SUBCOOLED BOILING-INDUCED VIBRATION OF A SINGLE HEATER ROD CONFINED WITH METALLIC WALLS

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ABSTRACT

Some existing studies have suggested that subcooled boiling on the surface of a heating rod in water induces a vibration of the rod itself. Considering nuclear power generation with light water reactors, latency of this phenomenon in their reactor cores or spent fuel pools should be investigated, because systems of both Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR) allow long fuel rods to heat themselves in water. After the Fukushima Daiichi accident, such investigations especially for the cases of abnormal situations or unexpected severe accidents are being important. A series of studies to accumulate fundamental understandings of this phenomenon, so-called “Subcooled Boiling-Induced Vibration (SBIV)”, has been conducted by the authors through the experiments with a simple system of a single heater rod installed in atmospheric static water. Acceleration of the SBIV of the superheated rod was measured by an accelerometer under the various subcooling conditions, and the degree of subcooling of the water was controlled by electrical power input to the heater rod. The SBIV was investigated to be varied depending on generation, growth, moving, departure and condensation of bubbles due to subcooled boiling on or near the rod surface. The present study clarified that the SBIV of the single rod showed the characteristic power spectrum of its vibration, focusing on influences by metallic walls to confine the water passage for the heater rod, from the point of view of thermal conditions and bubble behaviors near the rod.

KEYWORDS
Subcooled boiling, Rod vibration, Bubble behavior, SBIV, Nuclear power utilization

1. INTRODUCTION

Flow-induced vibration (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 a significant fretting wear on fuel rod cladding and consequent leakage of fuel. For the system of BWR, several researchers studied effects of boiling phenomena on the fuel rod vibration in the reactor core. Miyano et al. [1] observed the boiling effect on the system of flow loop using 9 x 9 BWR fuel assembly array. Nematollahi et al. [2] conducted experiments of the Subcooled Boiling-Induced Vibration (SBIV) under the flow conditions with higher degrees of subcooling (10-80K). These two studies suggested the important effects of the SBIV.

On the other hand, the system of PWR employs single phase flow of light water under high pressure, but subcooled boiling in the local region might occur at hotter water channel among the temperature distribution of the core, in particular under high duty operation of the core to generate thermal power effectively even as a normal operation. The local subcooled boiling may not cause a significant vibration of fuel rods because subcooled boiling is quite low under a normal operation and the influence of such boiling on the SBIV could be negligible. No fuel leakage or fretting wear due to the SBIV under normal operation has been reported yet. However, considering irregular situations or conditions at sever 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.

In order to investigate the influences of the SBIV on PWR nuclear power plants, which could be critical under a specific situation or could be ignorable, the fundamental phenomena of the SBIV have to be made clear and understood. Komuro et al. [3] performed some experiments with a single cylindrical heater in static water under an atmospheric pressure condition, and confirmed the SBIV of a single heater rod as a fundamental study. In addition, Takano et al. [4] performed the experiments to observe the SBIV of a single heater rod in the case of the existence of a metallic wall near the rod. As a further investigation on the wall effect to the SBIV, this paper describes the case of the single heater rod confined with the metallic walls arranged in parallel at both sides of the rod.

2. PREVIOUS EXPERIMENTS FOR SINGLE HEATER ROD

Fundamental studies on the SBIV of a single heater rod installed in the center of a water tank have been performed [3]. Figure 1 depicts the experimental apparatus consisting of a water tank and a single heater rod fixed at its top onto the roof of the water tank, with an accelerometer attached at its bottom end. The degree of subcooling of the water in the tank was controlled by heat generation of the heater rod. Subcooled boiling due to the heat generation induced the SBIV of the heater rod.

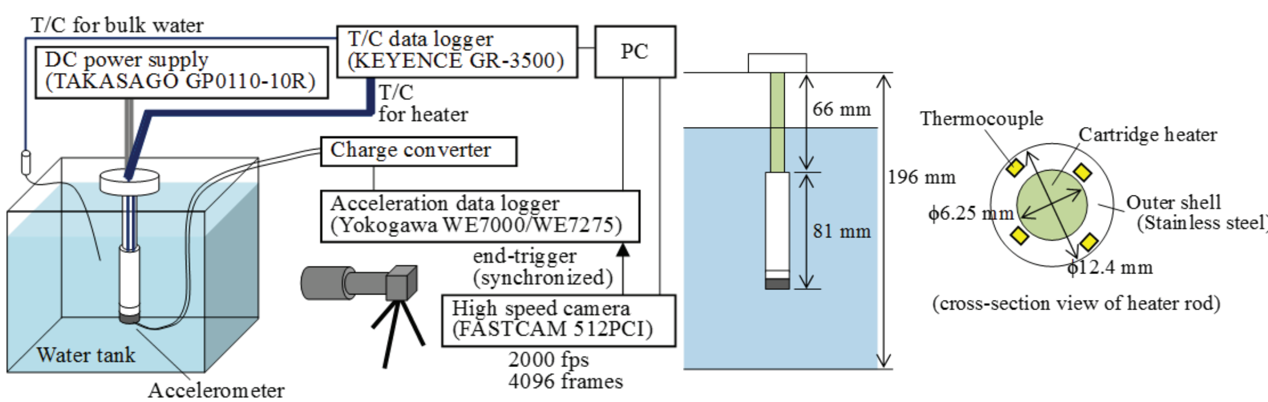


Figure 1. Experimental apparatus in previous studies

Komuro et al. [3] observed the SBIV of the single heater rod as the conditions of pool boiling and natural convection in the range of the degree of subcooling from ΔT_{sub} = 0K (i.e., a saturation condition) to 10K. Results of the observation made it clear that the SBIV of the single heater rod showed the unique power spectrum density of the measured acceleration and the peaks of the power spectrum density in some specific frequencies, which were influenced by the bubble behavior due to subcooled boiling.

Takano et al. [4] conducted the SBIV experiment by using the same experimental apparatus as the previous study by Komuro et al [3]. They investigated on the SBIV of the heater rod located near a metallic wall with 5mm-gap from the heater rod surface. From the experimental results with the variation of the degree of subcooling up to ΔT_{sub} = 7K together with the variation of the degree of superheat at the heater rod surface, the effect of the wall was clarified as the increase of the acceleration of the SBIV towards the wall. In this experiment, the typical bubble size under lower degree of subcooling was less than 5mm. An experiment with a smaller gap distance between the rod and the wall should be conducted because the distance of the gap between fuel rods in a fuel assembly for the conventional PWR is approximately 3mm. Results of such an experiment with a smaller gap distance can be useful considering situations at precipitous pressure drop in the core or under loss of coolant at spent fuel pit. In order to investigate effects of the distance of the gap, Takano et al. [5] conducted the SBIV experiments by using the same apparatus with the heater rod located at the gap distances of 1mm and 3mm from the wall. They confirmed that smaller distance of the gap provided the SBIV of the heater rod with significant influences due to the bubble behavior in the gap, such as coalescence with small bubbles, growth and horizontal movement around the rod, quite different from that in the other side of the rod without the wall, in particular for the case of 1mm-gap.

3. EXPERIMENTAL APPARATUS AND CONDITIONS

3.1. Experimental apparatus

As the series of the investigation on the SBIV based on the previous studies mentioned above, the present study by using the same apparatus, shown in Figure 1, with the single heater rod confined with the metallic walls arranged in parallel at both sides of the rod was conducted to investigate the effect of the "parallel" walls on the SBIV under low degree of subcooling.

In order to observe the vibration of a single rod due to the 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. Figure 2 shows the schematic view of this experimental apparatus, and the information of the apparatus is summarized in Table I. The heater rod was a metallic cartridge heater, manufactured by Watlow, welded to a stainless steel shell. The heat flux on the heater rod surface was controlled by the DC power supply. The temperatures of the heater rod were monitored by four thermocouples installed into the outer shell of the heater rod at four locations in the radial direction, respectively. The temperature of the bulk water was monitored by a thermocouple installed in the water tank. The vapor bubbles are generated and condensed on the surface of the heater rod as subcooled boiling, which induces a radial vibration of the heater rod. The data acquisition of the visual images taken by the high speed camera was synchronized with the end trigger signal of the accelerometer by the high speed camera's control unit.

In the experiment, two stainless-steel walls of 2mm thickness were arranged in parallel at both sides of the heater rod with a certain gap appeared in Figure 2, where the gap distance was set as 1mm or 3mm.

3.2. Conditions of experiment

The conditions of the present study are shown in Table I. All the experiment was carried out under an atmospheric pressure. The degree of subcooling, ΔT_{sub} was controlled by the power supply into the cartridge heater after the deaeration from the bulk water by the immersion heater once to the saturated boiling. Sampling frequency for the acceleration of the heater rod was 10kHz. During change of the degree of subcooling in the range from ΔT_{sub} = 1K to 8K, the measuring period for one condition was kept 2 seconds. X-direction was set in parallel to the walls, and Y-direction was set perpendicular to the walls, which is the direction facing the walls from the heater rod. The video record of bubble behaviors at or near the surface of the heater rod on one condition was during 2 seconds.

The degree of subcooling was a parameter in the experiment, 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, which was calculated from the temperatures measured by the thermocouples installed in the outer shell of the heater rod, in the assumption that the heat flux at the outer shell was uniform, using the following Eq. (1):

$$q' = -2\pi\lambda r \frac{dT}{dr} = const. \quad (1)$$

The signals obtained from the accelerometer were processed by Fast Fourier Transformation (FFT) into the power spectral density (PSD). The root-mean-square (RMS) values of the acceleration signals were obtained in X- and Y-directions respectively, and their combination was treated as the RMS values of the acceleration of the heater rod vibration.

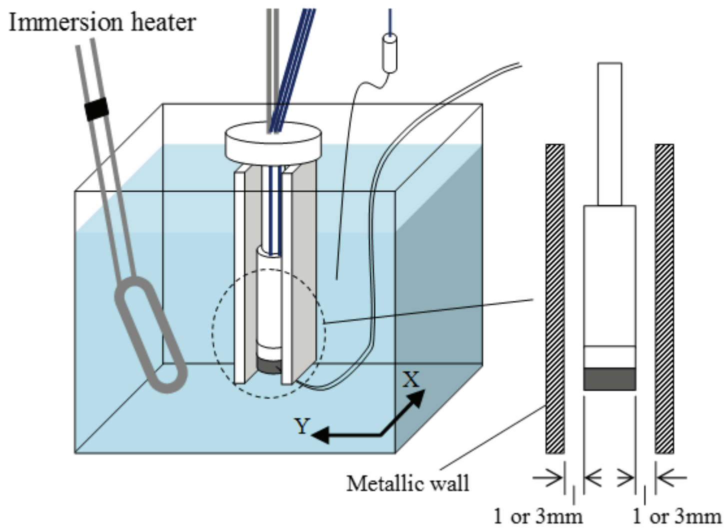


Figure 2. Experimental apparatus for the present study

Table I. Conditions and parameters for the present study

Dimensions of water tank	150 x 150 x 196mm (same as the previous studies)
Dimensions of heater rod	As shown in Figure 1 (same as the previous studies)
Material of walls, thickness	Stainless steel, 2mm
Gap distance between heater rod and each of walls	1 or 3mm (two cases)
Bulk water in water tank	Purified water, deaeration before experiments
Subcooled boiling, convection in bulk water	Pool boiling, natural convection
Range of degree of subcooling	1K ~ 8K (controlled as an experimental parameter)
Superheat at heater rod surface	17.5 ± 0.5K (constant)

4. RESULTS OF EXPERIMENT

4.1. In case of 3mm-gap to each wall

4.1.1. Observation of generated bubble behavior around the heater rod

Figure 3 shows the behaviors of generated bubbles observed from X-direction axially along the heater rod, under ΔT_{sub} of 1K, 3K, 6K and 8K, respectively.

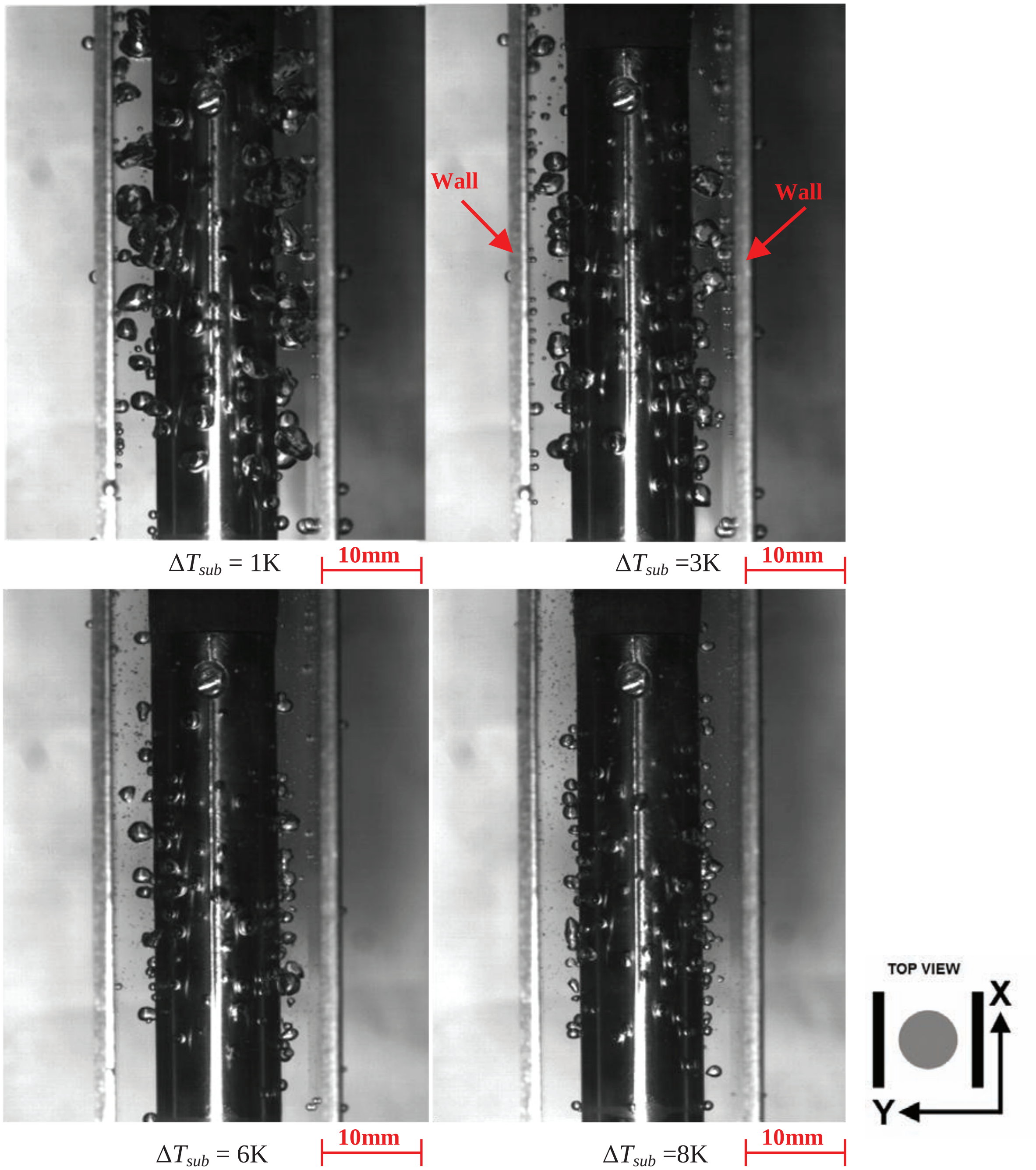


Figure 3. Observation of bubble behavior on heater rod with 3mm-gap to each wall

Following decrease of ΔT_{sub}, bubbles grew larger, up to around 3mm in diameter under the condition of ΔT_{sub} = 1K, before their condensation. The bubbly flow smoothly moved upwards in natural convection and without an irregular behavior of large bubbles even under the condition of ΔT_{sub} = 1K. The condition at each side of the heater rod in Y-direction had no difference, which seemed to realize the commensurate behavior of generated bubbles in both sides.

4.1.2. Acceleration trend of heater rod vibration

The generated bubbles induced the vibration of the heater rod, which were measured by the accelerometer installed at the bottom-end of the heater rod. Figure 4 shows trends of the measured acceleration in X- and Y-directions under the condition of ΔT_{sub} =6K. The acceleration RMS value of the heater rod vibration in Y-direction, which is perpendicular to the wall, was 21% larger than that in X-direction.

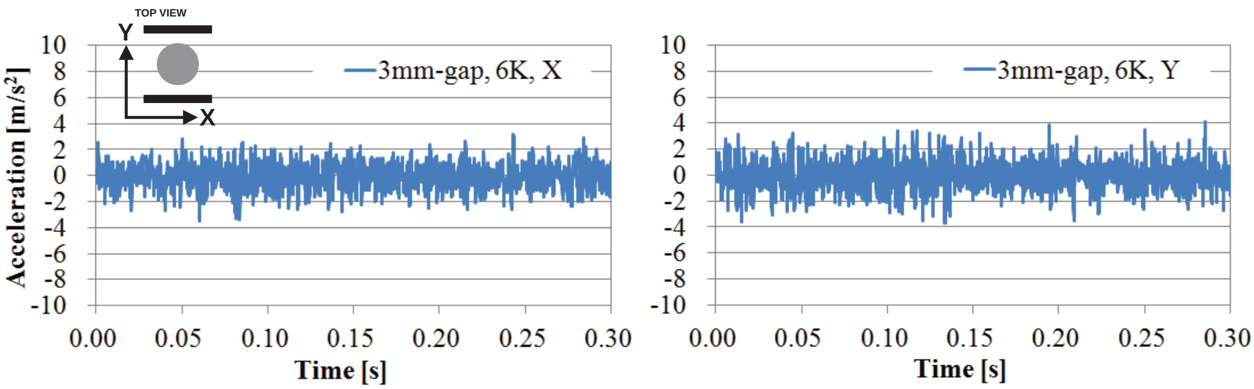


Figure 4. Acceleration of heater rod with 3mm-gap to each wall (ΔT_{sub} = 6K)

4.1.3. Trajectory of acceleration

The trajectory of the acceleration in X-Y plane during 1 second under the condition of ΔT_{sub} = 6K is shown in Figure 5. From this figure, it is obvious that the SBIV of the heater rod was somehow influenced by the existence of the two parallel walls, because the vibration acceleration in Y-direction towards the wall was approximately 10% larger than that in X-direction.

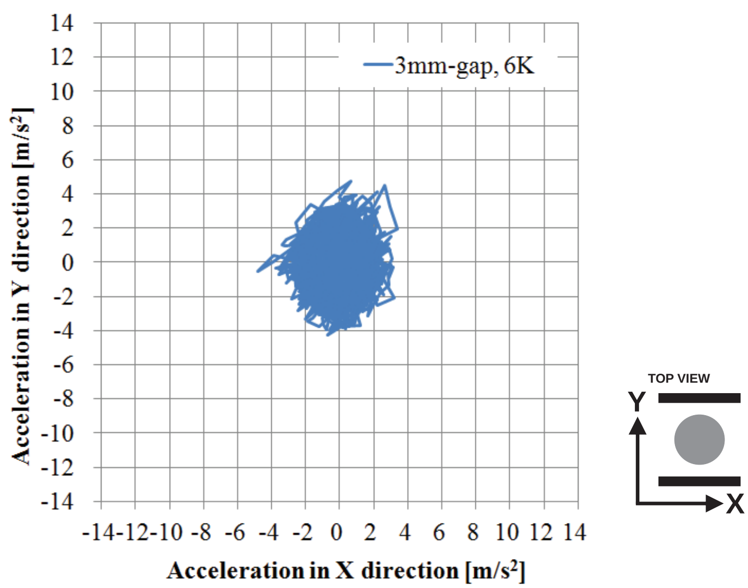


Figure 5. Acceleration trajectory of heater rod with 3mm-gap to each wall (ΔT_{sub} = 6K)

4.2. In case of 1mm-gap to each wall

4.2.1. Observation of generated bubble behavior around the heater rod

Figure 6 shows the behaviors of generated bubbles observed from X-direction axially along the heater rod, under ΔT_{sub} of 1K, 3K, 6K and 8K, respectively. In the range of ΔT_{sub} = 1K to 8K, bubbles grew to significantly larger than 3mm in longer diameter of an ellipsoid, and few small bubbles were found at the surface of the heater rod. Under the conditions of ΔT_{sub} = 1K and 3K, such large bubbles growing up to more than 10mm at each side of the heater rod moved to X-direction, to open area without a wall, and coalesced together in X-direction. The coalesced large bubbles rose up, wrapping partly around the rod.

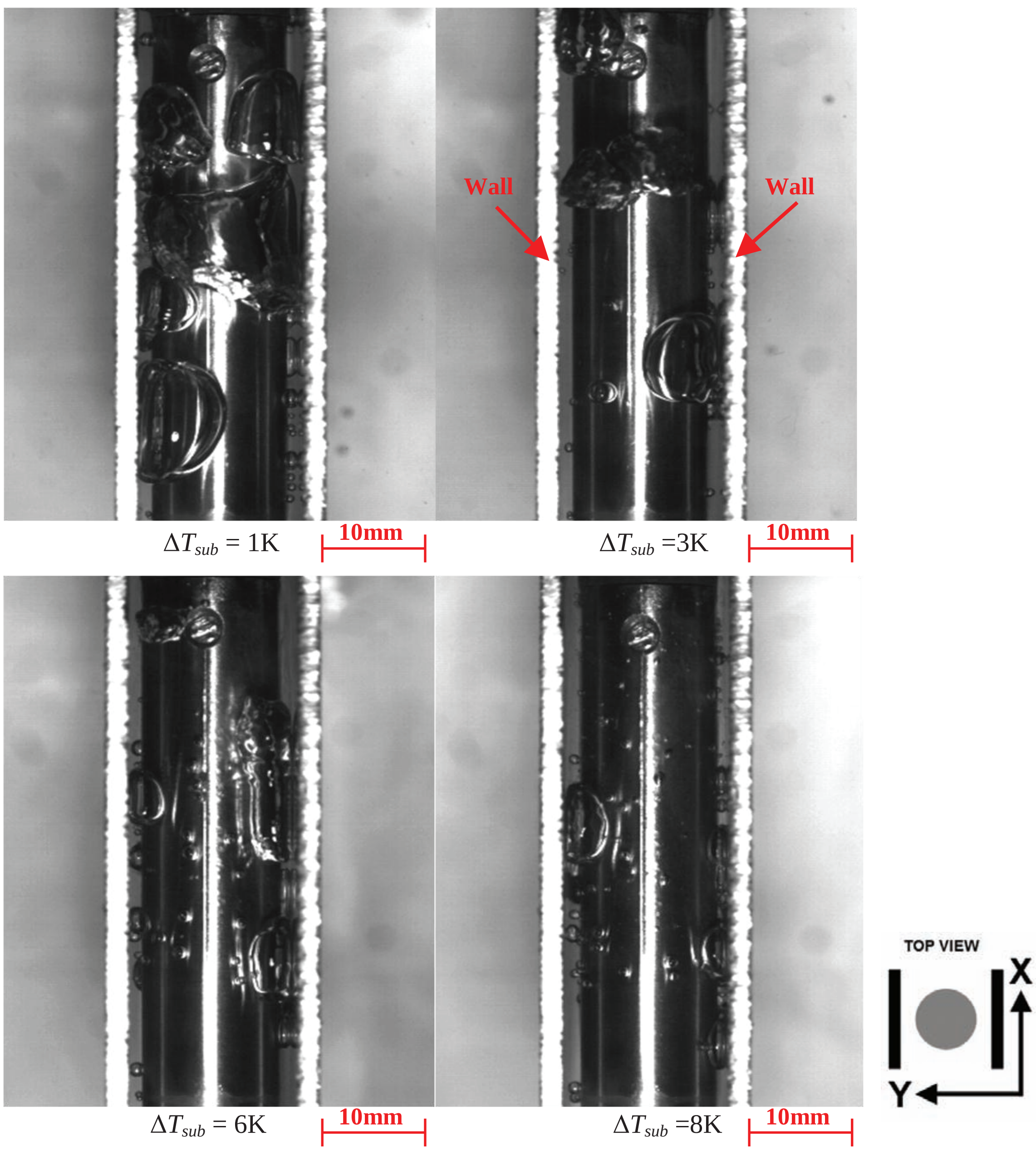


Figure 6. Observation of bubble behavior on heater rod with 1mm-gap to each wall

4.2.2. Acceleration trend of heater rod vibration

Figure 7 and Figure 8 show the measured acceleration in X- and Y-directions under the conditions of ΔT_{sub} = 1K and 6K, respectively. The acceleration RMS value of the rod vibration in Y-direction (toward the walls) was 9% larger than that in X-direction under the conditions of ΔT_{sub} = 1K, and 10% larger than that in X-direction under the conditions of ΔT_{sub} = 6K.

The acceleration in the case of 1mm-gap under the condition of ΔT_{sub} = 6K seemed not to be different both in X- and Y-directions from the case of 3mm-gap under the same condition, which can be confirmed in Figure 8. This is interesting because, as confirmed in Figure 6, the bubble behavior in the case of 1mm-gap under the condition of ΔT_{sub} = 6K was obviously different from that in the case of 3mm-gap under the same condition shown in Figure 3.

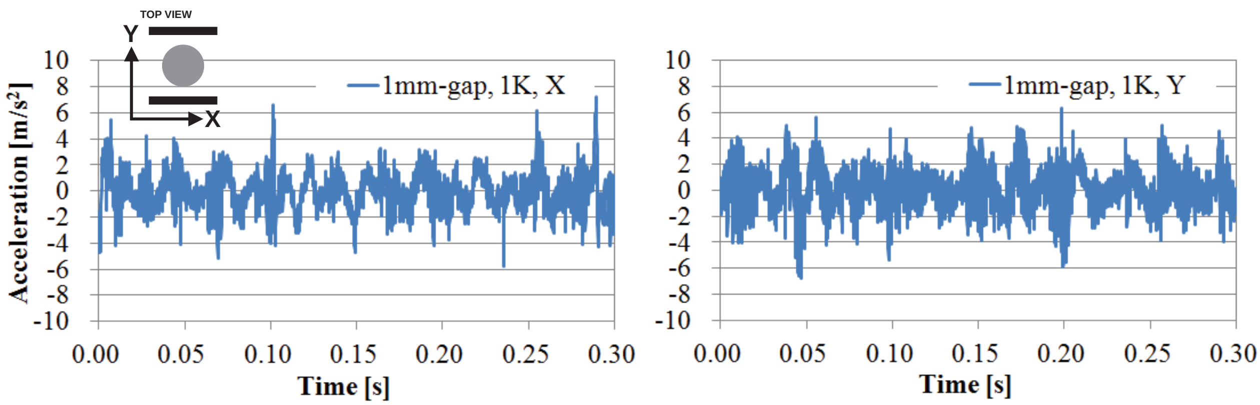


Figure 7. Acceleration of heater rod with 1mm-gap to each wall (ΔT_{sub} = 1K)

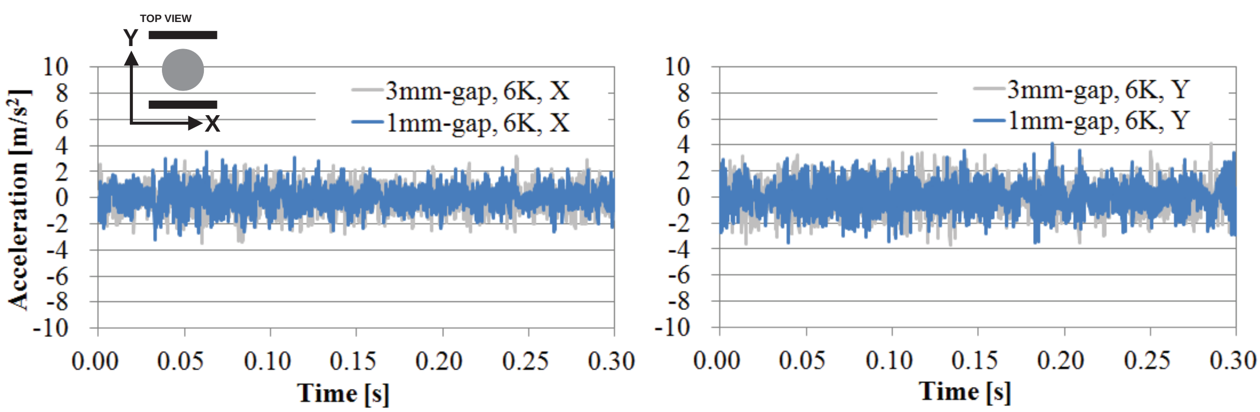


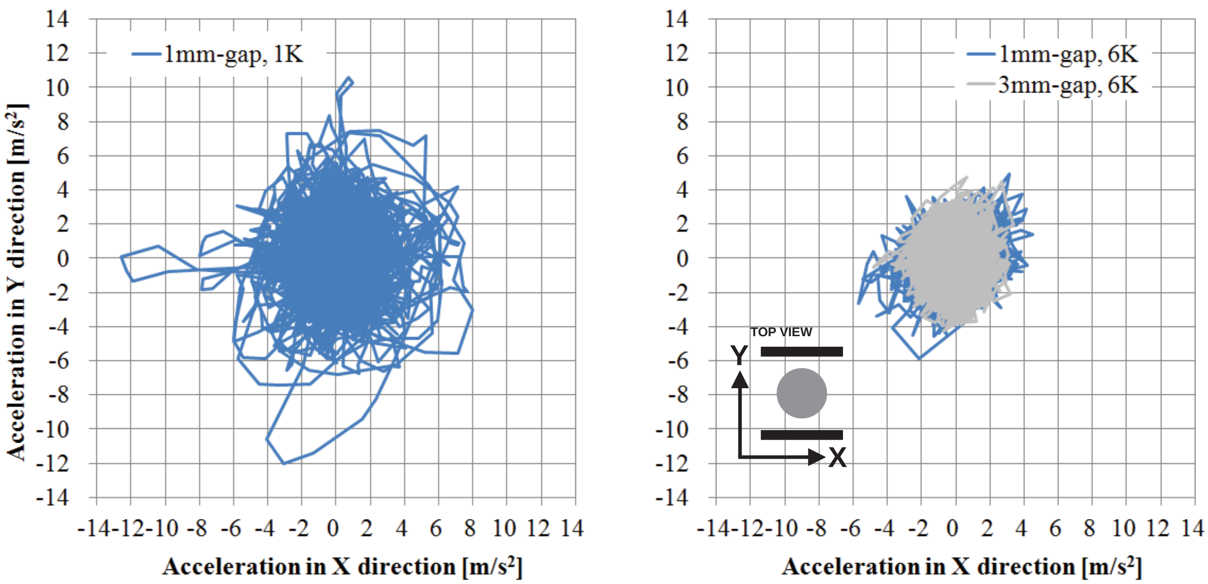
Figure 8. Acceleration of heater rod with 1mm-gap to each wall (ΔT_{sub} = 6K)

Regarding the bubble behavior under the condition of ΔT_{sub} = 1K, the sharp and large variation of the acceleration data was obvious both in X- and Y-directions and this trend was slightly stronger in Y-direction. This trend of the acceleration data reflects that the large bubbles in the gap between the heater rod and the wall influenced on the SBIV in Y-direction, as well as on the SBIV in X-direction after the large bubbles moved towards X-direction, coalesced and wrapped in X-direction, and departed from the heater surface in X-direction as shown in Figure 6. The bubble behavior could induce periodical pressure change onto the heater rod both in X- and Y-directions, which corresponds to the trend in Figure 7.

4.2.3. Trajectory of acceleration

The trajectories of the measured acceleration in X-Y plane during 1 second under the conditions of ΔT_{sub} = 1K and 6K are shown in Figure 9. From the aspects of comparison with the data in the case of 3mm-gap and comparison between under the conditions of ΔT_{sub} = 1K and 6K, the data trend of the trajectories in Figure 9 is corresponding to the investigation on acceleration shown in Figure 7 and Figure 8.

The trajectory under the conditions of ΔT_{sub} = 1K in Figure 9 seemed to show change of direction of acceleration vector like rotation, which could be consist with the behavior of the large bubbles moving from Y-direction to X-direction and coalescing in X-direction, shown in Figure 6.



ΔT_{sub} = 1K ΔT_{sub} =6K

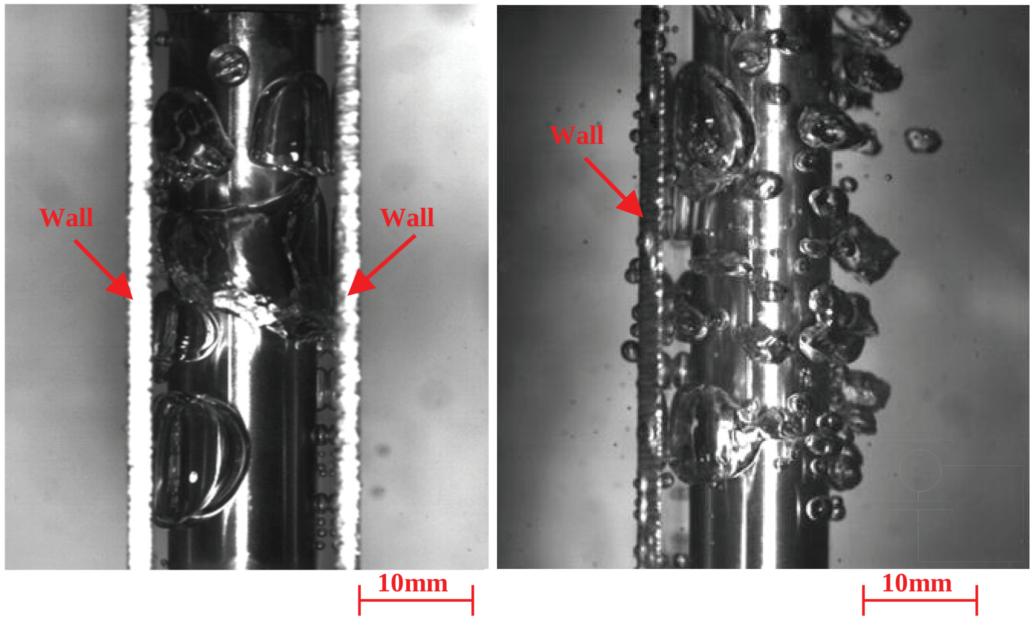
Figure 9. Acceleration trajectory of heater rod with 1mm-gap to each wall

5. DISCUSSIONS

5.1. Bubble behavior

The bubble behaviors are compared in the case of 1mm-gap under the condition of ΔT_{sub} = 1K between this study (Parallel walls case) and the previous study (Single wall case) [5] as shown in Figure 10. From the point of view of large bubble generation, the condition in the region of the gap between the heater rod and the wall could be similar both in Parallel walls case and Single wall case. In the aspect of small bubble generation, few small bubbles were existed not only in the gap region but also at the heater rod surface in X-direction in Parallel walls case, while many of small bubbles were observed in particular at the rod surface in the side without the wall in Single wall case.

In Parallel walls case, large bubbles grew and rose rapidly in narrow gap area at both sides with walls, and sometimes turned around the rod towards X-direction to coalesce with another large bubble. In the process of this behavior, the large bubbles seemed to sweep the heater rod surface rapidly and remove the heat from the heater surface, which could reduce generation of small bubbles.



(a) Parallel walls case (Present study) (b) Single wall case (Previous study [5])

Figure 10. Bubble behavior around heater surface and wall (1mm-gap, ΔT_{sub} = 1K)

5.2. Trajectory of acceleration

In Figure 11 trajectories of acceleration obtained in Parallel walls case (the present study) are compared with Single wall case (the previous study) under the same conditions of 1mm-gap and ΔT_{sub} = 1K.

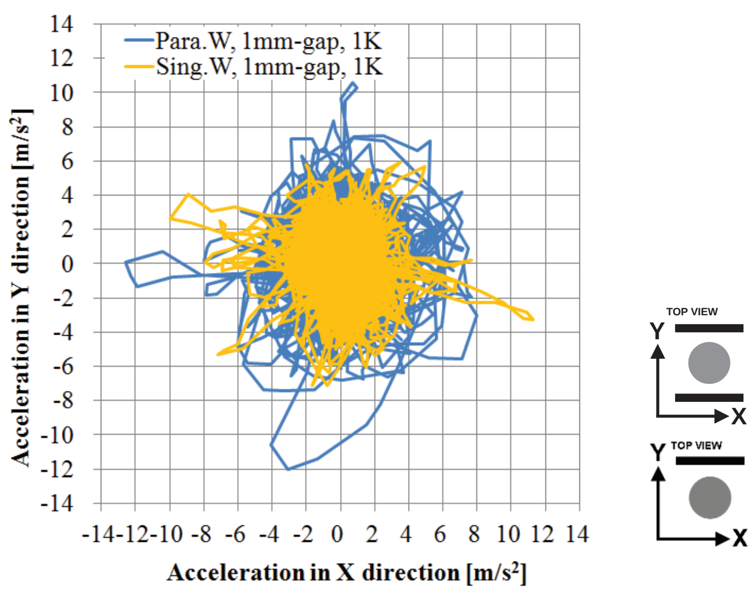


Figure 11. Acceleration trajectory of heater rod (1mm-gap, ΔT_{sub} = 1K)

Generally, the trajectory of acceleration in Parallel walls case was larger than that in Single wall case. There was not much difference in X-direction, but acceleration in Y-direction in Parallel walls case was obviously larger. The trajectory in Single wall case featured irregular changes in Y-direction, while it is found that the trajectory in Parallel walls case presented direction changes of acceleration vectors like corresponding to large bubble behavior mentioned in the chapter 4.2.3, which was not observed in Single wall case.

5.3. Acceleration RMS of vibration

In the case of 1mm-gap of the present study, the RMS values were calculated from the obtained acceleration data and depicted with the variation of the degree of subcooling respectively for X- and Y-directions in Figure 12. The acceleration in Y-direction was larger than that in X-direction, which is consistent with the confirmation on the trajectories of acceleration.

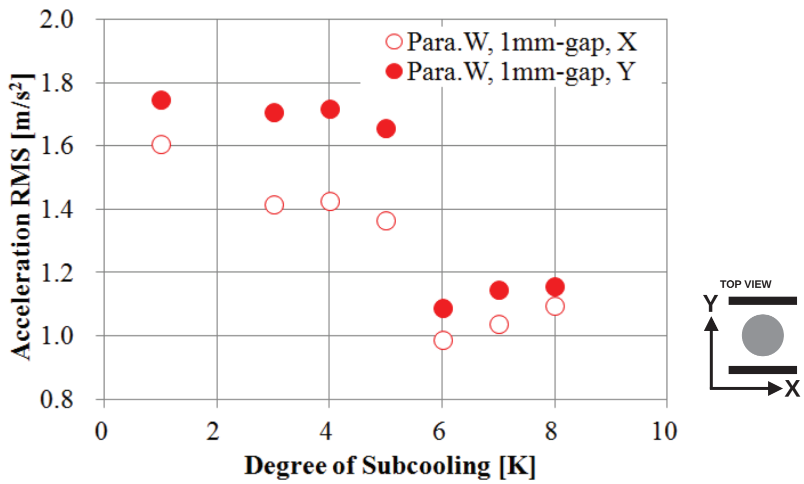


Figure 12. Acceleration PSD in the case of 1mm-gap

It should be noted that acceleration largely increased from ΔT_{sub} = 6K to 5K, roughly with 40% of increase. As mentioned before, behavior of large bubbles such as moving around the rod towards X-direction, coalescing, wrapping partly the rod and departing, is remarkable in the case of 1mm-gap under lower degree of subcooling. Considering this, change of the thermal hydraulic conditions from ΔT_{sub} = 6K to 5K could initiate the remarkable behavior of the large bubbles for the configuration with 1mm-gap between the heater rod and each of the walls in the experiment. No coalescence of large bubbles in X-direction was observed under the conditions of $\Delta T_{sub} > 6$K.

5.4. Acceleration PSD of Vibration

FFT of the acceleration data, obtained in X- and Y-direction respectively, are provided the power spectrum density (PSD) of the acceleration in Parallel walls case with 1mm-gap as shown in Figure 13. PSD in Parallel walls case with 1mm-gap under ΔT_{sub} = 1K is compared with that of Single wall case in Figure 14. By the external input to the experiment system, it was roughly confirmed that the first natural frequency of the heater rod was around 500Hz, which corresponds to the peak of PSD shown around 500 to 600Hz, both in Figure 13 and 14.

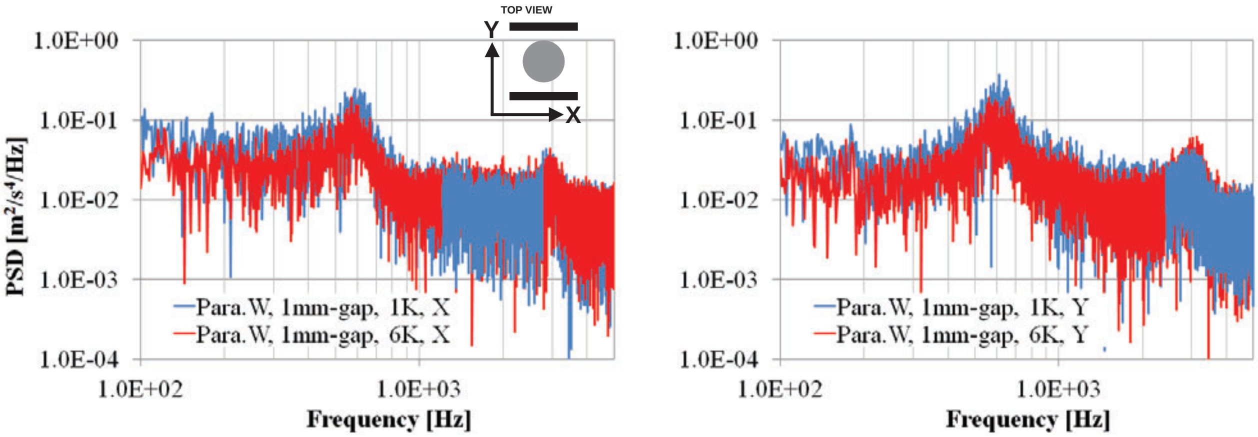


Figure 13. Acceleration PSD in Parallel walls case with 1mm-gap

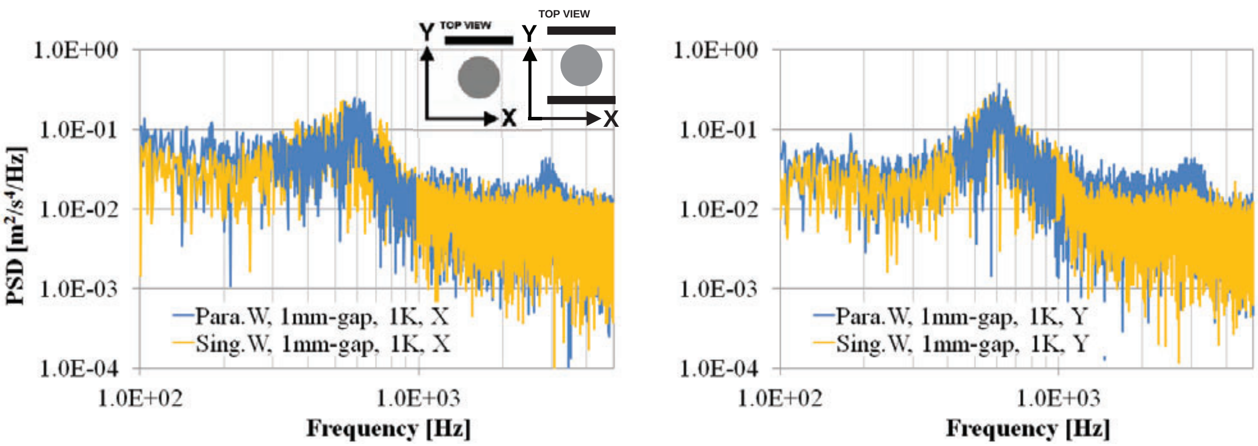


Figure 14. Acceleration PSD in Parallel walls case and Single wall case both with 1mm-gap

Figure 13 shows that no significant difference of PSD in the range of higher frequency (> 1kHz), while slight increase of PSD in the range of lower frequency (< 1kHz), for both in X- and Y-directions. Condensation of small bubbles not growing largely is considered to cause the SBIV in the range higher frequency, but few small bubbles were observed in the case of 1mm gap in Parallel walls case even under the condition of ΔT_{sub} = 6K. On the other hand, the remarkable behavior of the large bubbles was observed under the condition of ΔT_{sub} = 1K, which could correspond to the PSD increase in the range of lower frequency (< 1kHz).

Regarding to the differences of PSD in Figure 14, larger PSD in Single wall case in the range of higher frequency (> 1kHz) is confirmed in Y-direction, which could also correspond to the influence of small bubbles on the SBIV. In addition, larger PSD in Parallel walls case in the range of lower frequency (< 300Hz) in X-direction is significant. This means that the remarkable behavior of large bubbles in X-direction in Parallel walls case could influence on the SBIV of the heater rod.

The peak of PSD around 3000Hz both in X- and Y-directions clearly was confirmed in Parallel walls case in Figure 14. The frequency around 3000Hz is considered to be close to the second natural frequency of the heater rod, but further investigation on this point should be done in a future study.

6. CONCLUSIONS

In order to investigate the fundamental phenomena of the SBIV of a heater rod installed in the subcooled water, the experiments of a pool boiling under various degrees of subcooling by the simplified apparatus under an atmospheric pressure condition were performed. In the experiments, influence due to walls arranged in parallel at both sides of the vibrating heater rod was taken into account with the two conditions of 1mm-gap and 3mm-gap between the heater rod surface and each of the walls. The results of the experiments suggested the following points:

(1) The walls arranged in parallel at both sides of the heater rod with 1mm-gap and 3mm-gap obviously provided the influence on the SBIV of the heater rod as the larger acceleration onto the rod. The influence was not only in the direction towards the wall but also in the direction in parallel to the walls in the case of 1mm-gap, for which large bubbles played the remarkable role to move around the heater rod toward the direction in parallel to the walls, coalesce other large bubbles moving from the other side of the rod, wrap partly over the heater rod and depart from the rod.

(2) Acceleration largely increased from ΔT_{sub} = 6K to 5K, roughly with 40% of increase. This suggests that change of the thermal hydraulic conditions from ΔT_{sub} = 6K to 5K could initiate the above-mentioned remarkable behavior of the large bubbles for the configuration with 1mm-gap between the heater rod and each of the walls in the experiment. No coalescence of large bubbles in X-direction was observed under the conditions of ΔT_{sub} > 6K.

In conclusion, large bubbles generated in the narrow gap between the heater rod and the wall are one of the key factors to influence the SBIV of the heater rod, in particular in the case to confine thermal hydraulic conditions around the heater rod like the walls arranged in parallel at both sides of the heater rod.

The configurations of the experimental apparatus in the present study were simplified as opposed to the actual fuel assembly for PWR, as well as conditions of pressure and temperature in bulk water was limited. Taking these differences into consideration, for further investigation on the fundamental phenomena of the SBIV, more experiments with other types of configurations such as other arrangements of walls around the heater rod and the rod-bundle will be necessary.

NOMENCLATURE

q'	heat flux	(Wm^{-1})
r	distance from the center of the column in radial direction	(m)
T	temperature	(K)
λ	thermal conductivity	($Wm^{-1}K^{-1}$)

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