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# Vibration Characteristics of a Vertical Round Tube According to Heat Transfer Regimes

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## Abstract

This paper presents the results of an experimental work on the effects of boiling heat transfer regimes on the vibration. The experiment has been performed using an electrically heated vertical round tube through which water flows at atmospheric pressure. Vibration characteristics of the heated tube are changed significantly by heat transfer regimes and flow patterns. For single-phase liquid convection, the rod vibrations are negligible. However, On the beginning of subcooled nucleate boiling at tube exit, vibration level becomes very large. As bubble departure is occurred at the nucleation site of heated surface, the vibration decrease to saturated boiling region where thermal equilibrium quality becomes 0.0 at tube exit. In saturated boiling region, vibration amplitude increases with exit quality up to certain maximum value then decreases. At liquid film dryout condition, vibration could be regarded as negligible, however, these results cannot be extended to DNB-type CHF mechanism. Frequency analysis results of vibration signals suggested that excitation sources be different with heat transfer regimes. This study would contribute to improve the understanding of the relationship between boiling heat transfer and FIV.

# 1. Introduction

The dynamic interaction of structure and fluid is one of the most fascinating problems. Among these problems, flow-induced vibration (FIV) is one of the important concerns in numerous industrial fields, including the aerospace industry, civil engineering and nuclear engineering. In nuclear industry, many components, e.g., steam generators, condensers, piping systems and nuclear fuels, are subjected to high axial or cross flow which could often cause vibration problems, resulting in wear, fretting damage of those systems. Furthermore, the development of advanced nuclear reactors and the use of high-strength materials make structures become more slender and more susceptible to it.

Critical heat flux (CHF) is also regarded as another important parameter in operation and safety analysis of nuclear reactors and, consequently, has received a great deal of study. The condition constitutes an important limitation on the operation of boiling heat transfer systems. In heat-flux-controlled systems such as nuclear reactors, the consequence is a substantial increase in wall temperature, which may result in physical failure of heat transfer systems. Therefore, it should be assured that the condition could not be taken place in important heat transfer systems.

Recently, Hibiki and Ishii [1] carried out an experimental investigation on the effect of FIV on two-phase flow structure in vertical tube. They reported that the FIV drastically changed the void fraction profiles from “wall peak” to “core peak”. The fact means that CHF with environment of vibration might be also considerably changed. Therefore, to identify the vibration effect on CHF is very a crucial and practical problem. Unfortunately, in nuclear fuel assembly where parallel or axial flow is dominant, the presence of high heat load, complicated geometries and high turbulences make it extremely difficult to predict the CHF-FIV relation. In addition, during the several past decades, many researchers involved in FIV have conducted experimental and analytical studies especially on cross flow condition such as steam generator [2~5]. Such extensive works reveal much aspects of vibration in cross flow but the research activities related with axial-flow-induced vibration are rather rare. This is due to the fact that the problem is more severe in cross flow condition than in or axial flow condition. Although relatively small, the vibration in axial flow may cause impact, which may result in wear, fretting damage of fuel rod [6] and changes in local flow parameters, which result in the change of heat transfer rate or CHF [7~10].

Even though these two topics have traditionally been studied independently, a study closely linking them is highly desirable because a design to increase the CHF could induce the adverse FIV.  This would contribute to the design optimization of high heat flux equipments with enhancing the CHF while preventing FIV problems.

This paper presents the results of an experimental work on the effects of heat transfer regimes on vertical round tube vibration. It would contribute to improve the understanding of the relationship between boiling heat transfer/CHF and FIV.

# 2. Review of Available Literatures

In two-phase axial flow, possible vibration excitation mechanisms are classified by following four categories [11]; fluidelastic instability, phase-change noise, random turbulence excitation and acoustic resonance. Generally, vibration from boiling heat transfer process is correspond to phase-change noise. For examples, Collier and Thome (1994) [12] explains that “When either the local liquid temperature is increased above the corresponding saturation temperature or the local pressure is below the vapour pressure, bubble generation/growth could be occurred at the nucleation site of heated surface. Moreover, if high degrees of subcooling are involved, collapse/condensation of the vapour bubbles are activated. These processes are sometimes accompanied by the noise and vibration of the heating surface.

An exploratory experiment to study phase-change excitation mechanism was carried out by Pettigrew and Gorman (1973) [13]. They measured nucleate boiling noise on an electrically heated cylinder inserted in an axial flow test section connected to a steam-water loop. The cylinder heat flux was raised from 0 to 1600kW/m$^2$. They found that for mean steam qualities greater 10 percent, the effect of nucleate boiling and subcooled nucleate boiling at the surface of the cylinder were negligible. The same result was reported in experiment to study the vibration behavior of nuclear fuel under reactor condition (Pettigrew, (1992)) [14].

Celata et al. (1995) [15] made use of the accelerometric equipment used in boiling detection and CHF test facility used in hypervapotron experiments in order to simulate the subcooled boiling thermal hydraulics of a divertor tube mock-up. In their experiments, measurement of noise or vibration originated from the bubble growth and collapse was used as a method for the detection of the subcooled boiling phenomenon covering the whole heat transfer regime, on externally heated cylindrical channels from the single-phase up to the CHF. Their basic understandings are as follows:

i. At the onset of nucleate boiling, bubble cavities increase with the related noise emissions and then, with increasing heat flux, the accelerometer signal reaches a maximum.
ii. The signal can be quite stable during fully developed boiling (FDB), when the bubble dimensions and frequencies increase.
iii. At the higher heat flux, the vibrations reduce gradually because of the appearance of another phenomenon. In fact, due to the damping of the greater bubbles that begin to implode in the bulk of the fluid rather than on the heated surfaces, this padding effect procures a noticeable reduction of the vibrations.
iv. Approaching to the CHF, a sudden drop of the signal was recorded due to the vapour film formation on the inner tube surface.

These are considered as very comprehensive explanations about vibration characteristics at heating condition. Nevertheless, there are some limitations in application because of the data of short test section (e.g., L/D =10, 15) and somewhat different geometry.

Recently, Nematollahi et al. [16,17] give information on the intensive subcooled boiling-induced vibration in annular channel geometry under atmospheric condition. Their experimental works present the influence of subcooling temperature, linear power density and flow rate on heated tube vibration and they also indicated that the change in vibration level was remarkably varied with the transition from single-phase heat transfer to subcooled boiling heat transfer. Therefore, by measuring vibration signal, we could diagnose the heat transfer regime.

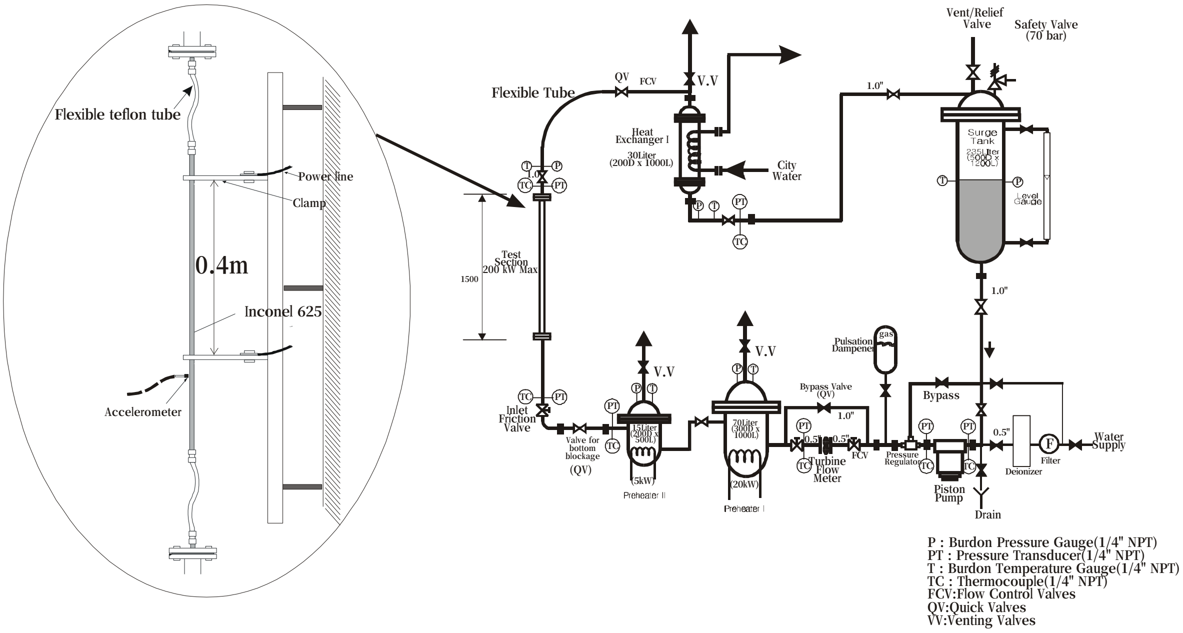

Fig. 1 Schematic diagram of the test loop and test section

## 3. Experiment

The experiments presented in this study have been carried out under atmospheric pressure condition. Fig. 1 shows the experimental loop and detailed view of test section. The test loop consists of round tube type test section, a main condenser, a displacement pump, a surge tank, a turbine flow meter, some valves and two preheaters. Each part is made of SUS-304 for the prevention of corrosion and connected with SUS-316 tubes of 1″ and ½″. Purified water was circulated by displacement pump and flow rate was controlled by two needle valves located at the upstream of flow meter and test section inlet. Test section was made of Inconel-625 round tube whose electrical and mechanical characteristics were well approved. Tube with inner diameter of 0.008m and heated length of 0.4m is instrumented with thermocouples to detect the incipient dryout and to trip the power controller. Three chromel-alumel (K-type) thermocoulpes are spot welded on the external surface of the tube. A pair of clamp type copper electrodes grabbed both ends of the test tube. In order to measure vibration in boiling heat transfer process, two charge-type piezoelectric accelerometers (Brüel & Kjær 4393) are tightly amounted to test tube just below lower copper clamp. In order to isolate the pump mechanical vibration, the end of the test section was connected to flexible Teflon tube with “Swagelok” fitting. The test section was uniformly heated by joule heating effect, and DC power (up to 40V, 5000A) was supplied by a transformer with silicon-controlled rectifiers (SCRs). The test section inlet and outlet bulk temperature were measured by T-Type thermocouples and inlet and outlet pressures were measured by strain pressure gauge made by Instech Limited. The volumetric flow rate into the test section was measured by Omega FTB 505 VDC turbine flowmeter which has the available range of 0.2 ~ 2.0 GPM.

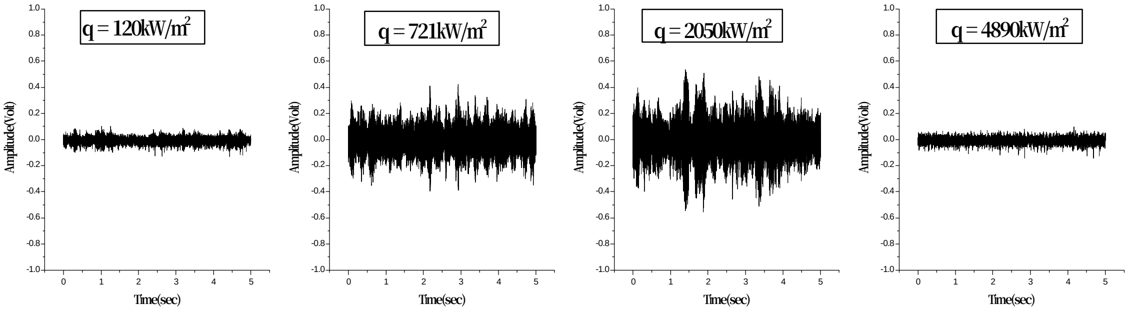

Fig. 2 Results of vibration signal at various heat flux (Gain = 10mV/m/s$^2$)

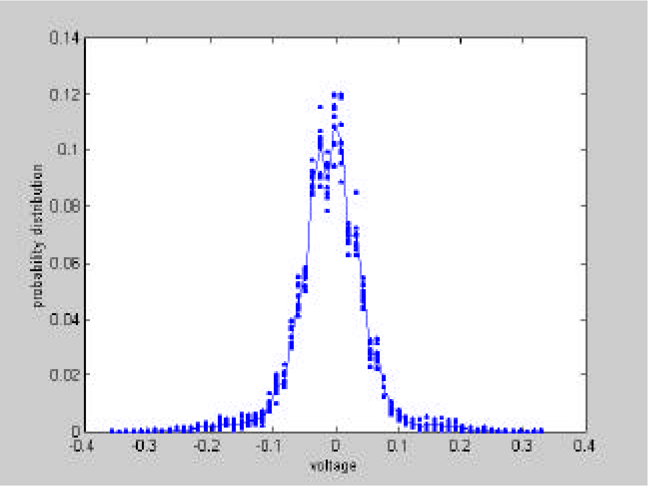

Fig. 3 the probability distributions for each ensemble data and total data

Through the data acquisition unit (HP3852A) and signal analyzer (HP35665A) for fast Fourier Transfer (FFT), digitized data from various sensors were recorded in real time, and some of them were also collected by computer system for later analysis. The test conditions are as follows:

| | |
|---|---|
| Inner diameter of tube ($D_i$) | 0.008 m |
| Outer diameter of tube ($D_o$) | 0.010 m |
| Heated length ($L_h$) | 0.4 m |
| Exit Pressure (P) | 101 kPa |
| Mass flux (G) | 718 ~ 1060 kg/m$^2$s |
| Inlet subcooling ($Dh_i$) | 318 kJ/kg |
| Applied heat flux (q) | 0 ~ 4901 kW/m$^2$ |

The test, carried out increasing the heat flux step by step, started from single-phase heat

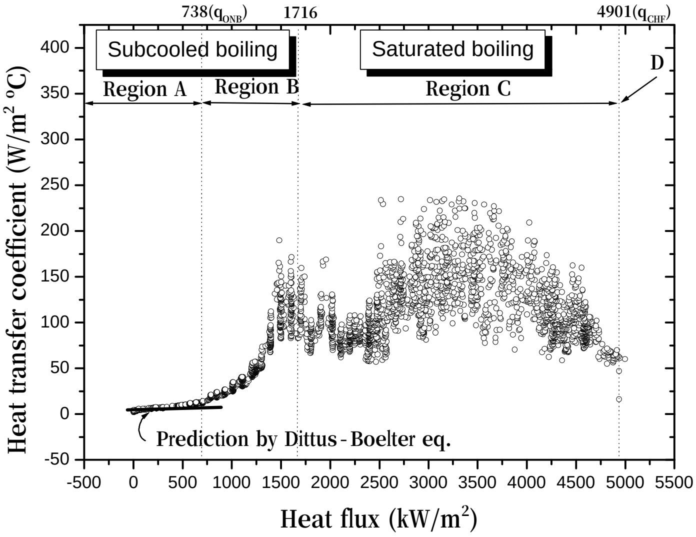

Fig. 4 Heat transfer coefficient from single-phase heat transfer region up to CHF condition
(Region A: Single-phase heat transfer; Region B: Subcooled boiling; Region C: Saturated boiling; Point D: CHF)

transfer region up to CHF condition. After it was confirmed that the steady state had been established in each step, fifty thousand of accelerometer signals were collected for five second. In Fig. 2, typical vibration signals are plotted according to time at various heat fluxes. Single sample data set of 50000 data can represent the random process consists of an infinite number of sample functions if the random signal is independent to absolute time and time interval. If the signal from accelerometer is stationary, the probability distributions for the ensemble are independent on absolute time. Fig. 3 represents the probability distributions for each 10 ensemble and total data.  Points and line are corresponds to ensemble probability distributions and overall probability distribution, respectively. From the figure, all ensemble have similar probability distributions. Therefore, the corrected vibration signals during the test are stationary. A stationary process is called an ergodic process if, in addition to all the ensemble averages being stationary with respect to a change of the time scale, the averages taken along any single sample are the same as the ensemble averages. During the test, we obtained data at the time of 0.1 ms and its average is -0.00694. For ergodic test, we calculated ensemble average at different time scale of 0.2 ms and 0.4 ms. the ensemble averages of 0.2 ms time have 1% of max error and the ensemble averages of 0.4 ms have 1.2% of max error So, it was confirmed that data correction process is ergodic with the change of the time scale.

## 4. Results and Discussions

Based on the deduced inner surface temperature from the measured outer surface temperature by solving simple conduction equation and measured bulk temperature at the end of the test section, the heat transfer coefficients ($h$) are plotted in Fig. 4 from single-phase

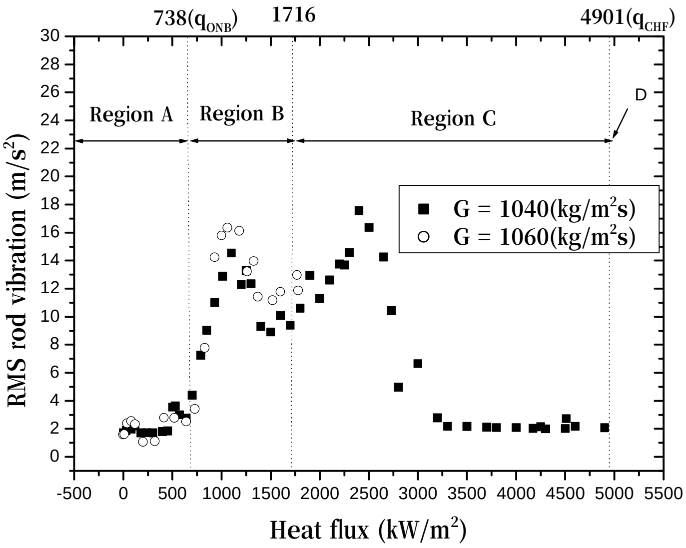

Fig. 5 RMS rod vibration from single-phase heat transfer region up to CHF condition
(Region A: Single-phase heat transfer; Region B: Subcooled boiling; Region C: Saturated boiling; Point D: CHF)

heat transfer region up to CHF condition. The prediction value of the well-known Dittus-Boelter equation for given flow and geometric condition also indicated in the figure. Region A, B, C and point D in Fig. 4 are correspond to single-phase heat transfer (non boiling) region, subcooled boiling region, saturated boiling region and CHF condition, respectively. In the single-phase convective heat transfer region, *h* is relatively constant. In the subcooled nucleate boiling region, *h* increases linearly with length up to the point where x = 0.0. In saturated boiling, *h* generally remains constant. However, large deviations of *h* exist in saturated boiling region of the figure. These deviations come from rapid variation on surface temperature due to periodical generation of dry patches. At CHF point, abrupt reduction of *h* is appeared as seen in the figure.

In this study, vibration amplitude will be discussed in terms of root mean square (RMS) value of acceleration signal. Fig. 5 shows RMS rod vibration according to heat transfer regime. There exist two peaks through the entire heat flux range. Two peak are appeared at q = 1210 and 2210 kW/m$^2$, whose thermal equilibrium quality become -0.05 and 0.07, respectively. The first peak is included in subcooled nucleate boiling region and the second peak in saturated boiling region at tube exit condition. Similar results are appeared in Fig. 6. It represents RMS rod vibration according to thermal equilibrium quality and flow pattern. Flow regime transition criteria proposed by Mishima and Ishii (1984) [18] used in this study. Also, we can find out that the first peak is included in bubbly flow region and the second peak in annular-mist flow region.

Frequency response results from at single-phase heat transfer region to at near CHF condition were illustrated in Figs. 7 ~ 10.

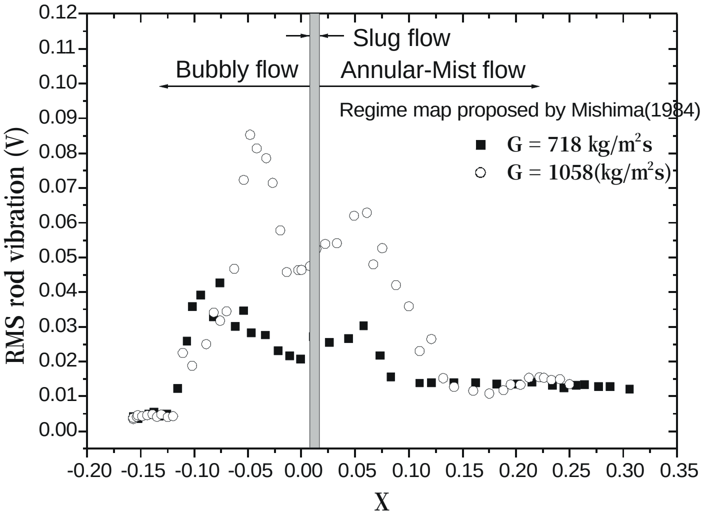

Fig. 6 RMS rod vibration according to flow patterns changes at tube exit

■ Vibration characteristics of single-phase heat transfer (Region A)

For single-phase heat transfer region, RMS rod vibration is negligible as seen in Fig. 5 ~ 6. The vibration level is equivalent to that of background signal. In region of convection to single-phase liquid, the surface temperature remains below that necessary for nucleation, therefore, it is impossible to work a vibration excitation source. However, some vibration could be generated in the process of enthalpy mixing in liquid phase. Local enthalpy deference can make local pressure difference that gives a shock to vibrate the surface. But their magnitude is very so small that can be ignored. Furthermore, random turbulence force might be possible to excite surface vibration, but still can be ignored. Frequency response results at single-phase heat transfer are depicted in Fig. 7. Several small peaks of relatively high frequency region are observed. Approaching to onset of subcooled nucleate boiling (ONB) heat flux ($q_{onb}$), the magnitude of $V^2$-RMS increases gradually and relatively low frequency components start to be observed.

■ Vibration characteristics of subcooled boiling region (Region B)

Based on the relationship between $q_{onb}$ and $(\Delta T_{sat})_{onb}$ suggested by Bergles and Rhosenhow (1963) [19], transition from single-phase heat transfer region to subcooled boiling region at tube upper end position is occurred when surface heat flux($q_{onb}$)is 738 kW/m$^2$ for G = 1040 kg/m$^2$s. RMS value of rod vibration abruptly increases in the near of $q_{onb}$, therefore it is reasonable to say that vibration measurement in heating condition can be an alternative method in the detection of onset of subcooled nucleate boiling [15]. With increasing heat flux, the accelerometer signal reaches maximum, and then decreases to saturated boiling region where thermal equilibrium quality becomes 0.0 at tube exit (Fig. 5~6). From Fig. 8, FFT results show that high frequency noise is still dominant in entire subcooled boiling region.

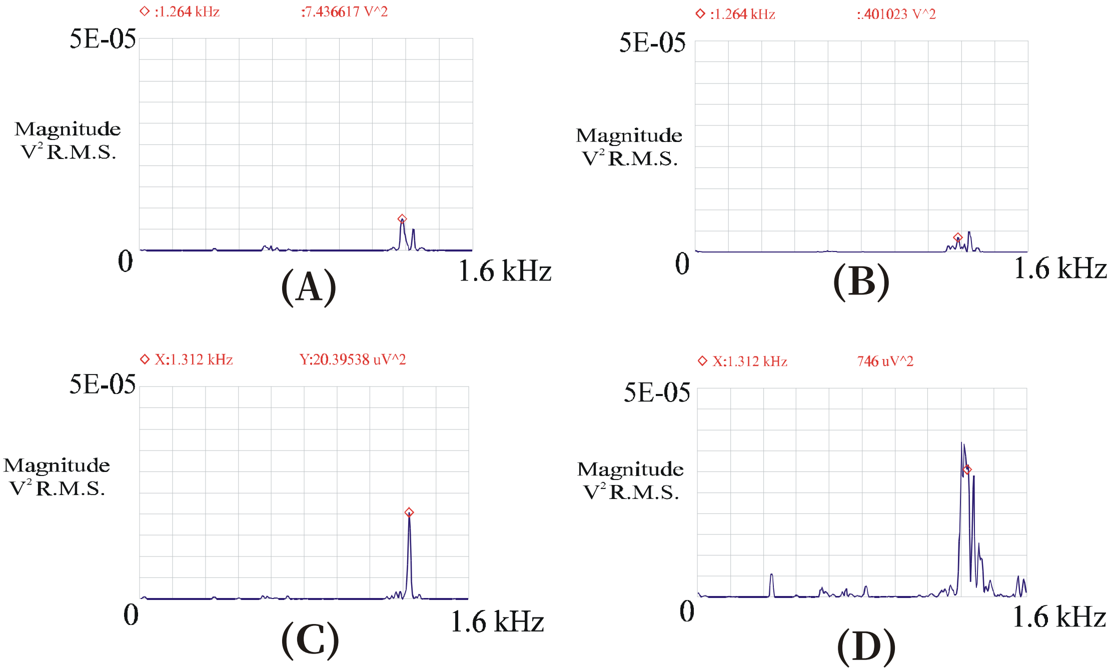

Fig. 7 Frequency response results at single-phase heat transfer regime and ONB

((a) $q$ = 0 kW/m$^2$, (b) $q$ = 150.8 kW/ m$^2$, (c) $q$ = 310.5 kW/ m$^2$, (d) $q$ = 735.2 kW/ m$^2$ (ONB))

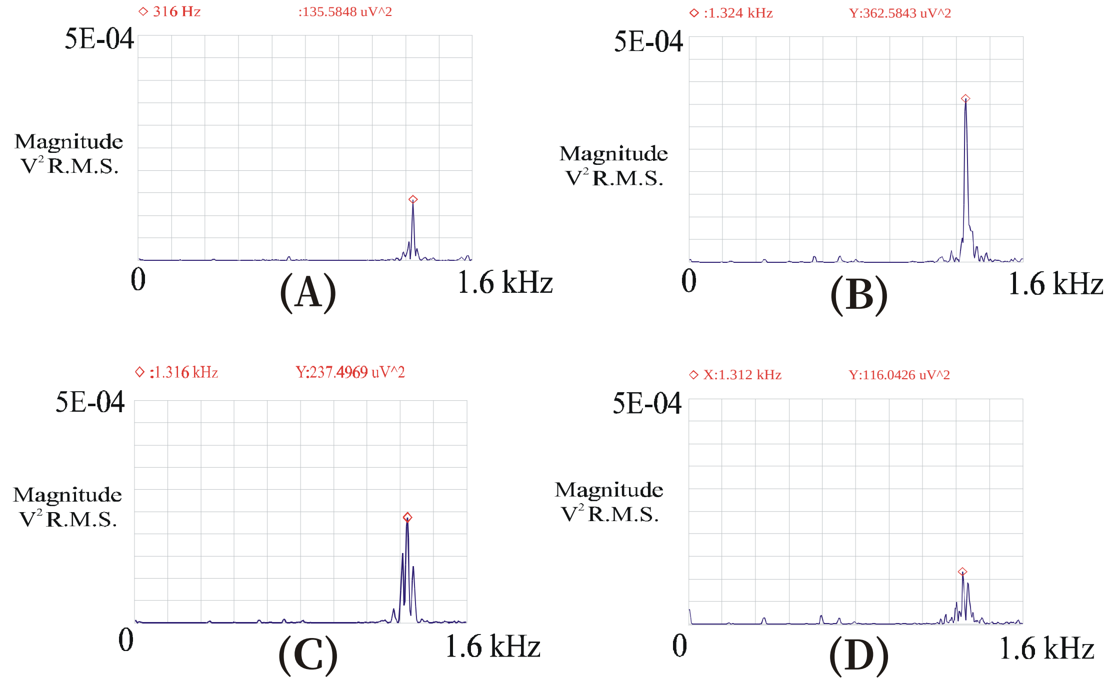

Fig. 8 Frequency response results at subcooled transfer regime

((a) $q$ = 882.3 kW/ m$^2$, (b) $q$ = 1024.7 kW/ m$^2$, (c) $q$ = 1212.1 kW/ m$^2$, (d) $q$ = 1518.8 kW/ m$^2$)

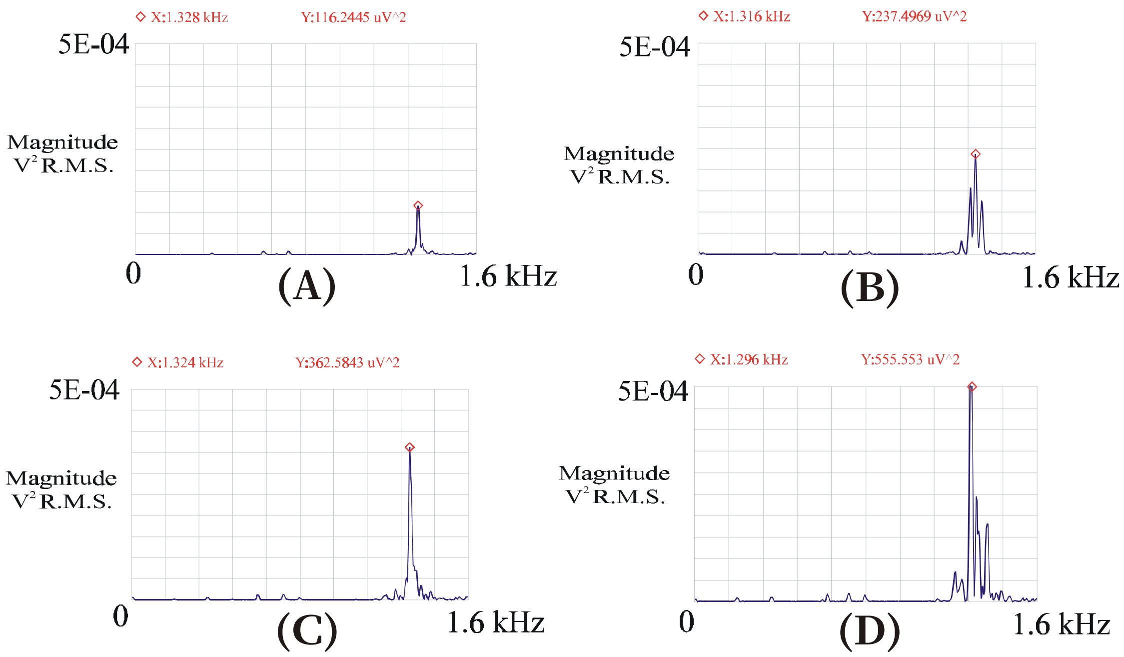

Fig. 9 Frequency response results at saturated heat transfer regime

((a) $q$ = 1725.7 kW/ m$^2$ ($X$ = 0.0), (b) $q$ = 2028.2 kW/ m$^2$ (Flow regime transition),
(c) $q$ = 2426.1 kW/ m$^2$, (d) $q$ = 2735.2 kW/ m$^2$ (Second peak))

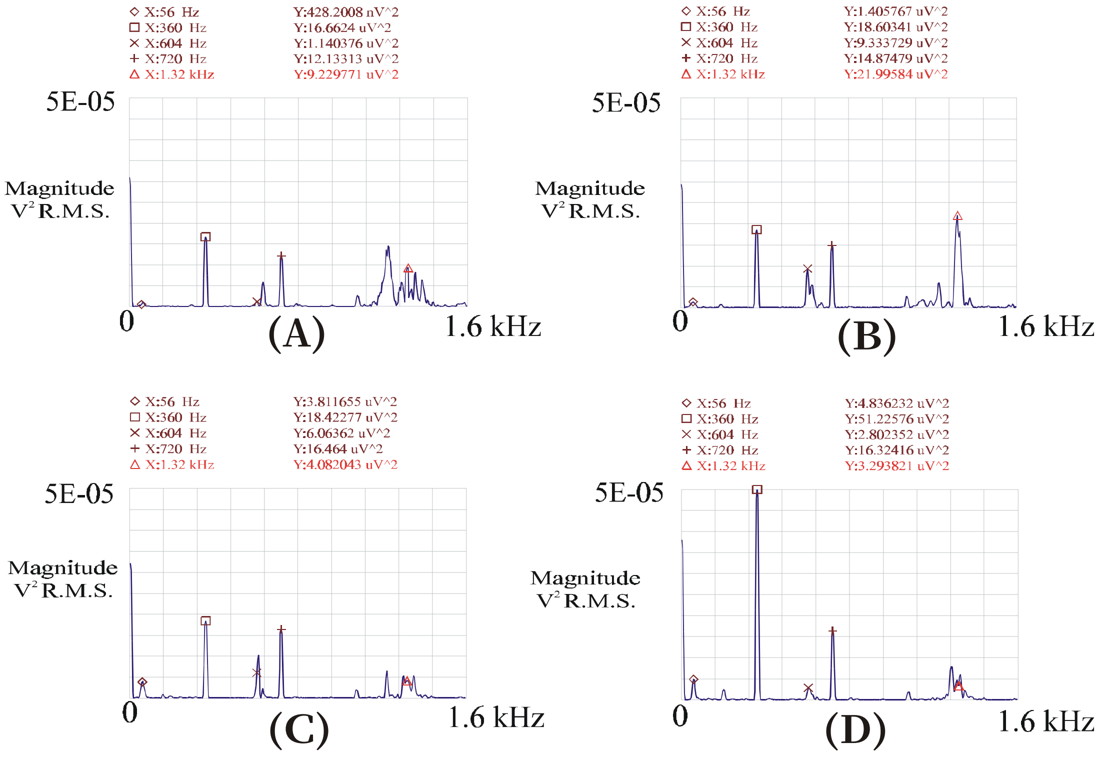

Fig. 10 Frequency response results at the near of CHF

((a) $q$ = 3527.6 kW/ m$^2$, (b) $q$ = 4022.0 kW/ m$^2$, (c) $q$ = 4609.3 kW/ m$^2$, (d) $q$ = 4805.9 kW/ m$^2$ (CHF))

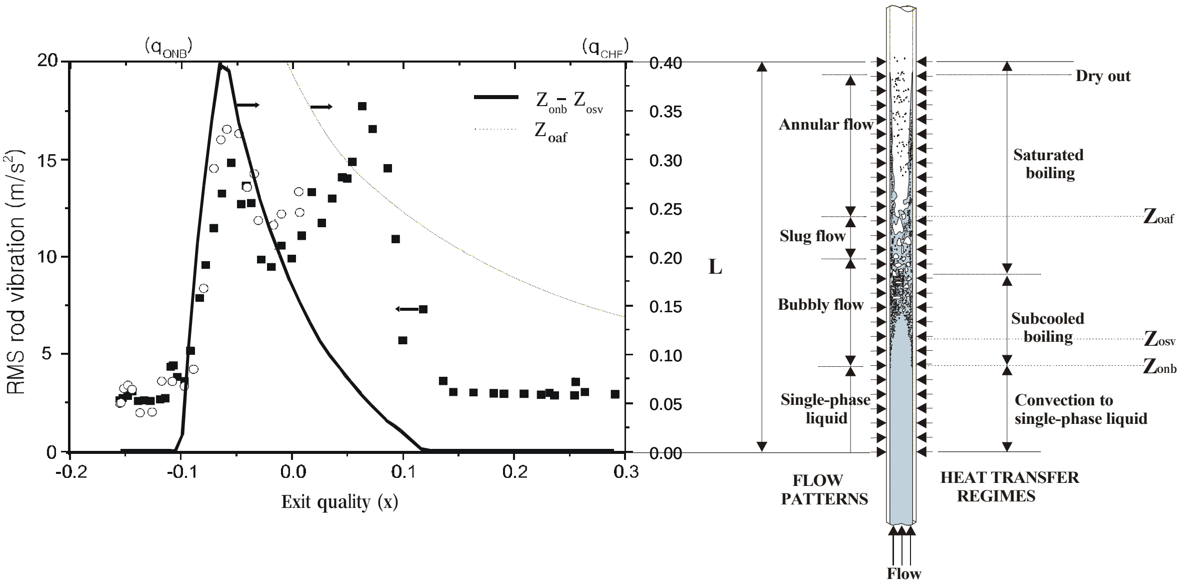

Fig. 11 Vibration characteristics in uniform heated vertical round tube

(D = 0.008m, L = 0.4m, P = 101kPa, G = 1040,1060kg/m$^2$s, $T_{in}$ = 23°C)

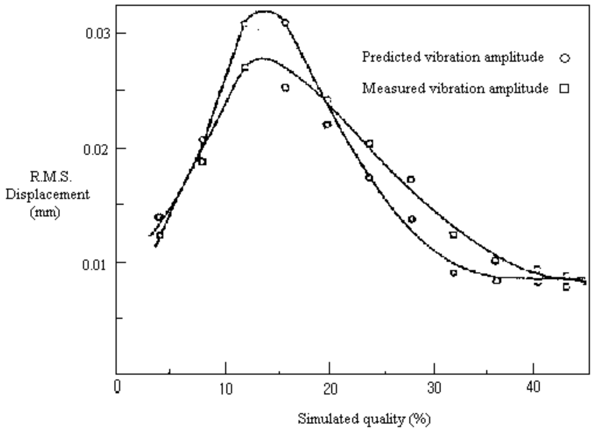

Fig. 12 Measured and predicted vibration amplitude verse simulated steam quality in axial two-phase flow (Gorman, 1971[21])

The number of nucleation site generally increases with surface heat flux and ONB position ($Z_{onb}$) moves down from tube exit to tube inlet. Consequently, highly intensive generation/growth and collapse/condensation of bubbles are occurred on the surface; hence increases vibration level. But at the higher heat flux, bubbles are likely to be condensed in liquid core rather than on heated surface, so bubble departure is occurred at the nucleation site of heated surface, that is, onset of significant void (OSV); bubble boundary layer thickness is increasing with heat flux, consequently, rod surface vibration decrease with heat flux. This is the reason why the first peak in vibration levels appeared at q = 1210 kW/m$^2$. In Fig. 11, more comprehensive illustration in view of channel length was suggested. In the figure, the OSV position (bubble detached point) was calculated along the channel height, based on Shah and Zuber (1974) model [20]. The difference between OSV position and ONB position, that is $Z_{osv}$-$Z_{onb}$,(bold line in Fig. 11) well represent vibration characteristics in subcooled boiling region. Therefore, it can be concluded that wall attached bubble is the most important parameter in subcooled boiling induced vibration.

- Vibration characteristics of saturated boiling region (Region C)

As heat transfer region change from sbucooled boiling to saturated boiling, vibration is increasing again and reach another maximum, then a noticeable reduction of the vibration is observed. Gorman (1971) [21] examined the effect of simulated steam quality on vibration amplitude in axial two-phase flow (Fig.12). According to the result, vibration increases with quality up to $x$ = 0.15, then decreases. Therefore, at relatively lower heat flux, vibration increase with thermal equilibrium quality. However, at the higher heat flux, the vibration is decreased significantly. The reduction of vibration seems to be related to the formation of liquid film on heating surface. Generally, as heat flux increases, annular flow pattern is dominant along the entire tube length. In annular flow regime, the bubble generation on heated surface is limited due to the thin liquid layer. This makes a significant reduction of vibration. So, it is reasonable to say that flow pattern changes have an effect on the vibration in saturated boiling region.

- Vibration characteristics of CHF condition (Point D)

Celata et al. [15] reported that, approaching to the CHF, a sudden drop of the signal had observed due to the vapour film formation on the surface. However, in this work, the sudden drop of vibration level was not observed as seen in Fig. 5~6. It seems that these different results come from different type of CHF mechanisms, that is, departure from nucleate boiling (DNB) and liquid film dryout (LFD). Celata et al.’s experimental data is for DNB type but the present CHF data is for LFD type. Therefore, it can be concluded that the vibration characteristics at CHF condition depends on the mechanism of CHF.

## 5. Conclusions and Recommendations

To find out the dynamic response of tube with heat transfer regime, vibration measurements are carried out under vertical upward flow at atmospheric condition. Several result of the present study are listed in the following:

(a) In region of convection to single-phase liquid, non-boiling region, the RMS of rod vibration is negligible
(b) In subcooled boiling region, wall attached bubble is the most important parameter in subcooled boiling induced vibration
(c) In saturated region, a noticeable reduction of the vibration is observed. It seems that the reduction of vibration are related to the formation of liquid

film on heating surface.

(d) At liquid film dryout condition, vibration could be regarded as negligible, however, these results cannot be extended to DNB-type CHF mechanism.

(e) Vibration characteristics of the heated tube are changed significantly by heat transfer regimes and flow patterns.

It is necessary to find out the effect of FIV on CHF as future works

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