the present study
Figure 2.1-2 Water tank and heater rod for the present study
Figure 2.2.1-1 Experimental apparatus for Exp.1
Figure 2.2.2-1 Configurations of walls around the heater rod for Exp.2
Figure 3.1.1-1 Temperature in the series of measurement in Exp.1
Figure 3.1.2-1 Behavior of bubbles around heater rod (Exp.1, No wall case)
Figure 3.1.2-2 Behavior of bubbles around heater rod (Exp.1, With wall case)
Figure 3.1.2-3 Acceleration at the bottom end of the heater rod (Exp.1, No wall case)
Figure 3.1.2-4 Acceleration at the bottom end of the heater rod (Exp.1, With wall case)
Figure 3.1.2-5 Acceleration of the heater rod in X-Y plane (Exp.1)
Figure 3.1.2-6 Acceleration RMS of the heater rod (Exp.1, With wall case)
Figure 3.2.1-1 Thermal conditions provided in Exp.2
Figure 3.2.2.1-1 Behavior of bubbles around heater rod with 3mm-gap (Single wall)
Figure 3.2.2.1-2 (1) Acceleration of heater rod (Single wall, 3mm-gap, $\Delta T_{sub} = 6.0$K)
Figure 3.2.2.1-2 (2) Acceleration of heater rod (Single wall, 3mm-gap, $\Delta T_{sub} = 7.0$K)
Figure 3.2.2.1-2 (3) Acceleration of heater rod (Single wall, 3mm-gap, $\Delta T_{sub} = 8.0$K)
Figure 3.2.2.1-3 (1) Acceleration of heater rod in the X-Y plane
(Single wall, 3mm-gap, $\Delta T_{sub} = 6.0$K)
Figure 3.2.2.1-3 (2) Acceleration of heater rod in the X-Y plane
(Single wall, 3mm-gap, $\Delta T_{sub} = 7.0$K)
Figure 3.2.2.1-3 (3) Acceleration of heater rod in the X-Y plane
(Single wall, 3mm-gap, $\Delta T_{sub} = 8.0$K)
Figure 3.2.2.2-1  Behavior of bubbles around heater rod with 1mm-gap (Single wall)

Figure 3.2.2.2-2 (1)  Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 3.2.2.2-2 (2)  Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 3.0K$)
Figure 3.2.2.2-2 (3)  Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 3.9K$)
Figure 3.2.2.2-2 (4)  Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 5.0K$)
Figure 3.2.2.2-2 (5)  Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 6.1K$)
Figure 3.2.2.2-2 (6)  Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 7.0K$)
Figure 3.2.2.2-2 (7)  Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 7.7K$)

Figure 3.2.2.2-3 (1)  Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 3.2.2.2-3 (2)  Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 3.0K$)
Figure 3.2.2.2-3 (3)  Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 3.9K$)
Figure 3.2.2.2-3 (4)  Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 5.0K$)
Figure 3.2.2.2-3 (5)  Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 6.1K$)
Figure 3.2.2.2-3 (6)  Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 7.0K$)
Figure 3.2.2.2-3 (7)  Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 7.7K$)

Figure 3.2.3.1-1  Behavior of bubbles around heater rod with 3mm-gap (Parallel walls)
Figure 3.2.3.1-2 (1)  Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{sub} = 6.0K$)
Figure 3.2.3.1-2 (2)  Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{sub} = 7.0K$)
Figure 3.2.3.1-2 (3)  Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{sub} = 7.5K$)
Figure 3.2.3.1-2 (4)  Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{sub} = 8.0K$)
Figure 3.2.3.1-3 (1) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 3mm-gap, $\Delta T_{sub} = 6.0K$)

Figure 3.2.3.1-3 (2) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 3mm-gap, $\Delta T_{sub} = 7.0K$)

Figure 3.2.3.1-3 (3) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 3mm-gap, $\Delta T_{sub} = 7.5K$)

Figure 3.2.3.1-3 (4) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 3mm-gap, $\Delta T_{sub} = 8.0K$)

Figure 3.2.3.2-1 Behavior of bubbles around heater rod with 1mm-gap (Parallel walls)

Figure 3.2.3.2-2 (1) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)

Figure 3.2.3.2-2 (2) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 3.0K$)

Figure 3.2.3.2-2 (3) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 4.0K$)

Figure 3.2.3.2-2 (4) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 5.0K$)

Figure 3.2.3.2-2 (5) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 6.0K$)

Figure 3.2.3.2-2 (6) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 7.0K$)

Figure 3.2.3.2-2 (7) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 8.0K$)

Figure 3.2.3.2-3 (1) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)

Figure 3.2.3.2-3 (2) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 1mm-gap, $\Delta T_{sub} = 3.0K$)

Figure 3.2.3.2-3 (3) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 1mm-gap, $\Delta T_{sub} = 4.0K$)

Figure 3.2.3.2-3 (4) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 1mm-gap, $\Delta T_{sub} = 5.0K$)

Figure 3.2.3.2-3 (5) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 1mm-gap, $\Delta T_{sub} = 6.0K$)

Figure 3.2.3.2-3 (6) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 1mm-gap, $\Delta T_{sub} = 7.0K$)

Figure 3.2.3.2-3 (7) Acceleration of heater rod in the X-Y plane  
(Parallel walls, 1mm-gap, $\Delta T_{sub} = 8.0K$)
Figure 3.2.4.1-1 Behavior of bubbles around heater rod with 3mm-gap (Corner walls)

Figure 3.2.4.1-2 (1) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{sub} = 6.0K$)

Figure 3.2.4.1-2 (2) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{sub} = 7.0K$)

Figure 3.2.4.1-2 (3) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{sub} = 7.5K$)

Figure 3.2.4.1-2 (4) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{sub} = 8.0K$)

Figure 3.2.4.1-3 (1) Acceleration of heater rod in the X-Y plane (Corner walls, 3mm-gap, $\Delta T_{sub} = 6.0K$)

Figure 3.2.4.1-3 (2) Acceleration of heater rod in the X-Y plane (Corner walls, 3mm-gap, $\Delta T_{sub} = 7.0K$)

Figure 3.2.4.1-3 (3) Acceleration of heater rod in the X-Y plane (Corner walls, 3mm-gap, $\Delta T_{sub} = 7.5K$)

Figure 3.2.4.1-3 (4) Acceleration of heater rod in the X-Y plane (Corner walls, 3mm-gap, $\Delta T_{sub} = 8.0K$)

Figure 3.2.4.2-1 Behavior of bubbles around heater rod with 1mm-gap (Corner walls)

Figure 3.2.4.2-2 (1) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)

Figure 3.2.4.2-2 (2) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 3.0K$)

Figure 3.2.4.2-2 (3) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 4.0K$)

Figure 3.2.4.2-2 (4) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 5.0K$)

Figure 3.2.4.2-3 (1) Acceleration of heater rod in the X-Y plane (Corner walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)

Figure 3.2.4.2-3 (2) Acceleration of heater rod in the X-Y plane (Corner walls, 1mm-gap, $\Delta T_{sub} = 3.0K$)

Figure 3.2.4.2-3 (3) Acceleration of heater rod in the X-Y plane (Corner walls, 1mm-gap, $\Delta T_{sub} = 4.0K$)

Figure 3.2.4.2-3 (4) Acceleration of heater rod in the X-Y plane (Corner walls, 1mm-gap, $\Delta T_{sub} = 5.0K$)

Figure 4.1-1 (1) PSD of acceleration under Subcool: 8K, Superheat: 17K (Exp.1)

Figure 4.1-1 (2) PSD of acceleration under Subcool: 10K, Superheat: 16K (Exp.1)

Figure 4.1-2 RMS of acceleration (Exp.1)

Figure 4.2.1-1 Rise velocity of a bubble (Single wall, 3mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 4.2.2-1  Vapor bubbles around the heater rod (1mm-gap, $\Delta T_{sub} = 6K$)
Figure 4.2.2-2  Vapor bubbles around the heater rod (1mm-gap, $\Delta T_{sub} = 1K$)
Figure 4.4.1-1  Relation between vertical velocity and vapor bubble diameter
Figure 4.4.2-1  Movement of a large bubble from the gap with a wall
Figure 4.5-1  Number of large bubbles (> 5mm in size)
Figure 4.6-1(1)  Acceleration of heater rod in the X-Y plane
                   (Single wall, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 4.6-1(2)  Acceleration of heater rod in the X-Y plane
                   (Parallel walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 4.6-1(3)  Acceleration of heater rod in the X-Y plane
                   (Corner walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 4.6-2  Acceleration RMS of the heater rod (1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 4.6-3  Acceleration of heater rod in X-Y plane (Parallel walls configuration)
Figure 4.7-1  RMS values of acceleration of the heater rod
Figure 4.7-2  Acceleration RMS values in the cases of 1mm-gap and 3mm-gap
Figure 4.8-1  Acceleration PSD in the cases of 1mm-gap (Single wall)
Figure 4.8-2  Acceleration PSD in the cases of 3mm-gap (Single wall)
Figure 4.8-3  Acceleration PSD in the cases of 1mm-gap (Parallel walls)
Figure 4.8-4  Acceleration PSD in the cases of 3mm-gap (Parallel walls)
Figure 4.8-5  Acceleration PSD in the cases of 1mm-gap (Corner walls)
Figure 4.8-6  Acceleration PSD in the cases of 3mm-gap (Corner walls)
Figure 4.8-7  First natural frequency of the heater rod depending on degree of subcooling
Figure 4.9-1  RMS values of displacement (Exp.2)
Figure 4.9-2  Acceleration, velocity and displacement (Single wall, 1mm-gap)
Figure 4.9-3  Acceleration, velocity and displacement (Parallel walls, 1mm-gap)
Figure 4.9-4  Acceleration, velocity and displacement (Corner walls, 1mm-gap)
Figure 5-1  Maximum bubble diameter depending on pressure and flow velocity
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.1</td>
<td>Conditions and parameters for Exp.1</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Conditions and parameters for Exp.2</td>
</tr>
<tr>
<td>2.3-1</td>
<td>Frequencies for appropriate treatment of acceleration data</td>
</tr>
<tr>
<td>3.2.1-1</td>
<td>Objectives of the structural constraints with metallic walls</td>
</tr>
<tr>
<td>3.2.2-1</td>
<td>List of data obtained in SBIV experiments of a Single wall configuration</td>
</tr>
<tr>
<td>3.2.3-1</td>
<td>List of data obtained in SBIV experiments of Parallel walls configuration</td>
</tr>
<tr>
<td>3.2.4-1</td>
<td>List of data obtained in SBIV experiments of Corner walls configuration</td>
</tr>
<tr>
<td>4.3-1</td>
<td>Estimated temperature around selected large bubbles</td>
</tr>
<tr>
<td>4.4.2-1</td>
<td>Horizontal velocities of selected large bubbles</td>
</tr>
<tr>
<td>4.4.2-2</td>
<td>Vertical velocities of selected large bubbles</td>
</tr>
<tr>
<td>4.4.2-1</td>
<td>Estimated vertical velocities of selected large bubbles</td>
</tr>
<tr>
<td>4.9-1</td>
<td>Displacement of heater rod in vibration (RMS values)</td>
</tr>
<tr>
<td>5-1</td>
<td>Structures and conditions in the experiments</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1 Background

In several and various fields of industries, kinds of structures are utilized in water with maintaining their designed functions. One of the important issues to be prevented is unexpected “vibration” of structures in water. Such unexpected vibration, that is, vibration beyond allowable ranges for design of structures may bring loss of their functions and besides, risks leading to severe incidents in use of them. Except for vibration triggered by rotation or translation of structures themselves, vibration of structures due to water can be classified into the following types;

(1) Vibration in flow
   (1)-a: in single phase flow
   (1)-b: in two-phase flow
(2) Vibration in pool boiling

Vibration of structures in flow is generally called “Flow-induced vibration (FIV)”. Studies on FIV already started regarding pipelines for oil more than half a century ago [1], and have been conducted so far by many researchers in various fields, such as pipelines [2][3], cables [4], bridges [5], towers [6], boilers [7], chemical reactors [8] and nuclear power reactors [9]–[12], as well as fundamental studies [13]. Focusing on light water reactors for nuclear power generation, several kinds of structures are used with water flow and issues related to FIV have occurred, for which effective countermeasures in design of such structures or as operational criteria have been taken [14][15]. Number of components such as reactor internals, associated piping, heat exchangers, steam generators and ancillary diagnostic equipment, can be listed and fuel assemblies are also one of the important components to be prevented from issues due to FIV on fuel rods. For pressurized water reactors (PWR) or boiling water reactors (BWR), approximately 4m-long fuel rods are bounded in a fuel assembly by spacer grids at some axial
elevations with almost constant spans, as shown in Figure 1.1-1. Fuel assemblies consisting of such fuel rods are installed in a reactor core and used in upstream of coolant water with high temperature. Thus, issues of FIV on fuel assemblies and fuel rods in water have been studied for several decades by many researchers or nuclear fuel vendors to investigate causes of significant fretting wear on fuel rod cladding with spacer grids (GTRF: Grid-to-Rod Fretting) and to apply effective modifications to design of fuel assemblies [16]–[21]. These are categorized in (1)-a, vibration in single phase flow. In addition, regarding vibration of a cylinder like a fuel rod in water, influence of added mass on vibration has been studied [22][23].

Moving to the categories (1)-b, vibration in two-phase flow, and (2), vibration in pool boiling, boiling is also considered for nuclear reactors. Some kinds of flow regime are confirmed under high pressure and high temperature [24] corresponding to conditions in PWR and BWR, and vibration of a structure in boiling water was also investigated [25]. Focusing on bubbles in water boiling, vapor bubbles are generated at surface of a heating structure and the bubbles grow, slip and move, collide, agglomerate, coalesce with other bubbles and depart from the heating surface, which has been studied by many researchers. Some studies treated fundamental behavior of a single bubble, as well as general studies on bubble dynamics and heat transfer [26]–[28]. Plesset and Zwick [29] and Mikic et al. [30] formulated bubble growth in superheated liquids, and some researchers tried to express a diameter of a bubble in pool boiling in relation to bubble frequency or rise velocity of a bubble [31]–[37]. Analytical approaches of modelling bubble behavior have been studies [38], and Ose and Kunugi modelled growth of a single bubble under subcooled pool boiling without use of any empirical formula [39]. Studies regarding condensation of a bubble can be also listed [40][41] and vibration caused by condensation of vapor was investigated [42]. Behavior of a bubble and heat transfer in a confined space [43][44] and dynamics of a bubble on a vertical heating surface [45]–[47] have been studied and modelled by other researchers. Formulation of microlayer on the heating surface is also one of important phenomena for vapor bubble generation [48].
Such behavior of bubbles enables to vibrate structures [49][50], which should be reduced typically in two-phase flow of boiling for the system of BWR. In the case of subcooled boiling, generated vapor bubbles are condensed by subcooled water. It could occur in any stages of bubble lifetime from just after generation to departure of grown bubbles. Vibration of a heating structure in subcooled boiling at high heat flux due to behavior of vapor bubbles was already pointed out in literature more than 40 years ago by Collier [51];

“At high heat fluxes the onset of subcooled boiling is encountered at high degrees of subcooling, and the vapour bubbles may grow and collapse whilst still attached to, or even sliding along, the heating surface.

These processes are sometimes accompanied by noise and vibration of the heating surface.”

Now, this phenomenon is called “Subcooled Boiling-induced Vibration” (SBIV).

In spite of the note for existence of SBIV, number of studies related to SBIV for these 40 years is countable. Some researchers focused influence of flow boiling on vibration of BWR type of fuel and, in 1990s, conducted experiments under demonstrative thermal conditions of BWR [52][53]. They confirmed influence of boiling on vibration of a heating structure and mentioned importance of behavior of generated bubbles on vibration, though behavior of bubbles itself leading to SBIV was not visually confirmed.

Since then, no remarkable studies were conducted except for a paper by Nematollahi [54], but recently, a fundamental phenomenon of SBIV was confirmed by Komuro et al. [55][56]. Behavior of bubbles at the surface of a single heater rod was observed with high-speed digital video camera and acceleration of the heater rod due to SBIV was monitored with an accelerometer installed on the heater rod. The experiments were under atmospheric pressure and the system for the experiments consisted of a water tank and a single heater rod hanging from the ceiling of the tank.
Figure 1.1-1 Nuclear fuel assembly for PWR and BWR

(a) PWR fuel assembly  
(b) BWR fuel assembly

(http://www.mnf.co.jp/en/)

(17 x 17 Lattice Design)
1.2 Review of the Literature

1.2.1 Flow-induced Vibration of Nuclear Fuel Rods

It was reported that the changes of the void fraction of coolant in BWRs influenced on the flow rate of the coolant and the neutron distribution, by Gialdi et al. [57]. Also Ikeda et al. [58] and M-Leuba et al. [59] reported that it sometimes caused the instabilities in the whole system.

For PWR, employing single phase flow of light water under higher pressure as its system than a BWR, a local subcooled boiling in the core under a normal operation may not cause significant vibrations of fuel rods because the subcooled boiling is so limited and the influence of such boiling on the SBIV could be negligible in comparison with the influence by the FIV. This is obvious because no fuel leakage or significant fretting wear due to the SBIV under a normal operation has been reported yet. However, considering under irregular situations or conditions at accidents like loss of coolant flow or system pressure drop, water easily can make subcooled boiling and the SBIV might be a significant issue until the system recovers.

FIV of fuel rods in the core of a nuclear power reactor is one of the most important items to be investigated in the aspect to avoid critical fretting wear on fuel rod cladding, leading to consequent leakage of radioactive materials. Many studies have been reported regarding this FIV and fuel designs against occurrence of critical fretting wear on fuel rods due to the FIV such as Kim et al. [60] and Yan et al. [61].

1.2.2 Subcooled Boiling-induced Vibration under Flow Boiling

As a demonstrative investigation on vibration of BWR fuel rods in two-phase flow, Miyano et al. [52] conducted flow tests with a 2×2 arrayed-partial structure of a BWR fuel assembly under conditions including the actual ones of BWR system such as system pressure, flow rate,
inlet subcooling and quality at outlet. The assembly of the 2×2 tube configuration consisted of heating tubes and non-heating tubes. From acceleration of the non-heating tube, amplitude of tube vibration increased as higher system pressure. Amplitude of tube vibration also increased in proportion to increase of void fraction. Higher natural frequency of the tubes following increase of void fraction was considered to be due to decrease of averaged density of water around the tubes, decrease of add mass to the tubes and increase of temperature.

In 1999, Nematollahi et al. [53] also conducted flow tests focusing on the SBIV under the flow conditions in the range of subcooling at the flow inlet from 10 to 80K, to observe boiling effects on fuel rod vibration including the SBIV. A tube of stainless steel in a transparent glass tube was installed in a test loop. At the end of the tube which protruded out of the loop, an accelerometer was setup to measure acceleration of tube vibration. The tube was heated due to electrical resistance by direct energization into the tube. Based on the results of the flow tests, it was point out that the SBIV depended on the degree of subcooling, which corresponded to behavior of bubbles such as growth and collapse.

These studies investigated the effect of SBIV in two-phase flow conditions, however, the fundamental phenomenon of the SBIV itself was not clarified as a separation from FIV.

1.2.3 Previous Experiment for a Single Heater Rod

Komuro et al. initiated the fundamental experiments on SBIV of a single cylindrical heater rod in a water tank as pool boiling under atmospheric pressure [55][56]. The heater rod was fixed at its top onto a ceiling of the water tank, with an accelerometer attached at its bottom free-end. Heat flux of the heater rod was controlled by supply of direct current to the heater. The range of the degree of subcooling in the experiments was from $\Delta T_{\text{sub}} = 0K$ (i.e., a saturation condition) to 10K. Fundamental phenomena of the SBIV of the heater rod was clarified as behavior of vapor bubbles around the heater rod and the following conclusion was led through investigation on the measured acceleration;
(1) Root mean square (RMS) values of acceleration indicated the minimum around $\Delta T_{sub} = 2\text{K}$.

(2) In the range of near saturation, departure of large bubbles from the heater rod induced vibration of the heater rod, while cycles from generation to departure and condensation of small vapor bubbles induced vibration in the range of larger degree of subcooling $\Delta T_{sub} > 20\text{K}$.

(3) Two peaks of power spectrum density (PSD) of acceleration processed by Fast Fourier Transform (FFT) were identified around 2000Hz, which slightly shifted depending on degree of subcooling in bulk water. The peak at the higher frequency was due to recoil to departure of vapor bubbles, and the other peak at the lower frequency was due to local pressure perturbation by condensation of larger bubbles.

In addition to the above, a SBIV experiment used by a heater rod covered with two different half-sides of stainless steel and cupper was conducted in the study. The result of the experiment suggested that vibration at the half side with higher thermal flux (cupper side) was dominant to vibration of the heater rod.
1.3 Objectives and Scope of This Study

Behavior of vapor bubbles leading to vibration of a heating structure can be considered as summarized in Figure 1.3-1, in which condensation of vapor bubbles is the remarkable behavior that occurs under subcooled water, leading to SBIV of the structure.

![Diagram showing behavior of bubbles and phenomena to vibration](image)

**Figure 1.3-1 Vibration of a heating structure in water with vapor bubbles**

Condensation of vapor bubbles can occur by contact to well-subcooled water in any behavior of bubbles in Figure 1.3-1. Behavior of bubbles itself encourages local natural convection bringing fresh subcooled water to other bubbles. Considering a situation in forced convection, water flow would encourage movement of bubbles as well as condensation of bubbles by supply of fresh subcooled water to the bubbles. When some structural constraint exists in the
vicinity of a heating structure, such a constraint would limit supply of fresh subcooled water to the region formed by the heating structure and the constraint and it would change thermal situation in the region, in particular in the case of pool boiling. In addition, such a constraint would spatially limit growth or movement of generated bubbles, or mechanically influence on SBIV of the heating structure such as additive mass effect and damping effect.

In the previous studies on a fundamental phenomenon of SBIV, no structural constraints was provided to the single heater rod, while the actual configuration of fuel rods in a fuel assembly for PWR and BWR is a bundle with approximately 3mm-gap distance between neighboring fuel rods. Besides, each of fuel rods is inserted to a small cell of a spacer grid at some elevation, in which the gap distance between the surface of the fuel rod and walls of the cell around the rod is approximately 1 to 2mm.

This study, therefore, focuses wall effects in the vicinity of a single heater rod on its SBIV to investigate if existence of a wall introduces any changes and if variation of structural constraints by walls presents any differences through behavior of generated bubbles. Correspondingly, the following two kinds of experiments were conducted in this study;

(1) Comparison of SBIV between the experiment on a single heater rod and that with a metallic wall near the heater rod

(2) Comparison of SBIV between three types of structural constraints formed by metallic walls around the heater rod.

In the experiment of the above (2), taking the actual distance between fuel rods into account, two different distances of the gap between the surface of the heater rod and each of the walls were set to provide different thermal conditions locally in the gap and influences on behavior of generated bubbles. These experiments under atmospheric pressure were easily handled as well as comparable to supposition that system pressure in a reactor core largely drops or loss of coolant in a spent fuel pit (SFP) occurs leading to subcooled boiling, though the normal operation for the core of PWR or BWR maintains high pressure of the system.
1.4 Structure of Thesis

This thesis consists of 6 chapters. In the chapter 1, SBIV is introduced along with some relating literatures by other researchers, and focused phenomena of vapor bubbles which significantly cause vibration of structures in subcooled water are illustrated. The objectives of the thesis and the structure of the thesis are also presented.

The chapter 2 describes experimental methodology which was taken in this present study to clarify the fundamental phenomena of SBIV in the case with structural constraints, including experimental apparatus, experimental conditions and date processing.

The chapter 3 describes results of the two kinds of experiments; Exp.1 and Exp.2.

In the chapter 4, investigation on behavior of bubbles relating to SBIV is presented, based on the experimental results shown in the chapter 3. The dynamics of generated vapor bubbles is interpreted with equations referring to literatures by other researchers.

The chapter 5 describes about implementation of the results in the present study to apply to actual cases for PWR fuel rods, taking structural and conditional differences into account.

The chapter 6 summarizes the present study to clarify concluding remarks together with a list of future works.
2. EXPERIMENTAL METHODOLOGY

2.1 Experimental Apparatus

As the series of the investigation on the SBIV based on the previous studies mentioned above, the present study also applied the same apparatus. In order to observe the vibration of a single rod due to the subcooled boiling, a single heater rod perpendicularly fixed at the top-end of the tank with an accelerometer installed at its bottom-end, was submerged in a water tank of 150mm x 150mm x 196mm. Figure 2.1-1 shows the schematic view of this experimental apparatus and Figure 2.1-2 is a picture of the water tank and the single heater rod.

The heater rod consisted of one cartridge heater (Watlow) welded to a stainless steel shell as shown in Figure 2.1-1. The heat flux on the heater rod surface was controlled by the DC power supply. The representative temperatures of the heater rod were monitored by four thermocouples installed into the outer shell of the heater rod at four locations in the cross-section, respectively. The temperature of the bulk water was controlled by an immersion heater and monitored by a thermocouple installed fairly far from the heater rod in the water tank.

A high speed camera captured the phenomena of the local boiling adjacent to the heater rod surface. The accelerometer was mounted at the free-end of the heater rod, which was covered by cray of metal to prevent leakage of hot water to get damaged during the experiment, to monitor the vibrations of the heater rod in two directions.

The natural frequency of the heater rod was roughly calculated by the well-known equation for a cantilever, which provides the first and second of estimated natural frequencies as approximately 500Hz and 3000Hz, respectively.
Figure 2.1-1 Experimental apparatus for the present study

Figure 2.1-2 Water tank and heater rod for the present study
2.2 Experimental Conditions

2.2.1 Exp.1: Influences of Wall Existence

(1) Metallic wall
Using the same experimental apparatus as Komuro et al. [55][56], the experiment of the SBIV were conducted to investigate influences in the case of setting a metallic wall with 5mm-gap distance from the heater rod surface. This experiment consisted of two types of conditions; one was the vibration test of a bare single rod (No wall), and the other was that of a single rod next to metallic wall (With wall) as shown in Figure 2.2.1-1.

![Experimental apparatus for Exp.1](image)

**Figure 2.2.1-1** Experimental apparatus for Exp.1

(2) Experimental conditions
This experiment was carried out at atmospheric pressure. In case of “No wall”, temperature of the bulk water in the tank gradually increased with increase of heat flux of the heater rod, and the heat flux was stably controlled when the degree of subcooling reached around 30K. Subcooled boiling was achieved in this temperature region, and then, the degree of subcooling was decreasing together with gradual increase of the superheat of the heater rod surface, which led to frequent vapor bubble generation, growth, departure, condensation and extinction on the
heater rod. The same procedure and control were taken also for “With wall” measurement in series. Heater rod surface temperature for the superheat was calculated with temperature measured by the thermocouples installed the outer shell of the heater, in the assumption that the heat flux in the outer shell was uniform.

Table 2.2.1-1 Conditions and parameters for Exp.1

<table>
<thead>
<tr>
<th>Material of wall, thickness</th>
<th>Aluminium, 32mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural constrains by a wall</td>
<td>2 cases (No wall, With wall)</td>
</tr>
<tr>
<td>Gap distance between heater rod and a wall</td>
<td>5mm</td>
</tr>
<tr>
<td>Bulk water in water tank</td>
<td>Purified water, deaeration before experiments</td>
</tr>
<tr>
<td>Subcooled boiling</td>
<td>Pool boiling</td>
</tr>
<tr>
<td>Range of degree of subcooling</td>
<td>7K ~ 76K (controlled as an experimental parameter)</td>
</tr>
<tr>
<td>Superheat at heater rod surface</td>
<td>-76 ~ 17K (controlled as an experimental parameter)</td>
</tr>
</tbody>
</table>
2.2.2 Exp.2: Influences of Wall Configuration

(1) Structural constraints by metallic walls

In the experiments, three cases of the structural constraints by metallic walls were applied as shown in Figure 2.2.2-1; Case1 is the case of Single wall, Case2 is the case of Parallel walls and Case3 is the case of Corner walls. Each of the walls, made of stainless steel with 2mm thickness, was arranged with 1mm-gap distance to the heater rod.

![Figure 2.2.2-1 Configurations of walls around the heater rod for Exp.2](image)

(2) Experimental conditions

All the experiments was carried out under an atmospheric pressure. The degree of subcooling, $\Delta T_{sub}$ was controlled by the power supply into the cartridge heater after the deaeration of the...
bulk water by the immersion heater once up to the saturated boiling. The acceleration of the heater rod by the SBIV was monitored with the accelerometer and sampling frequency was 10kHz. During change of the degree of subcooling in the range of low degree from 1K to 8K, the measuring period for one condition was kept 2 seconds. Behaviors of bubbles at or near the surface of the heater rod were recorded by the high-speed video camera FASTCAM (Photron, FASTCAM-512PCI) with 125fps. The video record on one condition was also during 2 seconds.

The degree of subcooling was a parameter in the experiments, while the degree of superheat at the rod surface was kept constant, which means that power supply to the heater was kept constant. In fact, the power supply of 180W provided the superheat of 17.5 ± 0.5K.

The conditions of this experiment is summarized in Table 2.2.2-1.

**Table 2.2.2-1 Conditions and parameters for Exp.2**

<table>
<thead>
<tr>
<th>Material of walls, thickness</th>
<th>Stainless steel, 2mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural constrains by walls</td>
<td>3 cases</td>
</tr>
<tr>
<td></td>
<td>(Single wall, Parallel walls, Corner walls)</td>
</tr>
<tr>
<td>Gap distance between heater rod and each of walls</td>
<td>1mm or 3mm</td>
</tr>
<tr>
<td>Bulk water in water tank</td>
<td>Purified water, deaeration before experiments</td>
</tr>
<tr>
<td>Subcooled boiling, convection in bulk water</td>
<td>Pool boiling, natural convection</td>
</tr>
<tr>
<td>Range of degree of subcooling</td>
<td>1K ~ 8K</td>
</tr>
<tr>
<td></td>
<td>(controlled as an experimental parameter)</td>
</tr>
<tr>
<td>Superheat at heater rod surface</td>
<td>17.5 ± 0.5K (constant)</td>
</tr>
</tbody>
</table>
2.3 Data Processing

For row data of the acceleration of the heater rod measured with the accelerometer, basic frequency is obtained by the sampling frequency divided by the total number of the data. A half of the sampling frequency of the acceleration corresponds to Nyquist frequency of the measured acceleration. When Fast Fourier Transformation (FFT) was applied to the measured acceleration, the obtained Power Spectrum Density (PSD) was treated in the range limited up to this Nyquist frequency to avoid aliasing. These frequencies are listed in Table 2.3-1 for Exp.1 and Exp.2.

<table>
<thead>
<tr>
<th></th>
<th>Sampling frequency</th>
<th>Basic frequency</th>
<th>Nyquist frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.1</td>
<td>20kHz</td>
<td>20000/20000</td>
<td>20000/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1.0Hz</td>
<td>= 10kHz</td>
</tr>
<tr>
<td>Exp.2</td>
<td>10kHz</td>
<td>10000/20000</td>
<td>10000/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 0.5Hz</td>
<td>= 5kHz</td>
</tr>
</tbody>
</table>

The power supply to the heater rod provided superheat at the surface of the heater rod, which was calculated from the temperatures measured by the thermocouples installed in the outer shell of the heater rod, in the assumption that the amount of heat value per unit length was uniform in a circumference at any radius of the outer shell, using the following Equation (1):

\[ Q' = -2\pi \lambda r_c \frac{dT}{dr_c} = \text{const.} \]  

Here, \( Q' \) means amount of heat value per unit length, W/m, \( \lambda \) means thermal conductivity, W/m/K, \( r_c \) means distance from the centre of the column in radial direction, m, and \( T \) means temperature, K.
3. EXPERIMENT AND RESULTS

3.1 Exp.1: Influences of Wall Existence

3.1.1 Procedure of measurement

The Exp.1 was carried out as a series of two types of experiments; one was for a bare single heater rod (No wall case), and the other was for a single heater rod in the vicinity of the metallic wall with 5mm-gap distance (With wall case). In No wall case, temperature of the bulk water gradually increased with increase of heat flux of the heater rod, and heat flux was stably controlled when degree of subcooling reached around 30K. Subcooled boiling was achieved in this temperature region, and then, degree of subcooling decreased together with gradual increase of the superheat of the heater rod surface, which led to frequent vapor bubble generation, growth, departure, condensation and extinction around the heater rod. The same procedure and control were taken also for measurement in With wall case in series, as shown in Figure 3.1.1-1.

![Figure 3.1.1-1 Temperature in the series of measurement in Exp.1](image-url)
3.1.2 Case of 5mm-gap distance to wall and case of no wall

(1) Behavior of bubbles around the heater rod

Pictures of bubbles around the heater rod under conditions of degree of subcooling $\Delta T_{\text{sub}} = 8\text{K}$ and 10K for No wall case and With wall case are shown in Figure 3.1.2-1 and Figure 3.1.2-2. For both of the figures, degree of superheat was 16 ~ 17K.

As a typical trend of generated vapor bubbles, the following was able to be observed;

(1) Vapor bubbles repeated growth and departure from their original sites for generation.

(2) Regardless of wall existence, bubbles grew larger under degree of subcooling $\Delta T_{\text{sub}} = 8\text{K}$ than under $\Delta T_{\text{sub}} = 10\text{K}$.

(3) Bubbles generated in the gap between the wall and the heater rod in With wall case seemed larger than in No wall case under the similar condition of temperature in bulk water. The size of growing bubbles under $\Delta T_{\text{sub}} = 10\text{K}$ was up to 1mm, and the size under $\Delta T_{\text{sub}} = 8\text{K}$ was up to 1.5 to 2mm.
Figure 3.1.2-1 Behavior of bubbles around heater rod (Exp.1, No wall case)

Figure 3.1.2-2 Behavior of bubbles around heater rod (Exp.1, With wall case)
(2) Acceleration trend of the heater rod vibration

Typical acceleration data measured under several temperature conditions with time are shown in Figure 3.1.2-3 for No wall case and Figure 3.1.2-4 for With wall case. Regardless of the wall existence, the acceleration at the bottom-end of the heater rod increased due to higher degree of superheat and lower degree of subcooling. From the measured acceleration in elapsed time, differences due to wall existence were hardly found.
Figure 3.1.2-3 Acceleration at the bottom end of the heater rod (Exp.1, No wall case)
(1) Subcool: 46.3K, Superheat: 1.6K

(2) Subcool: 10.4K, Superheat: 16.0K

(3) Subcool: 7.5K, Superheat: 16.4K

Figure 3.1.2-4 Acceleration at the bottom end of the heater rod (Exp.1, With wall case)
(3) Acceleration of the heater rod in X-Y plane

As shown in Figure 3.1.2-5, the measured acceleration data was plotted in X-Y plane both for No wall case and With wall case. Slight increase of acceleration in Y-direction, corresponding to the direction perpendicular to the wall was found. This tendency was clear in the comparison of root mean square (RMS) values of acceleration, which is shown in Figure 3.1.2-6.

Figure 3.1.2-5 Acceleration of the heater rod in X-Y plane (Exp.1)

Figure 3.1.2-6 Acceleration RMS of the heater rod (Exp.1, With wall case)
3.2 Exp.2: Influences of Wall Configuration

3.2.1 Procedure of measurement

In Section 3.1, Exp.1 clarified that the metallic wall located the single heater rod with 5mm-gap distance encouraged acceleration of the heater rod in the direction perpendicular to the wall, though bubbles generated around the heater rod were up to the size of a few millimeters, which was smaller than the gap distance. Besides, the range of degrees of subcooling in Exp.1 was not enough small to generate larger bubbles attaching the wall, as well as the degree of superheat at the surface of the heater rod was varied.

In this section, to focus on effects of closer gap distances to the wall and variation of wall configuration around the heater rod, the following three cases of the structural constraints by metallic walls and two kinds of gap distance were applied, as shown in Figure 2.2.2-1 in Section 2.2.2;

Case1 : Single wall configuration

Case2 : Parallel walls configuration
   (The heater rod was located between two walls in parallel.)

Case3 : Corner walls configuration
   (Two walls formed a 90 degree corner surrounding the heater rod.)

The objectives of the structural constraints with metallic walls are summarized in Table 3.2.1-1. In a conventional fuel assembly for PWR or BWR, a fuel rod is surrounded by other fuel rods with approximately 3mm pitch. In the position of a grid spacer, each fuel rod is located in each of grid cells of the grid spacer, where the gap distance between a fuel rod and a wall of a cell is approximately 1mm. As the normal operation, fuel assemblies are utilized in the reactor core under high pressure of the thermal-hydraulic system, where the size of bubbles would be significantly smaller than that under atmospheric pressure. On the other hand, assuming accidental situations such as sudden loss of the system pressure in the core or
loss of cooling function in a spent fuel pit, bubble generation in subcooled boiling under atmospheric pressure would be considerable.

Thermal conditions provided in Exp.2 is shown in Figure 3.2.1-1 in comparison to those in Exp.1 and in the study by Komuro et al. [55]

**Table 3.2.1-1 Objectives of the structural constraints with metallic walls**

<table>
<thead>
<tr>
<th>Structural constraints</th>
<th>Single wall</th>
<th>Basic case, to confirm effects of a single wall on behavior of bubbles and SBIV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel walls</td>
<td></td>
<td>To set two structural constrains in the same direction for the heater rod.</td>
</tr>
<tr>
<td>Corner walls</td>
<td></td>
<td>To set two structural constrains in different directions for the heater rod.</td>
</tr>
<tr>
<td>Gap distance to each wall</td>
<td>3mm</td>
<td>Closer than 5mm-gap, equivalent to the actual distance between fuel rods in a PWR or BWR fuel assembly.</td>
</tr>
<tr>
<td></td>
<td>1mm</td>
<td>Exaggerated case, to investigate difference of gap distance and observe a fundamental phenomenon of the SBIV significantly.</td>
</tr>
</tbody>
</table>

*Figure 3.2.1-1 Thermal conditions provided in Exp.2*
3.2.2 Single wall configuration

For a Single wall configuration, the data set shown in Table 3.2.2-1 was obtained in the experiments.

Table 3.2.2-1 List of data obtained in SBIV experiments of Single wall configuration

<table>
<thead>
<tr>
<th>Type of wall configuration</th>
<th>Gap to wall [mm]</th>
<th>Superheat at rod surface [K]</th>
<th>Subcooling in bulk water [K]</th>
<th>Bubble behavior</th>
<th>Acceleration at rod bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single wall</td>
<td>3</td>
<td>17.5 ± 0.5</td>
<td>1.0</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.0</td>
<td>√</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.0</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.0</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.0</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

3.2.2.1 Case of 3mm-gap distance to wall

(1) Behavior of bubbles around the heater rod

Figure 3.2.2.1-1 (1) to (8) show behavior of generated bubbles observed from the X-direction axially along the heater rod in the range of degree of subcooling from $\Delta T_{sub} = 1.0\text{K}$ to $8.0\text{K}$. The following behavior of such bubbles was generally remarkable;

(a) Regardless of degree of subcooling, vapor bubbles generated in the gap between the heater
rod and the wall rose upward in the gap.

(b) Down to $\Delta T_{\text{sub}} = 4.0\, \text{K}$, behavior of bubbles did not seem to be significantly different between that in the gap with the wall and in the opposite side of the heater rod without the wall.

(c) Under the condition of $\Delta T_{\text{sub}} = 1.0\, \text{K}$, the bubbles grew up in the gap with the wall to the size attaching the wall. There was no significant difference on the bubble behavior, though the departure of large bubbles and deformation of bubble shape in the gap seemed to be confined in comparison to those in the opposite side without a wall.
Figure 3.2.2.1-1 Behavior of bubbles around heater rod with 3mm-gap (Single wall) (1/2)
Figure 3.2.2.1-1 Behavior of bubbles around heater rod with 3mm-gap (Single wall) (2/2)
(2) Acceleration trend of the heater rod vibration

Figure 3.2.2.1-2 (1) to (3) show the measured acceleration trends in the X- and Y-directions under the condition of $\Delta T_{\text{sub}} = 6.0\,\text{K}$ to $8.0\,\text{K}$. The acceleration RMS value of the heater rod vibration in the Y-direction, which is perpendicular to the wall, was approximately 30% larger than that in the X-direction for all conditions from $\Delta T_{\text{sub}} = 6.0\,\text{K}$ to $8.0\,\text{K}$. Fluctuation of acceleration in X-direction observed in the magnified scale during 0.1sec in Figure 3.2.2.1-2 (1) and (2) trended almost stable, while periodical slight increase of acceleration was found in Y-direction.
Figure 3.2.2.1-2 (1) Acceleration of heater rod (Single wall, 3mm-gap, $\Delta T_{sub} = 6.0K$)
Figure 3.2.2.1-2 (2) Acceleration of heater rod (Single wall, 3mm-gap, $\Delta T_{sub} = 7.0K$)
Figure 3.2.2.1-2 (3) Acceleration of heater rod (Single wall, 3mm-gap, $\Delta T_{sub} = 8.0$K)
(3) Acceleration of the heater rod in X-Y plane

The acceleration of the heater rod in X-Y plane under the condition of $\Delta T_{\text{sub}} = 6.0\text{K}$ to $8.0\text{K}$ is shown in Figure 3.2.2.1-3 (1) to (3). From these figures, it is obvious that the SBIV of the heater rod was somehow influenced by the existence of the wall because the vibration acceleration in Y-direction perpendicular to the wall was larger than that in X-direction. Encouraged acceleration in Y-direction due to the wall was obvious.
Figure 3.2.2.1-3 (1) Acceleration of heater rod in the X-Y plane

(Single wall, 3mm-gap, $\Delta T_{sub} = 6.0K$)
Figure 3.2.2.1-3 (2) Acceleration of heater rod in the X-Y plane

(Single wall, 3mm-gap, $\Delta T_{sub} = 7.0$K)
Figure 3.2.2.1-3 (3) Acceleration of heater rod in the X-Y plane

(Single wall, 3mm-gap, $\Delta T_{sub} = 8.0$K)
3.2.2.2 Case of 1mm-gap distance to wall

(1) Behavior of bubbles around the heater rod

Figure 3.2.2.2-1 (1) to (7) show behavior of generated bubbles observed from the X-direction axially along the heater rod in the range of degree of subcooling from $\Delta T_{sub} = 1.0\text{K}$ to $7.7\text{K}$. The following behavior such bubbles was generally remarkable;

(a) Bubbles generated in the gap between the wall and the heater rod sometimes grew ellipsoidally to more than 10mm in the major axis of the ellipsoid under lower degree of subcooling. They seemed to slide and turned around the rod to the open space, i.e. to the direction without the wall. Such large bubbles fluctuated in shape and condensed due to fresh subcooled water in the open space on leaving the surface of the rod, but did not coalesce with other large bubbles. The number of nucleation sites on the surface of the heater rod seemed to be limited for such bubbles to grow large in the gap.

(b) In addition to the above-mentioned behavior of large bubbles, generation and condensation of small bubbles (up to 1 ~ 2mm) in a short cycle were found on the surface of the heater rod, in particular in the open space without a wall. Such small bubble generation seemed to be less in the gap, which is considered to be caused by growth of large bubbles in the gap consuming provided heat from the surface of the heater rod.

(c) Under degree of subcooling $\Delta T_{sub} = 1.0\text{K}$, bubbles at the side without a wall seemed to be developed slightly larger than in the case with 3mm-gap.
Figure 3.2.2.2-1 Behavior of bubbles around heater rod with 1mm-gap (Single wall) (1/2)
(7) $\Delta T_{\text{sub}} = 7.7\text{K}$

**Figure 3.2.2.2-1** Behavior of bubbles around heater rod with 1mm-gap (Single wall) (2/2)
(2) Acceleration trend of the heater rod vibration

Figure 3.2.2.2-2(1) to (7) show the measured acceleration in X- and Y-directions under the conditions from $\Delta T_{sub} = 1.0K$ to 7.7K. The acceleration RMS value of the rod vibration in Y-direction perpendicular to the wall was 20% larger than that in X-direction under the condition of $\Delta T_{sub}=1.0K$, and 49% increase under the condition of $\Delta T_{sub} = 6.1K$.

Acceleration in X-direction under the condition of $\Delta T_{sub} = 6.1K$ in Figure 3.2.2.2-2 (5) was slightly larger than that under the condition of $\Delta T_{sub} = 6.0K$ in the case of 3mm-gap distance shown in Figure 3.2.2.1-2 (1), while both are similarly stable in their trend in time. On the other hand, acceleration in Y-direction under the condition of $\Delta T_{sub} = 6.1K$ in Figure 3.2.2.2-2 (5) showed fluctuation with an amplitude more than $5m/s^2$ from time to time, which increased as closer to temperature saturation in bulk water. Such large fluctuation of acceleration was getting significant also in X-direction under the condition of $\Delta T_{sub} = 3.9K$ and 1.0K. This trend of acceleration at the bottom end of the heater rod was assumed to be caused by behavior of large bubbles in the direction, i.e., fluctuation and condensation of such large bubbles whose heat was removed by fresh subcooled water.
Figure 3.2.2.2-2 (1) Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 3.2.2.2-2 (2) Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 3.0K$)
Figure 3.2.2.2.2 (3) Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{\text{sub}} = 3.9K$)
Figure 3.2.2.2-2 (4) Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 5.0K$)
Figure 3.2.2.2-2 (5) Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 6.1K$)
Figure 3.2.2.2-2 (6) Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{sub} = 7.0K$)
Figure 3.2.2.2-2 (7) Acceleration of heater rod (Single wall, 1mm-gap, $\Delta T_{\text{sub}} = 7.7K$)
(3) Acceleration of the heater rod in X-Y plane

The acceleration of the heater rod in X-Y plane under the condition from $\Delta T_{sub} = 1.0\text{K}$ to $7.7\text{K}$ is shown in Figure 3.2.2.3 (1) to (7). Under the conditions of $\Delta T_{sub} = 6.1\text{K}$ and $7.7\text{K}$, in Figure 3.2.2.3 (5) and (7), encouraged acceleration in Y-direction due to existence of the wall was obvious, as the same as the trend in the case with 3mm-gap. Under the conditions of $\Delta T_{sub} = 1.0\text{K}$ and $3.9\text{K}$, in Figure 3.2.2.3 (1) and (3), acceleration in X-direction increased in comparison to that under $\Delta T_{sub} = 6.1\text{K}$ and $7.7\text{K}$ instead of slight decrease of acceleration in Y-direction, however.

This suggests the very important mechanism of the SBIV in the experiment, that is, the heater rod was vibrated under subcooled water caused by local pressure change due to fluctuation or condensation of bubbles. In particular, large bubbles growing in the narrow gap with the wall provide large fluctuation of acceleration onto the heater rod in the gap but in the open region without a wall when such large bubbles move out from the gap to the open region.
Figure 3.2.2.2-3 (1) Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 3.2.2.2-3 (2) Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 3.0$K)
Figure 3.2.2.2-3 (3) Acceleration of heater rod in the X-Y plane

(Single wall, 1mm-gap, $\Delta T_{sub} = 3.9K$)
Figure 3.2.2.2-3 (4) Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 5.0K$)
Figure 3.2.2.2-3 (5) Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 6.1K$)
Figure 3.2.2.2-3 (6) Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, $\Delta T_{sub} = 7.0$K)
Figure 3.2.2.2-3 (7) Acceleration of heater rod in the X-Y plane
(Single wall, 1mm-gap, \( \Delta T_{\text{sub}} = 7.7 \text{K} \))
### 3.2.3 Parallel walls configuration

For Parallel walls configuration, the data set shown in Table 3.2.3-1 was obtained in the experiments.

**Table 3.2.3-1** List of data obtained in SBIV experiments of Parallel walls configuration

<table>
<thead>
<tr>
<th>Type of wall configuration</th>
<th>Gap to wall [mm]</th>
<th>Superheat at rod surface [K]</th>
<th>Subcooling in bulk water [K]</th>
<th>Bubble behavior</th>
<th>Acceleration at rod bottom</th>
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<td>Parallel walls</td>
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</table>

### 3.2.3.1 Case of 3mm-gap distance to Wall

**1) Behavior of bubbles around the heater rod**

Figure 3.2.3.1-1 (1) to (8) show behavior of generated bubbles observed from the X-direction axially along the heater rod in the range of degree of subcooling from $\Delta T_{\text{sub}} = 1.0\text{K}$ to $8.0\text{K}$. The following behavior of such bubbles was generally remarkable;
(a) Regardless of degree of subcooling, vapor bubbles generated in the gap between the heater rod and the wall rose upward in the gap. Behavior of bubbles seemed to be the same in both of the gaps, which corresponded to the commensurate condition at both sides of the heater rod in Y-direction.

(b) Down to $\Delta T_{sub} = 4.0\text{K}$, behavior of bubbles did not seem to be significantly different between that in the gap with the wall and in the opposite side of the heater rod without the wall.

(c) Under the condition of subcooling less than 4.0K, in particular $\Delta T_{sub} = 1.0\text{K}$, the bubbles grew in the gap up to the size attaching the wall.

(d) Generally behavior of bubbles in each of the two gaps was similar to that observed in the gap in Single wall configuration with 3mm-gap distance. However, slightly more bubbles seemed to be generated at the surface of the heater rod in the direction parallel to the walls without a wall than in Single wall configuration with 3mm-gap.
Figure 3.2.3.1-1 Behavior of bubbles around heater rod with 3mm-gap (Parallel walls) (1/2)

(1) $\Delta T_{sub} = 1.0$K

(2) $\Delta T_{sub} = 2.0$K

(3) $\Delta T_{sub} = 3.0$K

(4) $\Delta T_{sub} = 4.0$K

(5) $\Delta T_{sub} = 5.0$K

(6) $\Delta T_{sub} = 6.0$K
Figure 3.2.3.1-1 Behavior of bubbles around heater rod with 3mm-gap (Parallel walls) (2/2)
(2) Acceleration trend of the heater rod vibration

Figure 3.2.3.1-2 (1) to (4) show the measured acceleration trends in the X- and Y-directions under the condition from $\Delta T_{sub} = 6.0$K to 8.0K. The acceleration RMS value of the heater rod vibration in the Y-direction, which is perpendicular to the wall, was 23% larger than that in X-direction under the condition of $\Delta T_{sub} = 6.0$K, and 31% larger under the condition of 8.0K. It was observed that fluctuation of acceleration in Y-direction seemed to slightly larger than that in X-direction, and quite small change of acceleration with a period of approximately 20msec was found in Y-direction under $\Delta T_{sub} = 6.0$K to 8.0K.
Figure 3.2.3.1-2 (1) Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{ab} = 6.0K$)
Figure 3.2.3.1-2 (2) Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{sub} = 7.0$K)
Figure 3.2.3.1-2 (3) Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{sub} = 7.5K$)
Figure 3.2.3.1-2 (4) Acceleration of heater rod (Parallel walls, 3mm-gap, $\Delta T_{sub} = 8.0K$)
(3) Acceleration of the heater rod in X-Y plane

The acceleration of the heater rod in X-Y plane under the condition from $\Delta T_{sub} = 6.0\,\text{K}$ to $8.0\,\text{K}$ is shown in Figure 3.2.3.1-3 (1) to (4). From these figures, it is obvious that the SBIV of the heater rod was somehow influenced by the existence of the wall because acceleration of the vibration in Y-direction towards the wall was larger than that in X-direction. Encouraged acceleration in Y-direction due to the walls was obvious.
Figure 3.2.3.1-3 (1) Acceleration of heater rod in the X-Y plane

(Parallel walls, 3mm-gap, $\Delta T_{sub} = 6.0K$)
Figure 3.2.3.1-3 (2) Acceleration of heater rod in the X-Y plane
(Parallel walls, 3mm-gap, $\Delta T_{sub} = 7.0K$)
Figure 3.2.3.1-3 (3) Acceleration of heater rod in the X-Y plane

(Parallel walls, 3mm-gap, ΔT_{sub} = 7.5K)
Figure 3.2.3.1-3 (4) Acceleration of heater rod in the X-Y plane

(Parallel walls, 3mm-gap, ΔT_{sub} = 8.0K)
3.2.3.2 Case of 1mm-gap distance to wall

(1) Behavior of bubbles around the heater rod

Figure 3.2.3.2-1 (1) to (6) show behavior of generated bubbles observed from the X-direction axially along the heater rod in the range of degree of subcooling from $\Delta T_{sub} = 1.0\text{K}$ to $8.0\text{K}$.

As observations of such bubbles, the following can be pointed;

(1) For all the range of $\Delta T_{sub}$ from 1.0K to 8.0K, bubbles in each of the gaps grew up to significantly larger in an ellipsoidal shape to reach the facing wall. Under $\Delta T_{sub} = 1.0\text{K}$, the longer diameter of such bubbles beyond a size of 10mm. These are the same as behavior of bubbles in the gap in the case of Single wall configuration. No difference was observed in each gap with the walls in this Parallel walls configuration.

(2) Ellipsoidal bubbles, largely grown in each of the gaps, slid on the surface of the rod to X-direction, to open region without a wall, and departed up from the rod or coalesced together before the departure. Coalesced large bubbles sometimes partly wrapped the surface of the heater rod, which was found under the condition of $\Delta T_{sub} = 1.0\text{K}$.

(3) Such ellipsoidal bubbles from each of the gaps and interfered bubbles were fluctuated and condensed due to fresh subcooled water in the open region without a wall, as clarified in Figure 3.2.3.2-1 (1), (3) and (4).

(4) In spite of such large size of bubbles, very few small bubbles were generated on the surface of the heater rod in X-direction.
Figure 3.2.3.2-1 Behavior of bubbles around heater rod with 1mm-gap (Parallel walls)
(2) Acceleration trend of the heater rod vibration

Figure 3.2.3.2-2(1) to (7) show the measured acceleration in X- and Y-directions under the conditions from $\Delta T_{\text{sub}} = 1.0\text{K}$ to $8.0\text{K}$. The acceleration RMS value of the rod vibration in Y-direction perpendicular to the wall was 8% larger than that in X-direction under the condition of $\Delta T_{\text{sub}}=1.0\text{K}$, and 11% increase under the condition of $\Delta T_{\text{sub}}=6.0\text{K}$.

Swell of acceleration in a cycle of 10 to 20msec was found in both X- and Y-directions, which was obvious under degree of subcooling less than $\Delta T_{\text{sub}}=6.0\text{K}$. In addition, fluctuation with an amplitude close to $10\text{m/s}^2$ or more from time to time was remarkable also both in X- and Y-direction. This swell rarely presented in the case of Single wall configuration and therefore, these reflected the phenomena of interfered large bubbles under subcooled boiling caused by the difference of constraints between Single wall configuration and Parallel walls configuration.
Figure 3.2.3.2-2 (1) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 3.2.3.2-2 (2) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 3.0K$)
Figure 3.2.3.2-2 (3) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{\text{sub}} = 4.0\text{K}$)
Figure 3.2.3.2-2 (4) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{sub} = 5.0$K)
Figure 3.2.3.2-2 (5) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{\text{sub}} = 6.0K$)
Figure 3.2.3.2-2 (6) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{\text{sub}} = 7.0\text{K}$)
Figure 3.2.3-2 (7) Acceleration of heater rod (Parallel walls, 1mm-gap, $\Delta T_{\text{sub}} = 8.0K$)
(3) Acceleration of the heater rod in X-Y plane

The acceleration of the heater rod in X-Y plane under the condition from $\Delta T_{sub} = 1.0K$ to 8.0K is shown in Figure 3.2.3.2-3 (1) to (7). Under the conditions of $\Delta T_{sub} = 6.0K$ and 8.0K, in Figure 3.2.3.2-3 (5) and (7), acceleration in Y-direction increased but not so obviously, though increased acceleration in Y-direction due to existence of the wall was obvious in the case with 3mm-gap distance.

Under the conditions of $\Delta T_{sub} = 1.0K$ and 4.0K, in Figure 3.2.3.2-3 (1) and (3), protuberant changes of the measured acceleration were found in X-direction and slightly larger in Y-direction. This trend of the acceleration can be well understood in small figures for every 125 msec in Figure 3.2.3.2-3 (1) to (3), which was also observed in the case of Single wall configuration with 1mm-gap distance but rather large than in the case of Parallel walls configuration. It is remarkable that protuberant changes of acceleration sometimes worked in a specific horizontal direction in a very short period and there was a period without such changes of acceleration.

82
Figure 3.2.3.2-3 (1) Acceleration of heater rod in the X-Y plane

(Parallel walls, 1mm-gap, $\Delta T_{\text{sub}} = 1.0K$)
Figure 3.2.3.2-3 (2) Acceleration of heater rod in the X-Y plane

(Parallel walls, 1mm-gap, ΔT_{sub} = 3.0K)
Figure 3.2.3.2-3 (3) Acceleration of heater rod in the X-Y plane

(Parallel walls, 1mm-gap, $\Delta T_{\text{sub}}$ = 4.0K)
Figure 3.2.3.2-3 (4) Acceleration of heater rod in the X-Y plane

(Parallel walls, 1mm-gap, $\Delta T_{sub} = 5.0K$)
Figure 3.2.3.2-3 (5) Acceleration of heater rod in the X-Y plane

(Parallel walls, 1mm-gap, $\Delta T_{sub} = 6.0K$)
Figure 3.2.3.2-3 (6) Acceleration of heater rod in the X-Y plane
(Parallel walls, 1mm-gap, $\Delta T_{\text{sub}} = 7.0\text{K}$)
Figure 3.2.3-3 (7) Acceleration of heater rod in the X-Y plane

(Parallel walls, 1mm-gap, \( \Delta T_{\text{sub}} = 8.0K \))
3.2.4 Corner walls configuration

For Corner walls configuration, the data set shown in Table 3.2.4-1 was obtained in the experiments.

Table 3.2.4-1 List of data obtained in SBIV experiments of Corner walls configuration

<table>
<thead>
<tr>
<th>Type of wall configuration</th>
<th>Gap to wall [mm]</th>
<th>Superheat at rod surface [K]</th>
<th>Subcooling in bulk water [K]</th>
<th>Bubble behavior</th>
<th>Acceleration at rod bottom</th>
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<td>Corner walls</td>
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3.2.4.1 Case of 3mm-gap distance to wall

(1) Behavior of bubbles around the heater rod

Figure 3.2.4.1-1 (1) to (3) show behavior of generated bubbles observed from the X-direction axially along the heater rod in the range of degree of subcooling from $\Delta T_{sub} = 6.0$K to $8.0$K. The following behavior of such bubbles was generally remarkable;

(a) Regardless of degree of subcooling, vapor bubbles generated in the gap between the heater rod and the wall rose upward in the gap. Behavior of bubbles did not seem to be significantly different between that in the gap and in the opposite side of the heater rod without the wall, which was very similar to that in the case of Single wall configuration.
Figure 3.2.4.1-1 Behavior of bubbles around heater rod with 3mm-gap (Corner walls)

(1) $\Delta T_{sub} = 6.0$K

(2) $\Delta T_{sub} = 7.0$K

(3) $\Delta T_{sub} = 8.0$K
(2) Acceleration trend of the heater rod vibration

Figure 3.2.4.1-2 (1) to (4) show the measured acceleration trends in the X- and Y-directions under the condition of $\Delta T_{\text{sub}} = 6.0\text{K}$ to $8.0\text{K}$. The acceleration RMS value of the rod vibration in Y-direction perpendicular to the wall was 26% larger than that in X-direction under the condition of $\Delta T_{\text{sub}} = 6.0\text{K}$, and 21% increase under the condition of $\Delta T_{\text{sub}} = 6.1\text{K}$. Considering the configuration of the two walls around the heater rod, RMS values in X- and Y-directions should be comparable. This point is a little strange but assumed to be caused by inhomogeneous distribution of sites for evaporation at the surface of the heater rod, because SBIV of the heater rod under such degree of subcooling in the gap of 3mm was governed by wakes due to small bubble generation and local pressure perturbation due to condensation of such small bubbles. Acceleration with time both in X- and Y-directions was also very similar to that in the case of Single wall configuration with 3mm-gap distance in the same range of degree of subcooling $\Delta T_{\text{sub}} = 6.0\text{K}$ to $8.0\text{K}$. 
Figure 3.2.4-1-2 (1) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{\text{sub}} = 6.0K$)
Figure 3.2.4.1-2 (2) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{sub} = 7.0K$)
Figure 3.2.4.1-2 (3) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{sub} = 7.5K$)
Figure 3.2.4.1-2 (4) Acceleration of heater rod (Corner walls, 3mm-gap, $\Delta T_{\text{sub}} = 8.0K$)
(3) Acceleration of the heater rod in X-Y plane

The acceleration of the heater rod in X-Y plane under the condition of $\Delta T_{sub} = 6.0K$ to $8.0K$ is shown in Figure 3.2.4.1-3 (1) to (4). Trends of acceleration found in these figures correspond to the trends of acceleration with time in X- and Y- directions, which means slightly increased acceleration in Y-direction. Acceleration in this case of Corner walls configuration seemed slight larger than that in the case of Single wall configuration in comparison under the same conditions of degree of subcooling and the same gap distance, 3mm.
Figure 3.2.4.1-3 (1) Acceleration of heater rod in the X-Y plane
(Corner walls, 3mm-gap, $\Delta T_{sub} = 6.0$K)
Figure 3.2.4.1-3 (2) Acceleration of heater rod in the X-Y plane

(Corner walls, 3mm-gap, $\Delta T_{sub} = 7.0K$)
**Figure 3.2.1-3 (3)** Acceleration of heater rod in the X-Y plane

(Corner walls, 3mm-gap, $\Delta T_{sub} = 7.5K$)
Figure 3.2.4.1-3 (4) Acceleration of heater rod in the X-Y plane

(Corner walls, 3mm-gap, $\Delta T_{\text{sub}} = 8.0K$)
3.2.4.2 Case of 1mm-gap distance to wall

(1) Behavior of bubbles around the heater rod

Figure 3.2.4.2-1 (1) to (6) show behavior of generated bubbles observed from the X-direction axially along the heater rod in the range of degree of subcooling from $\Delta T_{\text{sub}} = 1.0$K to 7.0K. The following behavior of such bubbles was generally remarkable;

(a) Large, ellipsoidal bubbles of vapor grew up to the size more than 10mm in each of the gaps with the walls, which is similar to the case of Single wall configuration, and such large bubbles moved out from each of the gaps, turning around the heater rod to the open region without a wall, which is similar to the case of Parallel walls configuration. The apparent difference from the case of Parallel walls configuration was that the open region without influences by the walls existed enough in the direction against the corner formed by the two walls in the case of Corner walls configuration, while such open region was limited between the two walls in the case of Parallel walls configuration. Therefore, large bubbles from each of the gaps in the case of Corner walls configuration were well fluctuated or condensed by fresh subcooled water in the direction against the corner, not interfering or coalescing each other so often.

(b) In addition, relatively small bubbles repeated their generation and condensation at the surface of the heater rod around the same direction, though very few small bubbles were found in the case of Parallel walls configuration.
Figure 3.2.4.2-1 Behavior of bubbles around heater rod with 1mm-gap (Corner walls)
(2) Acceleration trend of the heater rod vibration

Figure 3.2.4.2-2 (1) to (4) show the measured acceleration trends in the X- and Y-directions under the conditions of $\Delta T_{sub} = 1.0 \text{K}$ to $5.0 \text{K}$. The acceleration RMS values of the rod vibration in the X- and Y-directions were comparable, whose differences were just 3% under the condition of $\Delta T_{sub} = 1.0 \text{K}$ and 1% under the condition of $\Delta T_{sub} = 4.0 \text{K}$. This makes sense in the aspect of the configuration of the walls, which formed the same constraint to the heater rod both in the X- and Y-direction.

Swell of acceleration in a cycle of 10 to 20msec was found in both X- and Y-directions as similar to the case of Parallel walls configuration. Under degrees of subcooling $\Delta T_{sub} = 1.0 \text{K}$ and $4.0 \text{K}$, fluctuation with an amplitude more than $10 \text{m/s}^2$ was found from time to time. This is also similar to the case of Parallel walls configuration, but Figure 3.2.4.2-2 (1) to (3) show more frequent occurrence of such fluctuation than in the case of Parallel walls configuration.
Figure 3.2.4-2 (1) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 3.2.4-2 (2) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 3.0$K)
Figure 3.2.4.2-2 (3) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 4.0\,\text{K}$)
Figure 3.2.4-2 (4) Acceleration of heater rod (Corner walls, 1mm-gap, $\Delta T_{sub} = 5.0K$)
(3) **Acceleration of the heater rod in X-Y plane**

The acceleration of the heater rod in X-Y plane under the condition from $\Delta T_{\text{sub}} = 1.0\text{K}$ to $5.0\text{K}$ is shown in Figure 3.2.4.2-3 (1) to (4).

Under the conditions of $\Delta T_{\text{sub}} = 4.0\text{K}$ and $1.0\text{K}$, the acceleration was oriented in the direction towards the corner and its opposite side, and protuberant changes of the measured acceleration were large and significantly found in the same direction. This trend corresponds to the behavior of large bubbles observed in Figure 3.2.4.2-1 (1) to (6). The open region in the opposite side of the corner supplied enough subcooled water to large bubbles to make them fluctuated and condensed, which in turn provided local pressure change onto the heater rod to vibrate it in the direction towards the corner and its opposite side.

Small figures for every 125msec in Figure 3.2.4.2-3 (1) to (4) clarify that there were periods without such protuberant changes of the acceleration, which suggests temporary situation without enough subcooled water around large bubbles to condense them leading to SBIV with such protuberant changes of the acceleration.
Figure 3.2.4.2-3 (1) Acceleration of heater rod in the X-Y plane

(Corner walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)
Figure 3.2.4.2-3 (2) Acceleration of heater rod in the X-Y plane

(Corner walls, 1mm-gap, $\Delta T_{\text{sub}} = 3.0K$)
Figure 3.2.4.2-3 (3) Acceleration of heater rod in the X-Y plane

(Corner walls, 1mm-gap, $\Delta T_{sub} = 4.0K$)
Figure 3.2.4.2-3 (4) Acceleration of heater rod in the X-Y plane

(Corner walls, 1mm-gap, $\Delta T_{sub} = 5.0K$)
4. DISCUSSION

4.1 Encouraged Acceleration due to Existence of a Wall (Exp.1)

Exp.1 aimed to clarify influence of a wall in the vicinity of a heater rod on the SBIV of the heater rod. In fact, RMS values of acceleration showed the larger value in the direction perpendicular to the wall, as shown in Figure 3.1.2-6. Such a wall in the vicinity of the heater rod brings;

(1) Increase of temperature in the gap between the surface of the heater rod and the wall, and

(2) Limited mass working for vibration of the heater rod in the direction perpendicular to the wall.

The gap distance provided in the Exp.1 was 5mm, which was larger than the maximum size of vapor bubbles grown in the gap as observed. Considering this relation of dimensions, the influence of the above (2) can be ignored in this case. On the other hand, the above (1) was probably effective to encourage generation of larger bubbles than in the No wall case. Observation on vapor bubbles by the high speed digital video camera evidenced this phenomenon.

Komuro et al. [55][56] showed that the SBIV of a single heater rod was dominant to the vibration on the heating surface with higher thermal flux, to which the encouraged acceleration in the direction perpendicular to the wall in the Exp.1 is corresponding.

The Power Spectrum Densities (PSD) of acceleration signals processed by FFT of No wall case and With wall case are shown in Figure 4.1-1 (1) and (2). The PSD data of both No wall case and With wall case were similar. The peak of acceleration around 600 Hz corresponds to the acceleration in natural frequency. Under high superheat and low degree of subcooling, the
acceleration was increased in the region of up to 4000 Hz, which was affected by the subcooled boiling and the behavior of generated bubbles. In addition, significant two peaks of PSD in the region of around 2000Hz and 3000Hz, which were also influenced by the boiling and bubble behavior such as bubble generation, departure or condensation.

This agrees with the examinations conducted by Komuro et al. [55][56]. The two peaks under the low superheat 1.6K and high degree of subcooling 46.3K were found only in With wall case but this thermal condition in With wall case is enough to enhance the local boiling, compared with the thermal condition in No wall case, which were the superheat -6.9K and the degree of subcooling 42.4K. These PSD data did not show the significant differences between in No wall case and With wall case, but PSD data around 2000Hz to 3000Hz were slightly larger in With wall case. PDS of acceleration also indicated slight increase in the With wall case, particularly in the higher frequency region more than 1000Hz, which can be found in Figure 4.1-1.

Figure 4.1-1 (1) PSD of acceleration under Subcool: 8K, Superheat: 17K (Exp.1)

Figure 4.1-1 (2) PSD of acceleration under Subcool: 10K, Superheat: 16K (Exp.1)
In order to clarify the dependency of the acceleration on thermal conditions, the RMS values of acceleration are arranged with the superheat of the heater rod surface and degree of subcooling shown in Figure 4.1-2 (1) and (2), respectively.

As a general explanation, the acceleration of the heater rod vibration linearly increases with increase of degree of the superheat, as shown in Figure 4.1-2 (1). On the other hand, as confirmed in Figure 4.1-2 (2), the trend of the acceleration shows saturation with decrease of the degree of subcooling in the region of lower degree of subcooling. These trends could be explained as the different roles of degree of the superheat and subcooling to the bubble behavior affecting on the heater rod vibration. The superheat of the heater rod surface is considered to be the factor of dominating frequency of the vapor bubble generation, which could directly induce the rod vibration by wakes in the bubble generation. As for the degree of subcooling, it relates to movement, fluctuation, departure from the heater rod surface and condensation of bubbles. Under the higher degree of subcooling, a bubble grew at the evaporation site and was soon condensed due to the less buoyancy and high subcooling. When the degree of subcooling was not so high, the bubble could have time to grow and start sliding up on the surface and leaving to the bulk water. This trend became more significant as degree of subcooling was getting lower, where bubble size could be a few millimeters in diameter. This change of bubble behavior following the decrease of the degree of subcooling indicated the trend of acceleration versus the degree of subcooling shown in Figure 4.1-2 (2).

Confirmed in Figure 4.1-2 (2), the acceleration measured in With wall case was larger than that in No wall case in the direction perpendicular to the wall, which could be explained as the mechanism of encouraged acceleration of the SBIV towards the wall due to fluctuation or condensation of bubbles growing in the gap between the wall and the surface of the heater rod where thicker superheated microlayer was formed by the wall and it made bubbles grown larger.
(1) Dependency on degree of superheat

(2) Dependency on degree of subcooling

Figure 4.1-2 RMS of acceleration (Exp.1)
4.2 Behavior of vapor bubbles (Exp.2)

In the aspect of SBIV, condensation of bubbles and behavior of large bubbles to ingenerate local convection of subcooled water were investigated.

4.2.1 Case of 3mm-gap distance to wall

For all the three types of structural constraints, vapor bubbles generated in the 3mm-gap grew at their original sites on the surface of the heater rod or straightly rose up, and condensed regardless of degree of subcooling from $\Delta T_{\text{sub}} = 1$K to 8K. Maximum size of bubbles increased as decrease of degree of subcooling, but they condensed before reaching the same size as the gap distance, 3mm. Using captured pictures of video records, roughly-estimated rise velocity of bubbles were 0.3m/s for all the three types of structural constraints as typically shown in Figure 4.2.1-1, which is agreeable to the velocity calculated with force balance between buoyancy and drag force of an identically spherical vapor bubble. The size of bubbles was less than the gap distance between the heater rod and the wall. Such bubbles growing in the gap detached from the surface of the heater rod and rose straight without moving horizontally. In this case, SBIV of the heater rod occurred by wake due to bubble generation and pressure fluctuation in condensation. Bubbles rising up induced swirl of subcooling water locally.

![Figure 4.2.1-1 Rise velocity of a bubble (Single wall, 3mm-gap, $\Delta T_{\text{sub}} = 1.0$K)](image_url)
4.2.2 Case of 1mm-gap distance to wall

Figure 4.2.2-1 (1) to (3) show behavior of generated vapor bubbles axially along the heater rod during 64msec, under $\Delta T_{sub} = 6$K for the three cases of the structural constraints, respectively. Bubbles generated in the gap between each of the walls and the heater rod sometimes grew ellipsoidally up to around 10mm and seemed to slide slightly turning around the rod to the open region, the direction without the wall, which can be commonly explained for all the three cases. Such large bubbles were condensed on the way to leave from the surface of the heater rod, not coalescing with another large bubble. In the process of large bubble condensation, excitation force worked on the heater rod in X-direction. The nucleation sites for such bubbles to grow large on the surface of the heater rod seemed to be limited.

Single wall configuration:

In addition to the above-mentioned behavior of large bubbles, generation and condensation of small bubbles (up to 1 ~ 2mm) in a short cycle were observed on the surface of the heater rod, in particular in the open region.

Parallel walls configuration:

The above-mentioned behavior of large bubbles was observed in each gap with the two walls. These large bubbles from each gap sometimes came close, interfered together, but not coalesced. They were fluctuated and condensed by subcooled water near the surface of the rod in the open space in X-direction. Generation and condensation of small bubbles in a short cycle, which was seen in the case of Single wall, were rarely observed.

Corner walls configuration:

The above-mentioned behavior of large bubbles was observed in each gap with the two walls, while behavior of bubbles in the corner could not be observed. These large bubbles from each gap slid slightly turning around the rod to the open region.
respectively, and were fluctuated and condensed. In this case, generation and condensation of small bubbles in a short cycle were observed.

(1) Single wall configuration

(2) Parallel walls configuration

(3) Corner walls configuration

Figure 4.2.2-1 Vapor bubbles around the heater rod (1mm-gap, $\Delta T_{sub} = 6K$)
Figure 4.2-2 (1) to (3) show behavior of generated vapor bubbles axially along the heater rod during 64msec, under $\Delta T_{sub} = 1$K for the three cases of the structural constrains, respectively. Under $\Delta T_{sub} = 1$K, growth of bubbles was larger than under $\Delta T_{sub} = 6$K. The nucleation sites for such bubbles to grow large on the surface of the heater rod seemed to be limited also under $\Delta T_{sub} = 1$K.

Single wall configuration:
Generation and condensation of relatively small bubbles (up to around 5mm) were often observed on the surface of the heater rod, in particular in the open space without the wall. Large bubbles grown in the gap showed behavior similar to that under $\Delta T_{sub} = 6$K, but sometimes merged with small bubbles near the surface of the heater rod in the open region.

Parallel walls configuration:
The size of large bubbles grown in each gap sometimes reached around 15mm as an ellipsoid. Interfacial surface of these large bubbles was seen smooth. Such larger-grown bubbles from each gap often coalesced in the open space in X-direction to become further large, as if to wrap partly the rod surface. Generation and condensation of small bubbles in a short cycle were very few.

Corner walls configuration:
Generation and condensation of relatively small bubbles were observed on the surface of the heater rod, which seemed to be limited in the opposite direction to the wall corner. Bubbles in the gap grew largely more than 10mm size as an ellipsoid, and seemed to move or deform themselves towards the opposite direction to the wall corner, as if to wrap partly the rod surface, sometimes coalescing with other bubbles. Such large bubbles were quite fluctuated by subcooled water in the open region opposite to the corner.
Figure 4.2.2-2 Vapor bubbles around the heater rod (1mm-gap, $\Delta T_{sub} = 1K$)
As confirmed in Figure 4.2.2-1 and Figure 4.2.2-2, behavior of bubbles was significantly different between the cases of 3mm-gap distance and 1mm-gap distance. In Exp.2, heat flux at the surface of the heater rod was kept constant for all the measurement, and therefore the differences of bubble behavior between the two cases of the gap distance came from amount of subcooled water to contribute to removal of heat and thermal-hydraulic situation made by the bubble behavior itself. For the case of 3mm-gap distance, it can be considered that superheated microlayer at the surface of the heater rod was maintained slightly thicker in the gap than in the open region without a wall, but water in the gap was still enough to assist lift-off or condensation of the bubbles in the gap. In the case of 1mm-gap distance, further thicker microlayer was formed at the surface of the heater rod in the gap, which led to growth of larger bubbles. The 1mm-gap was too narrow to keep steady stream straightforward to the upper region, because growth of large bubbles prevented it. Therefore, large bubbles seemed to turn from the gap to the open region, from Y-direction to X-direction in Figure 4.2.2-2. This behavior of large bubbles could induce local cross flow into and from the gap and ingenerate swirl of subcooling water. This local natural convection of subcooling water contributed to condensation of such large bubbles and movement of large bubbles, leading to SBIV of the heater rod. In the case of 1mm-gap distance, it is considered that this tendency would be more significant under lower degree of subcooling, when larger bubbles grew in the gap.

In the case of Parallel walls, generation of small bubbles were rarely observed both under the condition of $\Delta T_{sub} = 1.0K$ and 6.0K. The area of the rod surface far from the edge of the walls was less in this case and it is considered that the heat removal from the rod surface was limited by growth of large bubbles. In the other cases of the structural constraints, there was the surface area without influences by walls; the opposite side from the wall in the case of Single wall configuration and the opposite side from the corner in the case of Corner walls configuration. Therefore, heat removal by small bubble generation and condensation by subcooled water occurred more in the cases of Single wall configuration and Corner walls configuration. In the aspect of the same heat removal from the heater rod by evaporation considered, almost no
generation of small bubbles in the case of Parallel walls configuration is agreeable to more large bubble growth in the same case.

In the cases of Parallel walls configuration and Corner walls configuration under the condition of \( \Delta T_{\text{sub}} = 1 \text{K} \), larger bubbles (J, K in Figure 4.2.2-2) seemed not easily to detach from the surface of the heater rod but to behave as if they partly wrapped the rod surface. This behavior is considered as a result due to heat removal only by larger bubbles in the region surrounded with hot water very close to saturation influenced by walls, where no small bubble generation occurred. In addition, these bubbles were finally quite fluctuated, which is obvious in the figure. This behavior evidently provided strong acceleration of vibration on the heater rod as SBIV.
4.3 Thermal conditions for growth of large bubbles

According to Mikic et al. [30], for a bubble growth in a uniformly superheated liquid, the radius of the bubble both for inertia controlled and diffusion controlled growth can be expressed as the non-dimensional radius in the form of Equation (2), in the case for a spherical bubble growing attached to a surface:

\[ r^* = \frac{2}{3} \left[ (r^* + 1)^{3/2} - (r^*)^{3/2} - 1 \right], \]  

(2)

where

\[ r^* = \frac{r(t)A}{B^2}, \quad t^* = \frac{tA^2}{B^2}, \]

\[ A = \left( \frac{\pi \Delta T h_{LV} \rho_v}{7 \rho_L T_{sat}} \right)^{1/2}, \quad B = \left( \frac{12}{\pi} \alpha_L \right)^{1/2} \cdot Ja, \]

\[ Ja = \frac{\Delta T \rho_L C_{pl}}{\rho_v h_{LV}}. \]

The typical shape of large bubbles observed in the gap between the heater rod and each of the walls in Exp.2 was a vertical ellipsoid, and this was assumed to be a disk. Here, a radius was calculated as a spherical bubble with the same volume as such a disk-like bubble, and temperature difference \( \Delta T \), which means temperature increase around the bubble from the saturated temperature, was estimated for each of the selected large bubbles growing in the gap shown in Figure 4.2.2-1 and Figure 4.2.2-2. Assuming applicability of Equation (2) to such large bubbles in the gap, estimation of temperature is summarized in Table 4.3-1.

For all the cases of the structural constraints by walls, in spite of \( \Delta T_{sub} = 1K \) or 6K, estimated temperature around the selected bubbles growing largely in the gap is 3 to 5K higher than the saturated temperature. This is rough estimation, but suggests that the 1mm-gap distance between the heater rod and each of the walls in the range of degree of subcooling from \( \Delta T_{sub} \)
=1K to 6K in Exp.2 provided thermal conditions enough to maintain superheated microlayer at the surface of the heater rod to urge bubbles grown such larger by supply of heat.

Table 4.3-1 Estimated temperature around selected large bubbles

<table>
<thead>
<tr>
<th>Figure / Case</th>
<th>$\Delta T_{sub}$ [K]</th>
<th>Bubble ID</th>
<th>Time to grow in the gap [msec]</th>
<th>Thickness of disk-like bubble [mm]</th>
<th>Max. diam. of disk-like bubble [mm]</th>
<th>Estimated temp. $\Delta T+100$ [deg-C]</th>
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<td>64</td>
<td>1</td>
<td>10.3</td>
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<td>80</td>
<td>1</td>
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<td>104</td>
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<td>1</td>
<td>8.3</td>
<td>103</td>
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<td>88</td>
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</table>
4.4 Velocity of large bubbles

In this section, relation between thermal balance for large bubbles and their velocity is investigated.

4.4.1 Case of 3mm-gap distance to wall

In this case, bubbles generated in the gap between the heater rod and a wall reached the maximum size approximately 3mm in diameter under lower degree of subcooling, and seemed to rise up straight in the gap without interference to a wall. Their vertical velocity was around 0.3m/s, which is agreeable with calculation in balance between buoyancy, gravity and drag force, as well as the experimental data in Figure 4.4.1-1, arranged by Ivey [32].

**Figure 4.4.1-1** Relation between vertical velocity and vapor bubble diameter [32]
4.4.2 Case of 1mm-gap distance to wall

In the case of $\delta_w = 1\text{mm}$, vertical-disk-shaped bubbles in 10mm size were generated in the gap with each walls, as shown in Figure 4.2.2-1 and Figure 4.2.2-2, for all the cases of structural constraints both under $\Delta T_{\text{sub}} = 1\text{K}$ and $6\text{K}$. Such bubbles moved out from the gap to the open region without walls, which is illustrated from a side view and a top view in Figure 4.4.2-1.

![Diagram showing movement of a large bubble from the gap with a wall](image)

**Figure 4.4.2-1** Movement of a large bubble from the gap with a wall

Table 4.4.2-1 shows horizontal velocities of such large bubbles typically observed in Figure 4.2.2-1 and Figure 4.2.2-2, which are roughly estimated from displacement of the horizontal edge of each bubble. Horizontal velocities range with the average value of 0.1m/s, though displacement of bubbles along the arc of the rod surface cannot be correctly read from the figures. Any correlation of the horizontal velocities to bubble sizes is not clearly confirmed. Any specific trend depending on degree of subcooling or structural constraints is not obvious, either.
Table 4.4.2-2 shows vertical velocities of the same large bubbles as for horizontal velocities in Figure 4.2.2-1 and Figure 4.2.2-2. Vertical velocities are roughly estimated from the displacement of the center of each bubble. Under the condition of $\Delta T_{sub} = 6K$, all the selected large bubbles (Bubble ID: A to F) moved upward at the constant speed in the range from 0.21 to 0.25m/s, regardless of the structural constraints by walls. Under the condition of $\Delta T_{sub} = 1K$, the selected large bubbles generated in the gap at a lower position of the heater rod (H, J, K) presented different trends of behavior, respectively. In the case of Single wall configuration, the bubble (H) moved upward at the constant speed similar to the bubbles under the condition of $\Delta T_{sub} = 6K$ (A to F). In the case of Parallel walls configuration, the bubble (J) grew larger in the process of turning around the heater rod to the open region, which was reflected to the increase of the rise velocity of the bubble from 0.24m/s to 0.46m/s. The bubble in the case of Corner walls configuration (K, L) grew larger than 10mm size in the gap between the wall and the heater rod, and moved upward turning around the rod with its size kept. This was reflected to the higher constant velocity, 0.31m/s and 0.43m/s. On the other hand, the selected large bubbles generated at a higher position of the heater rod (G, I) showed higher velocities; 0.31 and 0.36m/s. This can be explained as an influence due to motions of other bubbles beneath the bubbles (G, I).
Table 4.4.2-1 Horizontal velocities of selected large bubbles

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<th>Figure / Case</th>
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<th>16 $\rightarrow$ 32 [ms]</th>
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<td>-</td>
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Table 4.4.2-2 Vertical velocities of selected large bubbles

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<thead>
<tr>
<th>Figure / Case</th>
<th>$\Delta T_{sub}$ [K]</th>
<th>Bubble ID</th>
<th>0 $\rightarrow$ 16 [ms]</th>
<th>16 $\rightarrow$ 32 [ms]</th>
<th>32 $\rightarrow$ 48 [ms]</th>
<th>48 $\rightarrow$ 64 [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 4.2.2-1 (a) / Single wall</td>
<td>6.1</td>
<td>A</td>
<td>0.21</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-1 (b) / Parallel walls</td>
<td>6.0</td>
<td>B</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-1 (c) / Corner walls</td>
<td>6.0</td>
<td>C</td>
<td>0.21</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-2 (a) / Single wall</td>
<td>1.0</td>
<td>D</td>
<td>-</td>
<td>-</td>
<td>0.21</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-2 (b) / Parallel walls</td>
<td>1.0</td>
<td>E</td>
<td>-</td>
<td>0.21</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-2 (c) / Corner walls</td>
<td>1.0</td>
<td>F</td>
<td>-</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-2 (b) / Parallel walls</td>
<td>1.0</td>
<td>G</td>
<td>0.31</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-2 (c) / Corner walls</td>
<td>1.0</td>
<td>H</td>
<td>0.24</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-2 (b) / Parallel walls</td>
<td>1.0</td>
<td>I</td>
<td>0.36</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Figure 4.2.2-2 (c) / Corner walls</td>
<td>1.0</td>
<td>J</td>
<td>0.24</td>
<td>0.32</td>
<td>0.46</td>
<td>-</td>
</tr>
</tbody>
</table>
As for these obtained velocities in the horizontal and vertical directions, dynamics of such bubbles is explained with equations. Heat is supplied from the heater rod to a bubble as volume increase of vapor in the bubble through the effective area $S_{ht}$ of the microlayer on the surface of the heater rod, as expressed in Equation (3):

$$q'_{sup} = qS_{ht} = h_{LV} \rho_v \Delta V_B.$$  \hspace{1cm} (3)

The horizontal velocity of a large bubble can be expressed as Equation (4), in assumption that all amount of vapor generated by supplied heat per unit time from the microlayer into the bubble is used to volume increase of the bubble in the horizontal direction of the bubble movement with compensation to volume decrease in the opposite direction due to condensation by subcooled water:

$$v_B = \frac{\Delta V_B}{\pi \cdot \frac{D_B}{2} \cdot \frac{H_B}{2}} = \frac{4}{\pi} \cdot \frac{qS_{ht}}{D_B H_B \rho_v h_{LV}}.$$  \hspace{1cm} (4)

Here, the longitudinal cross-section of the bubble is assumed as an ellipse formed of $D_B$ and $H_B$ in Figure 4.4.2-1. Heat is supplied to the large bubble through the effective area $S_{ht}$ of the microlayer, which is the area connecting the bubble with the heater rod. Assuming that a force downward $F_S$ works on the bubble due to the area $S_{ht}$, balance of forces in the vertical direction working on the bubble consists of its buoyancy, gravity, drag force and the force $F_S$, as presented by the following Equation (5):

$$\rho_L g V_B = \rho_v g V_B + C_D \left( \frac{\pi \cdot \frac{D_B}{2} \cdot \frac{H_B}{2}}{2} \right) \frac{\rho_v v^2}{2} + F_S.$$  \hspace{1cm} (5)

The horizontal cross-section of the bubble is assumed to be the same as the longitudinal cross-section, an ellipse formed of $D_B$ and $H_B$. In addition, no interaction between bubbles and a wall is considered. With reference to Cornwell and Schüller [62], $F_S$ can be calculated as a downward vertical component of surface tension of the bubble by the following Equation (6):
\[ F_s = \frac{\pi}{4} \sigma \cdot a \cdot (1 - \cos \theta_a). \]  

This is based on the assumption that the effective area \( S_{ht} \) of the microlayer is a circle with the diameter of \( a \). These Equations (3) to (6) provide the relation between the two components of bubble velocity, in the vertical and the horizontal directions, associated with the effective area of the microlayer for heater transfer from the heater rod and the bubble. Representative values of horizontal velocities \( v_\theta \) and the major axis \( D_B \) of each bubbles are extracted, and for these values, the effective area of the microlayer \( S_{ht} \), the force due to surface tension \( F_s \) and vertical velocity \( v_z \) are estimated using with the equations, which are summarized in Table 4.4.2-3.

**Table 4.4.2-3 Estimated vertical velocities of selected large bubbles**

<table>
<thead>
<tr>
<th>Bubble ID</th>
<th>( \Delta T_{sub} ) [K]</th>
<th>( q ) [kW/m²]</th>
<th>( H_B ) [mm]</th>
<th>( D_B ) [mm]</th>
<th>( v_\theta ) [m/s]</th>
<th>( S_{ht} ) [mm²]</th>
<th>( F_s ) [( \mu )N]</th>
<th>( v_z ) [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.1</td>
<td>92.4</td>
<td>1.0</td>
<td>10.2</td>
<td>0.08</td>
<td>7.7</td>
<td>73.9</td>
<td>0.27</td>
</tr>
<tr>
<td>B</td>
<td>6.0</td>
<td>92.4</td>
<td>1.0</td>
<td>6.3</td>
<td>0.13</td>
<td>7.8</td>
<td>74.1</td>
<td>0.17</td>
</tr>
<tr>
<td>C</td>
<td>6.0</td>
<td>92.4</td>
<td>1.0</td>
<td>11.5</td>
<td>0.12</td>
<td>13.1</td>
<td>96.5</td>
<td>0.29</td>
</tr>
<tr>
<td>D</td>
<td>6.0</td>
<td>92.4</td>
<td>1.0</td>
<td>7.7</td>
<td>0.06</td>
<td>4.4</td>
<td>56.0</td>
<td>0.23</td>
</tr>
<tr>
<td>E</td>
<td>6.0</td>
<td>92.4</td>
<td>1.0</td>
<td>10.9</td>
<td>0.09</td>
<td>9.3</td>
<td>81.3</td>
<td>0.28</td>
</tr>
<tr>
<td>F</td>
<td>6.0</td>
<td>92.4</td>
<td>1.0</td>
<td>7.5</td>
<td>0.04</td>
<td>2.8</td>
<td>44.8</td>
<td>0.23</td>
</tr>
<tr>
<td>G</td>
<td>1.0</td>
<td>92.4</td>
<td>1.0</td>
<td>10.8</td>
<td>0.10</td>
<td>11.4</td>
<td>88.5</td>
<td>0.28</td>
</tr>
<tr>
<td>H</td>
<td>1.0</td>
<td>92.4</td>
<td>1.0</td>
<td>7.1</td>
<td>0.07</td>
<td>5.6</td>
<td>61.8</td>
<td>0.21</td>
</tr>
<tr>
<td>I</td>
<td>1.0</td>
<td>92.4</td>
<td>1.0</td>
<td>9.5</td>
<td>0.02</td>
<td>2.1</td>
<td>38.1</td>
<td>0.27</td>
</tr>
<tr>
<td>J</td>
<td>1.0</td>
<td>92.4</td>
<td>1.0</td>
<td>10.6</td>
<td>0.23</td>
<td>27.1</td>
<td>136.3</td>
<td>0.25</td>
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<tr>
<td>K</td>
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<td>92.4</td>
<td>1.0</td>
<td>15.8</td>
<td>0.15</td>
<td>26.3</td>
<td>134.4</td>
<td>0.35</td>
</tr>
<tr>
<td>L</td>
<td>1.0</td>
<td>92.4</td>
<td>1.0</td>
<td>12.3</td>
<td>0.11</td>
<td>15.0</td>
<td>101.5</td>
<td>0.30</td>
</tr>
</tbody>
</table>

* Representative value based on visual observation

** Estimation using with Equations (3) to (6)

In the process of the estimation, the angle formed between the bottom edge of the bubble and the surface of the heater rod, illustrated in Figure 4.4.2-1, is assumed as the right angle, 90°.
degree. The drag coefficient for a vertical disk $C_D = 1.1$ is used referring to Yoshitome [63], because Reynolds number is calculated as more than 3000 by Equation (7):

$$R_e = \frac{D v_z \rho_L}{\mu_L}.$$  \hspace{1cm} (7)

The estimated vertical velocities $v_z$ are quite close to the measured velocities shown in Table 4.4.2-2, which suggests that the dynamics of bubbles expressed by Equations (3) to (6) is convincing.

The force $F_S$ due to surface tension of such a large bubble is ingenerated by contact of the bubble with the microlayer on the heater rod, which means that such large bubbles still attached to the surface of the heater rod even in the open region moving out from the gap. Fresh subcooled water in the open region was enough to fluctuate and condense such large bubbles, and these phenomena lead to local pressure perturbation directly to vibrate the heater rod, i.e., SBIV of the heater rod.
4.5 Number of generated large bubbles

As observed by the high-speed digital video camera, in Exp.2, large bubbles were generated and showed remarkable behavior, which could influence on the SBIV of the heater rod. For understanding the trend of the large bubble generation, number of large bubbles in size more than 5mm was counted per second on the video records from one side of X-direction for each case of the structural constraints, and summarized in Figure 4.5-1.

Number of such large bubbles in the case of Corner walls configuration was almost the same as that in the case of Single wall configuration over the range of $\Delta T_{sub}$ from 1K to 8K, while significantly more large bubbles were generated in the case of Parallel walls configuration. In the case of Parallel walls configuration, number of large bubbles under $\Delta T_{sub} \geq 6K$ was one-and-a-half times as large as that in the other two cases, and almost double number under $\Delta T_{sub} \leq 4K$ of that in the other cases. This seems to correspond to number of exit from the gaps between the heater rod and each of the walls in the three cases of structural constraints. Looking from one side of X-direction, there was only one exit from the gap to the open region in the cases of Single wall configuration and Corner walls configuration, while there was one exit for each of two walls in parallel in the case of Parallel walls case.

Figure 4.5-1 shows number of large bubbles from one side to the heater rod, which means that up to 100 of large bubbles per second was considerable as maximum under $\Delta T_{sub} = 1K$, in fact. This is agreeable to the well-known life cycle of a vaper bubble generated under atmospheric pressure.

In the case of Parallel walls configuration, increase trend of large bubble number as decrease of degree of subcooling seemed to change between $\Delta T_{sub} = 4K$ and 6K. There is a possibility that local natural convection of subcooled water into the gaps was more developed to assist departure of bubbles under $\Delta T_{sub} \leq 4K$ thanks to movement of more large bubbles in the case of Parallel walls configuration.
Figure 4.5-1 Number of large bubbles (> 5mm in size)
4.6 Acceleration due to Behavior of Bubbles

Focusing on the trends of acceleration in the case with 1mm-gap distance to each of the walls under degree of subcooling $\Delta T_{\text{sub}} = 1\text{K}$, as shown in Figure 4.6-1 (1) to (3), acceleration corresponding to behavior of bubbles for each case of the structural constraints can be summarized in the following points;

(1) The SBIV of the heater rod was sometimes accelerated in more than 5m/s$^2$ up to around 15m/s$^2$, as superposed on steady acceleration within approximately 5m/s$^2$ both in X- and Y-direction in spite of the three cases of the structural constraints. This anisotropic and protuberant acceleration more than 5m/s$^2$ was caused by behavior of large bubbles such as the bubbles G to L in Figure 4.2.2-2. On the other hand, the steady acceleration within approximately 5m/s$^2$ is considered to be due to the bubble wake just after each of bubble generation occurring around the surface of the heater rod.

(2) In the case of Single wall configuration, the SBIV was accelerated in Y-direction towards the wall, which corresponds to the trend of acceleration RMS values in Figure 4.6-2. Large bubbles growing in size more than 5mm in the gap, such as the bubble G or H in Figure 4.2.2-2, were condensed or detached from the heater surface near the gaps, in favour of Y-direction. In addition, small bubbles grew, detached and were condensed around the opposite region of the heater surface far from the wall in Y-direction.

(3) In the case of Parallel walls configuration, bubbles grew in both of the gaps to each wall and became larger in comparison with the case of Single wall configuration. Besides, such large bubbles moved closer to X-direction from both of the gaps, and accordingly sometimes interfered or coalesced together, which can be confirmed in Figure 4.2.2-2. The structural constraint by the two parallel walls with the heater rod in between made the thermal situation where large bubbles could behave in favour of X-direction. And such behavior of large bubbles could be reflected in the protuberant acceleration in X-direction, which confirmed in Figure 4.6-1(2). In addition, frequency of acceleration
beyond approximately 5m/s² in X- and Y-directions in the case of Parallel walls configuration (Figure 4.6-1 (2)) seemed to be more than in the case of Single wall configuration (Figure 4.6-1 (1)) and Corner walls configuration (Figure 4.6-1 (3)). This corresponds to the trend that number of large bubbles in the case of Parallel walls configuration was almost double in comparison with the case of Single wall and Corner walls configuration.

(4) The significant trend of the SBIV accelerated in the direction of the wall corner and its opposite direction is remarkable in the case of Corner walls configuration. The behavior of large bubbles similar to the case of Single wall configuration occurred from each of the two walls, and generation and condensation of small bubbles were found also in the direction of the wall corner. This was reflected in the trend of the acceleration in this case of Corner walls configuration.

![Figure 4.6-1(1) Acceleration of heater rod in the X-Y plane](image)

(Single wall, 1mm-gap, ΔT_{sub} = 1.0K)
Figure 4.6-1(2) Acceleration of heater rod in the X-Y plane

(Parallel walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)

Figure 4.6-1(3) Acceleration of heater rod in the X-Y plane

(Corner walls, 1mm-gap, $\Delta T_{sub} = 1.0K$)
For Parallel walls configuration, the data of the measured acceleration are plotted in X-Y plane for some conditions of degree of subcooling in the bulk water, as shown in Figure 4.6-3. Under $\Delta T_{\text{sub}} = 6\text{K}$ and $8\text{K}$, as shown in Figure 4.6-3 (d) and (e), acceleration in the case of 1mm-gap distance shows the slight trend encouraged towards X-direction, the region without the walls, in comparison with the case of 3mm-gap distance. It is considered that this corresponds to large bubbles which grew in the gap and moved on the heater rod to X-direction. Under $\Delta T_{\text{sub}} = 5\text{K}$, the above trend of the acceleration was more obviously confirmed in Figure 4.6-3 (c).

Under lower degree of subcooling such as $\Delta T_{\text{sub}} = 1\text{K}$ and $4\text{K}$, protuberant changes of the acceleration were found both in X- and Y-direction as shown in Figure 4.6-3 (a) and (b). For deeper understanding on this trend, the acceleration data broken into every 0.125 seconds in Figure 4.6-1(2) under $\Delta T_{\text{sub}} = 1\text{K}$ is investigated. Bubbles grew quite large in the gap between the heater rod and the wall, moved on the heater rod surface to the open region and often interfered with other large bubbles which came from the other wall. This behavior of large bubbles is considered to be corresponding to protuberant changes of acceleration in X-direction, which was caused by fluctuation or condensation of large bubbles. Figure 4.6-1(2) makes it clear that such protuberant acceleration up to $15\text{m/s}^2$ was superposed on steady acceleration around $5\text{m/s}^2$. 

**Figure 4.6-2** Acceleration RMS of the heater rod (1mm-gap, $\Delta T_{\text{sub}} = 1.0\text{K}$)
Figure 4.6-3 Acceleration of heater rod in X-Y plane (Parallel walls configuration)
4.7 Acceleration RMS of Vibration

In the cases of 1mm-gap distance and 3mm-gap distance in Exp.2, RMS values were calculated from the obtained acceleration data and depicted with the variation of degree of subcooling respectively for X- and Y-directions for each of the three cases of structural constraints in Figure 4.7-1 and Figure 4.7-2.

In the range of degree of subcooling from $\Delta T_{sub} = 6$K to 8K, acceleration RMS values are compared between the three types of structural constraints for X- and Y-direction in Figure 4.7-1. For the cases of Single wall configuration and Parallel walls configuration, RMS values in Y-direction, perpendicular to the wall(s) were reasonably larger than those in X-direction, because larger bubbles in the gap to the wall in Y-direction, where growth of large bubbles were thermally assisted due to the constraint by the wall, were fluctuated and condensed by subcooled water and the SBIV of the heater rod was encouraged in Y-direction. On the other hand, RMS values of acceleration in Y-direction in the case of Corner walls configuration seemed too large than expected in the aspect of even configuration both in X- and Y-directions. Here, one of the reasons for the trend is assumed as inhomogeneous distribution of evaporation sites on the surface of the heater rod as explained in Section 3.2.4.1.

In Figure 4.7-2, the following points are remarkable;

(1) In the cases of Single wall configuration and Parallel walls configuration, acceleration RMS values in Y-direction, perpendicular to the walls, was larger than that in X-direction, parallel to the walls, regardless of degree of subcooling and gap distance. This obviously presented the effect by walls in the vicinity of the heater rod on SBIV of the heater rod.

(2) In the case of Corner walls configuration, RMS values of acceleration both in the X- and Y-directions are compatible in the range of degree of subcooling $\Delta T_{sub} \leq 4$K, which is agreeable to the even configuration of the walls and the heater rod in X- and Y-direction, while RMS values in Y-direction were obviously larger than those in X-direction in the range of $\Delta T_{sub} \geq 6$K.
Figure 4.7-1 RMS values of acceleration of the heater rod

(1) Single wall configuration
(2) Parallel walls configuration
(3) Corner walls configuration

Figure 4.7-2 Acceleration RMS values in the cases of 1mm-gap and 3mm-gap
4.8 Acceleration PSD of Vibration

For Single wall configuration, FFT of the obtained acceleration data in the directions of X and Y respectively provided the power spectrum density (PSD) in the case of 1mm-gap distance to the wall as shown in Figure 4.8-1, and PSD of acceleration in the case of 3mm-gap is shown in Figure 4.8-2. By the external input to the experiment system, it is roughly confirmed that the first natural frequency of the heater rod is around 500 to 600Hz, which corresponds to the peak of PSD shown around 500 to 600Hz in Figure 4.8-1 and Figure 4.8-2. The causes of the SBIV on the heater rod are considered as the following two main phenomena; (a) condensation of small bubbles, and (b) fluctuation and condensation of largely-grown bubbles. The phenomenon (a) could be dominant under high degree of subcooling or in the case of 3mm-gap distance in Exp.2, appearing as high frequency vibration in the range over 1000Hz in Figure 4.8-1 and Figure 4.8-2. The phenomenon (b) could be dominant under low degree of subcooling, appearing as increase of PSD in the range of frequency less than 100Hz. In the case of Single wall configuration, the phenomenon (b) was remarkable around 50Hz. These correspond to SBIV, though increase of PSD of acceleration around the first natural frequency of the heater rod, which was more obvious in Y-direction in the case of Single wall configuration, is considered as random vibration due to wakes at evaporation on the surface of the heater rod.

For Parallel walls configuration, Figure 4.8-3 and Figure 4.8-4 show PSD of acceleration. Under all the conditions of $\Delta T_{\text{sub}}$ in these figures, peaks of PSD around the first natural frequency of the heater rod are obvious and larger in Y-direction, which is similar to the case of Single wall configuration. This is reasonable, because the random vibration presenting around the first natural frequency of the heater rod was caused by wakes in evaporation that occurred more in the gaps with the walls both in the cases of Single wall configuration and Parallel walls configuration, with increase following decrease of $\Delta T_{\text{sub}}$. Focusing on the PSD in the range of frequency less than 100Hz, several peaks are obviously found as decrease of $\Delta T_{\text{sub}}$ in the case of Parallel walls configuration in Figure 4.8-3. Figure 4.5-1 shows number of large bubbles in size more than 5mm counted from one side of X-direction during one second,
which increased up to around 50Hz as decrease of $\Delta T_{\text{sub}}$ to 1K. Considering the trend in the figure, it can be said that the several peaks of PSD in the range of frequency less than 100Hz in Figure 4.8-3 corresponded to behavior of the large bubbles such as sudden pressure change by condensation in the open region from each wall.

For Corner walls configuration, Figure 4.8-5 and Figure 4.8-6 show PSD of acceleration. In the case with 3mm-gap distance in the range of degree of subcooling from $\Delta T_{\text{sub}} = 6K$ to $8K$, spectrum is similar to that both in the case of Single wall configuration and Parallel walls configuration under the same conditions of degree of subcooling. On the other hand, in the case of 1mm-gap distance, it is remarkable as the case of Corner walls configuration that almost comparable levels of peaks in the lower range of frequency less than 100Hz and around the first natural frequency of the heater rod, 500Hz, are found, which suggests more active fluctuation and condensation of large bubbles in the case of Corner walls configuration. In addition, spectrum is almost similar both in X- and Y-directions in this case. In the case of Corner walls configuration, peaks of PSD in the range less than 100Hz increased as decrease of degree of subcooling in the case with 1mm-gap distance as shown in Figure 4.8-5, but peaks near 100Hz were not clearly found, which is different from the case of Parallel walls configuration.

According to the above investigation on peaks of acceleration PSD in the frequency range less than 100Hz between the three types of wall configuration, the trends of these peaks well correspond to number of large bubble generation clarified in Figure 4.5-1.

Changes of the first natural frequency of the heater rod following degree of subcooling, which were extracted from maximum peaks of acceleration PSD around 500 to 600Hz in Figure 4.8-1 to Figure 4.8-6, are shown in Figure 4.8-7 (a) to (c). Generally the first natural frequency increases slightly as decrease of degree of subcooling. This can be considered as influence of added mass in subcooled water around the heater rod, decreasing its density due to subcooled boiling.
Figure 4.8-1 Acceleration PSD in the cases of 1mm-gap (Single wall) (1/2)
Figure 4.8-1 Acceleration PSD in the cases of 1mm-gap (Single wall) (2/2)
Figure 4.8-2 Acceleration PSD in the cases of 3mm-gap (Single wall)
Figure 4.8-3 Acceleration PSD in the cases of 1mm-gap (Parallel walls) (1/2)
Figure 4.8-3 Acceleration PSD in the cases of 1mm-gap (Parallel walls) (2/2)
Figure 4.8-4 Acceleration PSD in the cases of 3mm-gap (Parallel walls)
Figure 4.8-5 Acceleration PSD in the cases of 1mm-gap (Corner walls)
Figure 4.8-6 Acceleration PSD in the cases of 3mm-gap (Corner walls)
Figure 4.8-7 First natural frequency of the heater rod depending on degree of subcooling
4.9 Excitation Force due to Behavior of Bubbles under Subcooled Boiling

For Exp.2, displacement of the heater rod in SBIV is calculated based on the measured acceleration, which is shown in Figure 4.9-1 for all the three cases of structural constraints. RMS values of displacement are approximately ~0.3mm for all the three cases.

<table>
<thead>
<tr>
<th>Structural constraint</th>
<th>Gap distance to wall</th>
<th>Displacement, RMS values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single wall configuration</td>
<td>1mm and 3mm</td>
<td>&lt; 0.31 mm</td>
</tr>
<tr>
<td>Parallel walls configuration</td>
<td>↑</td>
<td>&lt; 0.31 mm</td>
</tr>
<tr>
<td>Corner walls configuration</td>
<td>↑</td>
<td>&lt; 0.33 mm</td>
</tr>
</tbody>
</table>

As investigated in Section 4.8, the causes of the SBIV on the heater rod are considered as the following two main phenomena; (a) condensation of small bubbles, and (b) fluctuation and condensation of largely-grown bubbles. In addition to these two, random vibration due to wakes at evaporation on the surface of the heater rod is considered. The estimated displacement is a result mainly superposing these three kinds of vibration. Typical trends of acceleration, velocity and displacement are shown in Figure 4.9-2, Figure 4.9-3 and Figure 4.9-4 for each case of structural constraints. In these figures, it can be found that displacement corresponding to large change of acceleration, which is considered to reflect fluctuation or condensation of large bubbles in SBIV, is 0.05mm to 0.1mm. On the other hand, acceleration in high frequency by small bubble generation hardly impacts on the displacement of the heater rod, which agrees with that Nematollahi [54] described an excitation force in the order of $10^{-4}$N by such small bubbles under high degree of subcooling.

For the above displacement due to bubble fluctuation or condensation, up to 0.1mm, treating it simply as that in the first mode vibration of a cantilever, the maximum excitation force is estimated under the following assumptions;

(1) Excitation force worked at a point in the middle of the length of the cantilever,
(2) The representative diameter of the cantilever is the thinner part of the heater rod, and
(3) The heater rod was made of uniformed stainless steel.

Consequently, the maximum excitation force is estimated to approximately 2.5N.

In Section 4.4.2, it is clarified that surface tension of a large bubble provides the bubble with
the force \( F_S \) downward during the bubble attaches on the surface of the heater rod. During this
period, surface tension of the bubble working along the periphery of the effective microlayer
in Figure 4.2.2-1 also provides the heater rod with the force \( F_N \) normal to the rod surface. The
force \( F_N \) can be calculated by Equation (8), with similar consideration to Cornwell and
Schüller [62]:

\[
F_N = \pi \sigma \cdot a \cdot \sin \theta_a.
\]  

(8)

Assuming \( \theta_a = 90^\circ \) as same as in Section 4.2.2, the normal force \( F_N \) is calculated as \( 2 \times 10^{-4} \) to
\( 5 \times 10^{-4} \) N for the large bubbles in Table 4.4.2-3, which is an order of magnitude smaller in the
aspect of excitation force inducing vibration of the heater rod as estimated above, 2.5N. Considering
that sudden reduction of vapor pressure in a bubble working through the effective
microlayer may cause excitation force to vibrate the heater rod, the force due to pressure \( F_P \) is
calculated with the vapor pressure at 100 deg-C and the effective area of the microlayer \( S_{ht} \) for
the bubbles in table 4.4.2-3.

\[
F_P = p_{v,100} \cdot S_{ht}
\]  

(9)

The force due to pressure \( F_P \) is estimated in the range from 0.2 to 2.7N, which is agreeable to
the estimated excitation force, 2.5N. This suggests that the vibration due to large bubbles
clarified in this study is SBIV of the heater rod caused by pressure fluctuation and condensation of such bubbles.
(a) Single wall configuration

(b) Parallel walls configuration

(c) Corner walls configuration

Figure 4.9-1 RMS values of displacement (Exp.2)
(a) $\Delta T_{sub} = 1.0\, K$

(b) $\Delta T_{sub} = 6.1\, K$

Figure 4.9-2 Acceleration, velocity and displacement (Single wall, 1mm-gap)
Figure 4.9-3 Acceleration, velocity and displacement (Parallel walls, 1mm-gap)

(a) $\Delta T_{\text{sub}} = 1.0 \text{K}$

(b) $\Delta T_{\text{sub}} = 6.0 \text{K}$
Figure 4.9-4 Acceleration, velocity and displacement (Corner walls, 1mm-gap)
5. IMPLEMENTATION

In the experiments, acceleration of SBIV on the single heater rod made of stainless steel was investigated. The structure and conditions are again summarized in Table 5-1, in comparison with those in actual PWRs, considered as situations without forced flow of water in case of accidents.

**Table 5-1 Structures and conditions in the experiments**

<table>
<thead>
<tr>
<th></th>
<th>Present study</th>
<th>PWR fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiments</strong></td>
<td></td>
<td>(1) loss of cooling function in reactor core</td>
</tr>
<tr>
<td>Heating rod</td>
<td></td>
<td>(2) loss of cooling function in spent fuel pit</td>
</tr>
<tr>
<td>Heating rod</td>
<td>- Stainless steel bar</td>
<td>- UO$_2$ ceramics + Zirconium tube</td>
</tr>
<tr>
<td></td>
<td>$\rho_S \approx 8$g/cm$^3$</td>
<td>$\rho_{UO_2}$: $\approx 10.6$g/cm$^3$ [64]</td>
</tr>
<tr>
<td></td>
<td>$E_S \approx 18$MN/mm$^2$</td>
<td>$E_{UO_2}$: $\approx 0.2$MN/mm$^2$ [65]</td>
</tr>
<tr>
<td></td>
<td>- 150mm length</td>
<td>- 4000mm length</td>
</tr>
<tr>
<td></td>
<td>- fixed at the top</td>
<td>- Fixed at 9 elevations (500mm span)</td>
</tr>
<tr>
<td>Structural constraints</td>
<td>- Configurations by metallic walls with 1mm or 3mm-gap distance</td>
<td>- A bunch of fuel rods bound by spacer grids with small cells</td>
</tr>
<tr>
<td></td>
<td>- 3mm-gap between neighboring two rods</td>
<td>- 3mm-gap</td>
</tr>
<tr>
<td></td>
<td>- 1mm-gap to thin metallic wall of a spacer grid cell</td>
<td>- 1mm-gap to thin metallic wall of a spacer grid cell</td>
</tr>
<tr>
<td><strong>Thermal flux of heater rod</strong></td>
<td>$\approx 0.13$</td>
<td>$\approx 0.5$</td>
</tr>
<tr>
<td><strong>Temperature of bulk water</strong></td>
<td>~100</td>
<td>~350</td>
</tr>
<tr>
<td><strong>System pressure</strong></td>
<td>0.1</td>
<td>~15.7</td>
</tr>
<tr>
<td><strong>Degree of subcooling</strong></td>
<td>1 ~ 8</td>
<td>0 ~</td>
</tr>
</tbody>
</table>
As clarified in Table 5-1, the structural constraints provided in Exp.2 were considerably demonstrative to those in an actual fuel assembly for PWR, as well as for BWR, i.e., 3mm-gap distance between the heater rod and a wall corresponds to the actual distance between two fuel rods in a fuel assembly and 1mm-gap distance set in Exp.2 corresponds to the actual distance between a fuel rod and thin metallic wall of a spacer grid cell gripping the fuel rod.

In the aspect of thermal conditions and pressure, the case of PWR fuel (1) in reactor core is significantly different from the experiments in the present study. Ünal [66] summarized data of maximum bubble diameter in water obtained in his experiments including data by other investigators [67]–[70], together with their relating parameters such as pressure, degree of subcooling, flow velocity and thermal flux, which are shown in Figure 5-1. This figure suggests very smaller diameter of vapor bubbles under high pressure, even with high thermal flux, like conditions in core of PWR (1) in Table 5-1. This means that the SBIV caused by large bubbles observed in the present study would be hardly occurred for the case of PWR fuel (1). On the other hand, sizes of bubble diameter seem to be unstable even on similar conditions under the atmospheric pressure.

In a study on FIV of PWR fuel rod, relation between excitation force working on a fuel rod and its corresponding displacement is analyzed [16]. According to the study, around 1N of excitation force at the middle of a grid span provides approximately 0.2mm of displacement of the fuel rod, in the case of the first mode of fuel rod vibration with around 45Hz of the first natural frequency under water. In Section 4.9, 2.5N of assumed force is estimated, even though it is quite conservative, and such excitation force could provide more displacement in the case for an actual fuel rod in comparison with the study by Choi et al. [16]. In addition, the first natural frequency of an actual fuel rod, shown in the above-mentioned study [16], is close to the frequency which was found in the Section 4.8 as a result of large bubble fluctuation or condensation in SBIV.
Figure 5-1 Maximum bubble diameter depending on pressure and flow velocity [66]-[70]
Considering these differences and similarities in conditions, the experimental results of SBIV obtained in Exp.2 could be referred for cases on actual fuel assemblies such as loss of cooling function in spent fuel pit, as shown in Table 5-1. Even though a large difference on thermal flux is found and generated vapor bubbles would be smaller in the case of spent fuel pit, further investigation taking realistic situations into account, such as subcooled boiling in a small channel surrounded by fuel rods, will be necessary.
6. CONCLUDING REMARKS AND FUTURE WORKS

In order to investigate the fundamental phenomena of the SBIV of the heater rod installed in subcooled water, the experiments of subcooled pool boiling by the simplified experimental apparatus under atmospheric pressure were performed. In the experiments, influences by wall existence and due to wall configurations arranged in the three cases, Single wall, Parallel walls and Corner walls configuration, are focused. The results of the experiments and investigation clarified the following points in the aspect of SBIV of the heater rod;

(1) Existence of a wall in the vicinity of a heater rod increases local temperature of water in the gap between the surface of the heater rod and the wall, higher than that in the region without a wall. This encourages growth of bubbles in the gap and such bubbles condense in the gap, which leads to larger acceleration of SBIV of the heater rod in the direction perpendicular to the wall.

(2) Lower degree of subcooling, close to saturation, leads to growth of larger vapor bubbles in the gap between the surface of the heater rod and a wall. Such large bubbles, moving out from the gap to the open space and detaching from the heater rod, cause vibration of the heater rod. In this process, such large bubbles contact to subcooling water and in turn, perturbation and condensation of the bubbles induce SBIV of the heater rod. This is the mechanism of the SBIV in the directions without a wall in Exp.2.

(3) Estimation of local superheat around large bubbles growing in the gap between the surface of the heater rod and a wall suggests formation of microlayer enough thick to encourage large bubbles.

(4) Horizontal and vertical velocities of large bubbles moving out from the gap between the
surface of the heater rod and a wall were estimated based on visual observation of behavior of bubbles by the high speed digital video camera. The area of the microlayer effective to contribute heat transfer for vapor supply was estimated by horizontal velocities and the equation of heat and mass balance, and the force downwards due to surface tension working along the area was taken into account for calculation of vertical velocities of large bubbles in force balance with buoyancy, gravity and drag force. These calculated vertical velocities agree to the estimated ones based on pictures by the high speed digital video camera. This indicates that such large bubbles are forced by the heater rod in supplying heat through microlayer at its surface to the bubbles even in the direction without a wall, which is an evidence backing direct influence of perturbation and condensation of the large bubbles on the SBIV of the heater rod.

(5) Dependency of acceleration of the SBIV on frequency, the random vibration encouraging the first natural vibration of the heater rod and the specific vibration in the range less than 100Hz under lower degree of subcooling, was clarified. The specific vibration in the range less than 100Hz was varied by the three types of difference of the wall configurations, which agrees to frequency of large bubble generation in the experimental results.

(6) SBIV for actual fuel rods of PWR or BWR was discussed based on the results obtained in the experiments and investigation on the fundamental phenomena of the SBIV of the single heater rod with the metallic walls. Geometry of actual fuel for PWR of BWR is quite different from that of the heater rod used in the experiments. Fuel rods of PWR and BWR are 4m long and bound at several axial positions with about 500mm interval, while approximately 3mm-gap distance between fuel rods and approximately 1mm-gap distance between a fuel rod and a cell strap of a spacer grid are close to the provided conditions in the SBIV experiments. Assuming a loss of cooling function in a spent fuel pit of a PWR power plant, thermal conditions similar to the experiments such as subcooled boiling under atmospheric pressure could be considered. For this case, possibility of SBIV on fuel rods should be deeply investigated together with assumed
actual phenomena.

Through this study, it can be said that metallic walls in the vicinity of the single heater rod well maintain superheated microlayer at the surface of the heater rod in the region formed with the walls, which encouraged growth of larger bubbles in the region and interaction between the generated bubbles and the heater rod. This influences represented differences of acceleration of SBIV from the reference case without a wall and depending on wall configurations.

Behavior of bubbles influencing on SBIV was observed by the high-speed digital video camera in the experiments of this study, but the direction for the observation was limited because of the metallic walls. Besides, the metallic walls used for the experiments did not demonstrate a bunch of heating rods.

For future works, the following points are expected to be investigated;

(1) Observation of bubbles from the opposite side of a wall by using transparent material for the wall such as acryl with tolerance against high temperature and refraction index equivalent to water. Observation of bubbles from two different direction enables investigation from the point of stereo view.

(2) Three walls surrounding the heater rod.

(3) Group of rods, consisting of one heater rod in the middle and eight rods with the same geometry as the heater rod surrounding the heater rod.

(4) A bunch of heater rods.

In addition to the above points, synchronized measurement between high-speed video recording, local temperature measurement and acceleration measurement should be challenged to enable deep investigation on relation between behavior of vapor bubbles and SBIV of the heating structure.
REFERENCES


ACKNOWLEDGMENT

After ten years’ interval since my graduation of master’s degree in mechanical engineering at Kyoto University, I was provided with the opportunity to study thermal hydraulics for nuclear engineering under supervision of two respected professors; Professor Emeritus Akimi Serizawa of Kyoto University, who included me as a member in his laboratory to start the course of my doctoral program in October 2004, and Professor Tomoaki Kunugi, who has been supervising me to reach the final stage of the program until now in July 2016. Professor Emeritus Serizawa opened my eyes to the field of thermal hydraulics, in particular for dynamics of bubbles and two phase flow. Professor Kunugi led me to understanding of physical phenomena relating to dynamics of vapor bubbles through several discussions. Besides, Professor Kunugi has always encouraged me to take steps with his invaluable guidance, continued patience and tireless support, even though I have taken such a long period for my doctoral program. Here, I would like to take the opportunity to express my sincere gratitude to my supervisors, Professor Emeritus Serizawa and Professor Kunugi.

I would also like to extend my sincere thanks to Dr. Zensaku Kawara and Dr. Takehiko Yokomine, for all the support and advice they provided regarding experiments and evaluations in my study. I am thankful to Professor Takayuki Sasaki, as well as Dr. Kawara and Dr. Yokomine, for his reviewing my thesis and providing valuable comments to improve the quality of dissertation.

For initiation of the SBIV experiments and many of valuable experimental data including clear pictures of bubble behavior, I greatly appreciate the excellent support by Mr. Yoshiteru Komuro and Mr. Yusuke Hashimoto, both of whom are now active in industry. I thank Mr. Mao Takeyama for his temperature measurement around the heater rod, which is very interesting related to my study. I also acknowledge the excellent support from Dr. Yasuo Ose,
Dr. Yukihiro Yonemoto and all the members I shared time with in the laboratory of Professor Emeritus Serizawa and Professor Kunugi.

Of course, I thank very much my bosses at work and co-workers for their cooperation and support through this period of my doctoral program.

Lastly, I would like to express my appreciation to my family: my parents, parents-in-law, my wife and my son. Without their love, encouragement and support, I could not have come this far. I dedicate this thesis to them.

Kobe, July 19th 2016