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Flow-induced vibration in two-phase flow with wire coil inserts

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Abstract

Information of flow-induced vibration (FIV) in two-phase flow with wire coil inserts at atmospheric pressure, is presented in this study. FIV was measured in an upward vertical tube for four different wire coil inserts using an air–water mixture as process fluid. Vibration increased along with mass flux and quality. The narrower wire coils produced more vibration. The FIV prediction correlation for two-phase flow with wire coil inserts was experimentally developed with coefficient correlation value of 0.956.

Keywords: Flow-induced vibration; Two-phase flow; Wire coil

1. Introduction

Flow-induced vibration (FIV) of power and process plant components is a relatively unregulated technology by industry codes and standards. To a large extent FIV is an operational problem that has relatively little direct impact on public safety. Yet flow-induced vibration is often viewed as too mysterious one for the average practicing engineers to understand. The investigating method of predicting the vibrations of stable tubes and rods in response to external turbulent flows is important. At any instant of time, the surface pressures will exert a net lateral force on the rod and make turbulence-induced vibration. The vibration of the fuel rods contacting with the spacer grid makes scratch and damage on the cladding cover that results radioactive material release. A spacer grid with mixing vane and ribbed tube are designed to make high turbulence for higher heat transfer rate and critical heat flux (CHF) enhancement, that induces more vibration in the channel.

The purpose of this study is to develop FIV prediction correlation which includes geometric effect of wire coil designed to generate swirl flow, under two-phase flow condition.

2. Background

Many studies have been carried out on gas–liquid two-phase flow, because heat transfer enhancement is an important theme in order to improve performance of heat exchangers and steam generators. The bubble departure from the tube wall is retarded in subcooled flow boiling and low-quality region under microgravity. Therefore, it is necessary to positively remove the bubbles near the wall surface, because departure from nucleate boiling (DNB), in which there is a shift to film boiling from nucleate boiling, is apt to occur. When DNB occurs, the wall temperature rises rapidly. For this purpose, it is possible to improve the heat transfer coefficient and the critical heat flux pressing against the wall surface of the liquid phase and the droplet by the centrifugal force due to the swirl flow. When a swirl flow generator such as a twisted tape and a wire coil is inserted into a circular tube, the realization is possible. However, an increase of the energy consumption in the entire system including the pumping poser of the heating medium is generated, because the flow resistance also increases.

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Many studies have been published on the flow characteristics of gas–liquid two-phase flows in circular tubes using experimental and theoretical analysis. Studies of the flow characteristics in the circular tube with a swirl flow generator have been made: the study of the flow patterns and flow characteristics in a vertical twisted-tape-inserted tube by Lee et al. (1996, 1998), the study of the vertical upward flow in a grooved tube by Nishikawa et al. (1973), the studies of the flow characteristics in a horizontal tube with helical ribs of a rectangular or a circular shape installed on the inner surface by Lan et al. (1997), and the study of the suppression of droplet entrainment with the aim of improving evaporative heat transfer by Namie and Shiozaki (1990). Takeshima et al. (2002) investigated flow pattern, average void fraction, and pressure drop of an upward air–water two-phase flow in vertical tubes.

It is widely known that the heat transfer coefficient and the CHF are improved when swirl flow generators such as wire coils and twisted tapes are used. In regard to wire coil inserts, there are recent reports by Inaba et al. (1994) and Shoji et al. (1998) dealing with the heat transfer coefficient and the flow resistance in the transition region from laminar flow to turbulent flow for single-phase flows. An experimental investigation of the critical heat flux in subcooled flow boiling of water has been carried out by Celata et al. (1994) who found that use of turbulence promoters in a tube with a wire coil is an effective method for subcooled flow boiling CHF. Takeshima et al. (2002) investigated average void fraction, the local void fraction distribution and liquid film thickness of an upward air–water flow in vertical tubes, and reported that the average void fraction in tubes with wire coils is lower than in a smooth tube and decreases with the wire diameter owing to the centrifugal force of the swirl flow which concentrates bubbles at the center of the tube, that the local liquid film thickness becomes more uniform with a decrease in the pitch of the wire coil, and that the liquid film becomes thicker after the passage through the wire coil with an increase in the wire diameter.

Prediction of FIV is very important to prevent fuel damage in nuclear reactor. But, it is very complicated problem for mixture of fluid and vibration mechanism. Au-Yang (1975) performed vibration measurement in water flowing pipe and suggested empirical prediction correlation. FIV can be easily predicted using this correlation after measuring dynamic pressure fluctuation. This correlation is based on the experiment data of single phase pipe flow only.

Swirl flow is a hot issue for turbulent mixing and heat transfer. Swirl flow has centrifugal force that concentrates bubble at the center resulting liquid film thickening and CHF enhancement. There is little information about the vibration generated by swirl flow especially in two-phase flow condition. This study may provide information of vibration production by two-phase flow with swirl generator.

3. Experiments

The experimental study has been carried out under the conditions of atmospheric pressure. The test loop consists of a tube type test section, an air–water separator, a displacement pump, a surge tank, a turbine flow meter, ball and needle valves and an air blower. The schematic diagram of the test loop is drawn in Fig. 1. Each part is made of SUS-304 for the prevention of corrosion and connected with SUS-316 tubes of 2 in and 1 in.

The test section is constructed with circular acryl pipe of 25 mm inner diameter. Total length of the test section is 2 m. Entrance part for fully developed flow is 1 m, test part is 50 cm and outgoing section is 50 cm. The schematic diagram of the test section is drawn in Fig. 2. Four type swirl generating wire coils can be inserted in the middle part of test section changing wire thickness and twisting pitch length. Thickness is 2 mm and 3 mm, and pitch length is 25 mm and 50 mm. Wire coils are made of steel. Honey comb is inserted at the water inlet to stabilize flow.

Two B&K vibration accelerometers are attached at the center position of measure part of test section. All sensors

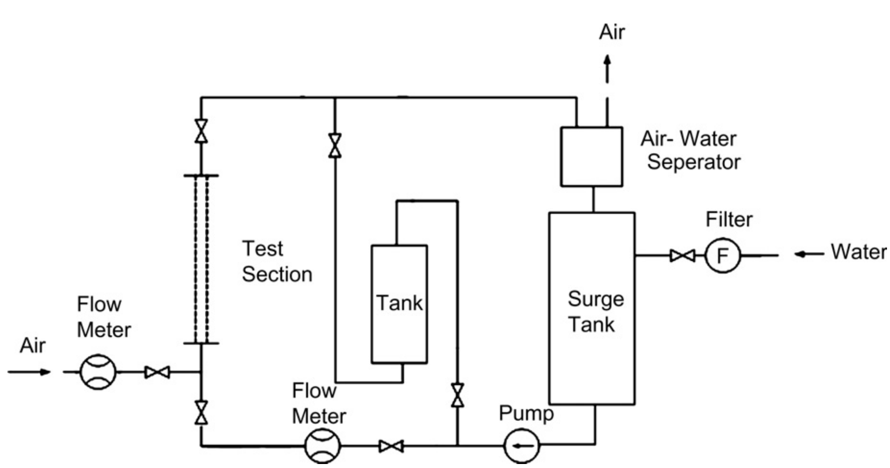


Fig. 1. Schemetic diagram of the experimental test loop.

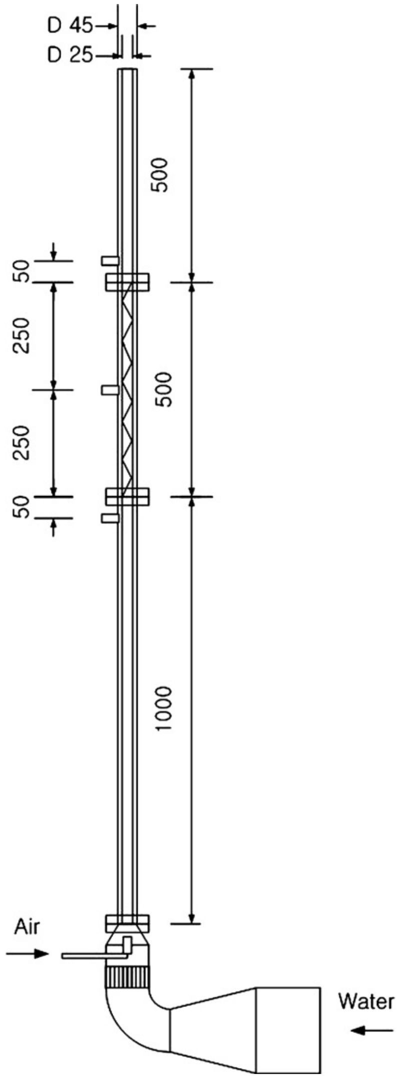


Fig. 2. Schematic diagram of the experimental test section.

use B&K NEXUS amplifier for band filtering from 1 Hz to 1 kHz and all signals transfer personal computer with data acquisition book. All random data has sampling rate of 2500 sample/s and total sampling time of 4 s.

Test was performed at atmospheric pressure condition under non-heating condition. Air–water was used as working flow. Experimental conditions are described in Table 1,

Table 1
Experimental conditions and ranges

Test section		
1	Smooth tube	
2	2 mm	25 mm
3	2 mm	50 mm
4	3 mm	25 mm
5	3 mm	50 mm
Flow condition		
j_L (m/s)	0.10–3.06 m/s	
j_G (m/s)	4.08–49.0 m/s	
P (kPa)	1.013 kPa	

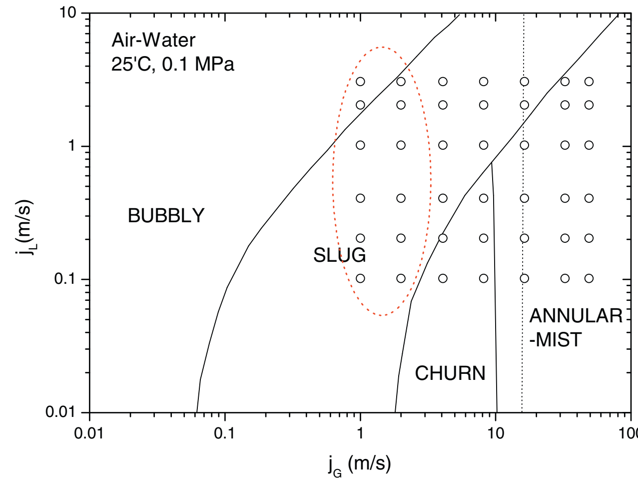


Fig. 3. Experimental flow range and Mishima-Ishii flow regime map.

and marked with circle in the flow regime map based on Mishima and Ishii (1982) model in Fig. 3.

4. Results and discussion

Totally, 210 experimental FIV data sets were collected under five different geometric conditions changing water mass flux and air mass flux. Mainly acceleration of test tube was measured at the middle of test part. Five test conditions are Smooth tube, wire coil A (thickness = 2 mm, pitch length = 25 mm), wire coil B (thickness = 3 mm, pitch length = 25 mm), wire coil C (thickness = 2 mm, pitch length = 50 mm) and wire coil D (thickness = 3 mm, pitch length = 50 mm).

4.1. FIV in water flow with twisted wire

Vibration of the test tube was measured in single-phase flow of water with and without wire coil inserts changing water mass flux from 100 kg/m^2 s to 306 kg/m^2 s. The

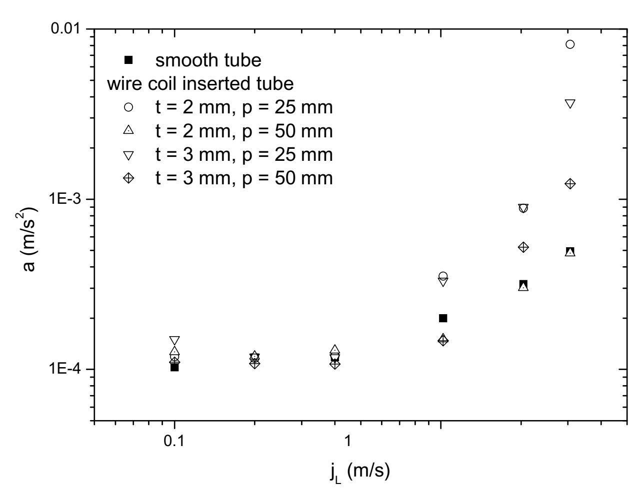


Fig. 4. Water mass flux effect on vibration in smooth tube and twisted wire inserted tube.

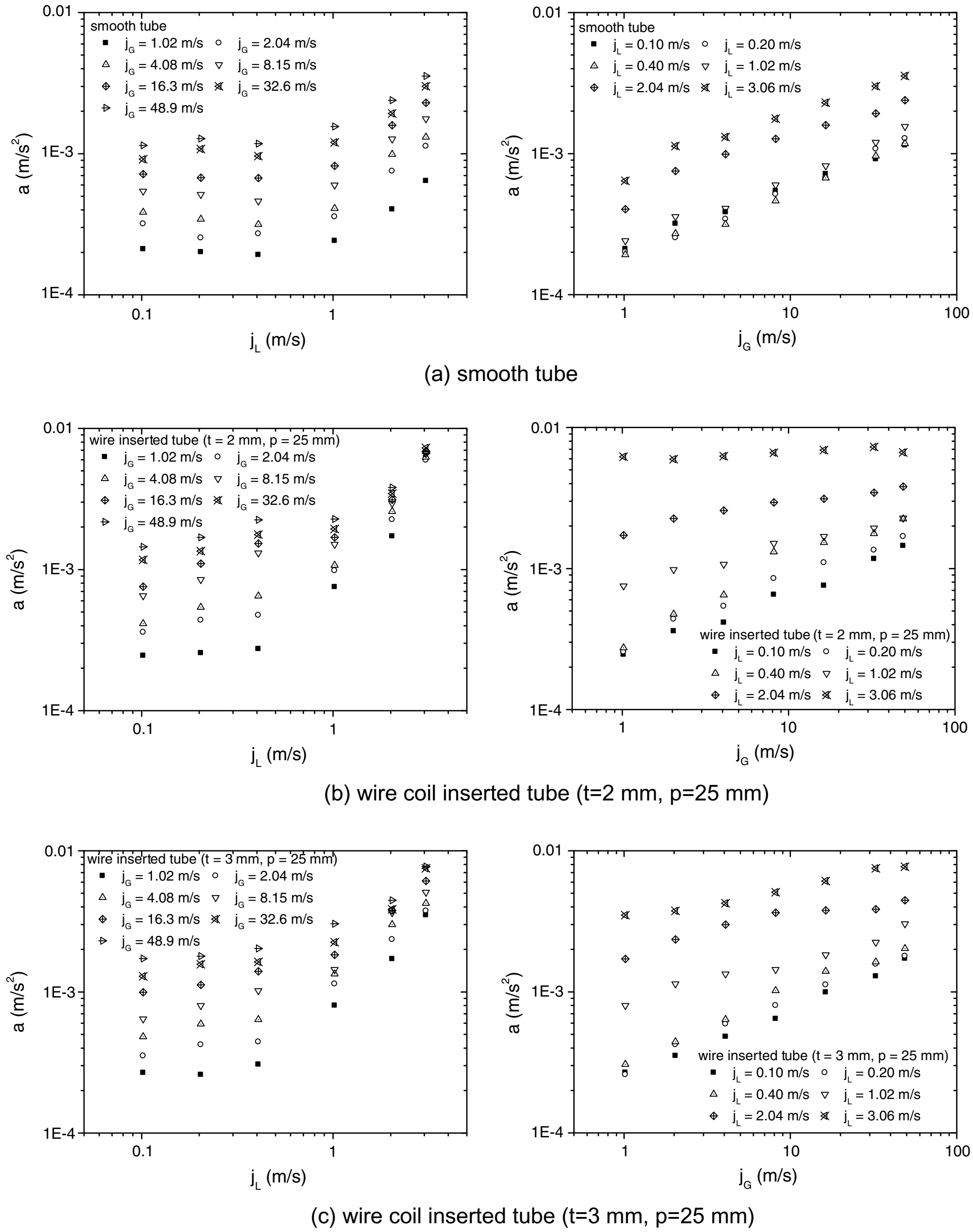
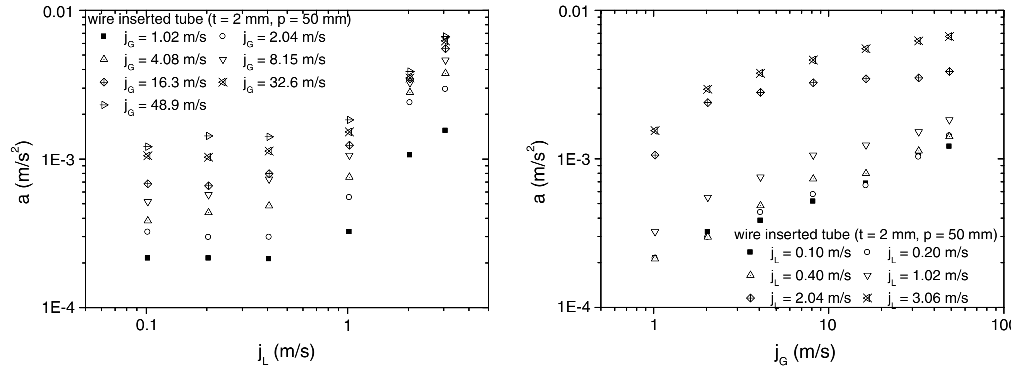


Fig. 5. Mass flux effect on vibration.

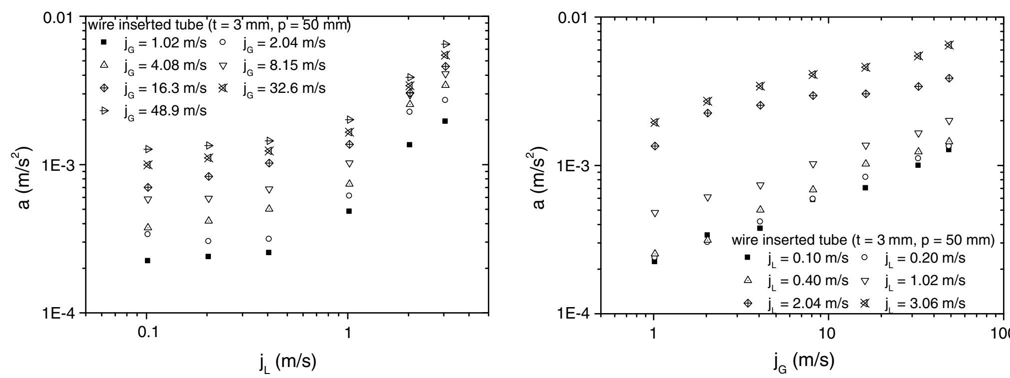
resultant data is shown in Fig. 4. Tube vibration increased as water mass flux increased, and wire coil inserts conditions produced more vibration than no-wire coil inserts (smooth tube) condition. The pitch length of a wire has significant effect on vibration increment: the wire coil with shorter pitch length produced higher vibration amplitude. The thickness of a wire showed adverse results with same pitch length. Vibration increment was mainly affected by pitch length of a wire and the effect of the thickness of a wire was a little. In low water mass flux, thick and narrow twisted wire inserts made the highest vibration result like previously reported data. In high water mass flux, thin and narrow twisted wire inserts made a little more vibration result. It seems that high turbulence force which is made by high mass flux has moved lighter thin wire directly.

4.2. FIV in air–water mixture flow with twisted wire

The tube vibration of the test section was measured in two-phase air–water mixture flow with and without wire coil inserts changing water mass flux and air mass flux. The resultant data is shown in Fig. 5. Air insertion promoted vibration increment especially in low water mass flux condition. Wire coil insertion effect on vibration was increased dependant on water mass flux increment, but air-induced vibration was decreased at high water mass flux. The effect of air insertion on vibration was decreased



(d) wire coil inserted tube (t=2 mm, p=50 mm)



(e) wire coil inserted tube (t=3 mm, p=50 mm)

Fig. 5 (*continued*)

especially at the case of narrow wire coil insertion. Air mass flux changing made no significant difference on vibration at high water mass flux when wire coil was inserted in the tube. It seems that high water mass flux makes turbulence force high that enforce low density air move to center core of the tube and reduces the vibration force generated by air mass flux for it can not face the wall of the tube. So, two-phase effect on vibration is almost zero at high water mass flux condition when wire coil is inserted in the tube. But, water mass flux effect on vibration becomes more powerful when wire coil is inserted in the tube. It seems that wire insertion makes turbulence force and resultant vibration is increased. The enforced vibration seems to come from the turbulence not from swirl for its intensity is too high to regard that it comes from swirl generation by wire coil insertion.

Overall vibration results are drawn in Fig. 6, with the flow pattern map based on Mishima and Ishii (1982) model to investigate characteristic of vibration at each flow pattern in the case of wire coil insertion. Takeshima et al. (2002) reported that: the bubble-to-slug transition occurred at lower air flow rates in the tubes with wire coils than in the smooth tube at higher water flow rates ($j_L \geqslant 0.5$ m/s). In the case of a tube with a wire coil, gas slugs were observed in the tube at the middle. It is considered that the bubbles dispersed by turbulent flow energy form gas slugs by the centrifugal force due to the wire coil. As a result, the larger the wire diameter and the higher the superficial water velocity are, the earlier the bubble-to-slug transition occurs. The slug-to-churn transition occurs at slightly lower air flow rates in tubes with wire coils than in a smooth tube.

Fig. 6 shows that vibration increment in slug flow is larger than other flow pattern and this situation is decreased when flow pattern is changed to annular flow. This shows that vibration detection may be used as flow pattern distinguishing method. Higher vibration produced by wire coil insertion, can be explained by turbulence energy and early flow pattern changing from bubble to slug. The vibration increasing effect of the wire coil was higher especially in slug flow and flow pattern was easily changed to slug flow when flow pattern was bubbly flow by centrifugal force that makes bubble to center gathered and makes it not easy to disperse bubble.

4.3. Correlation work

Based on experimental results, an FIV prediction correlation was developed, which properly reflect the vibration amplitude in two-phase air–water mixture flow with wire coil inserts. Parametric analyses were performed and resultant data are plotted in Fig. 7. Analytically conducted parameters were superficial water velocity, superficial air velocity, pitch length of the wire and thickness of the wire.

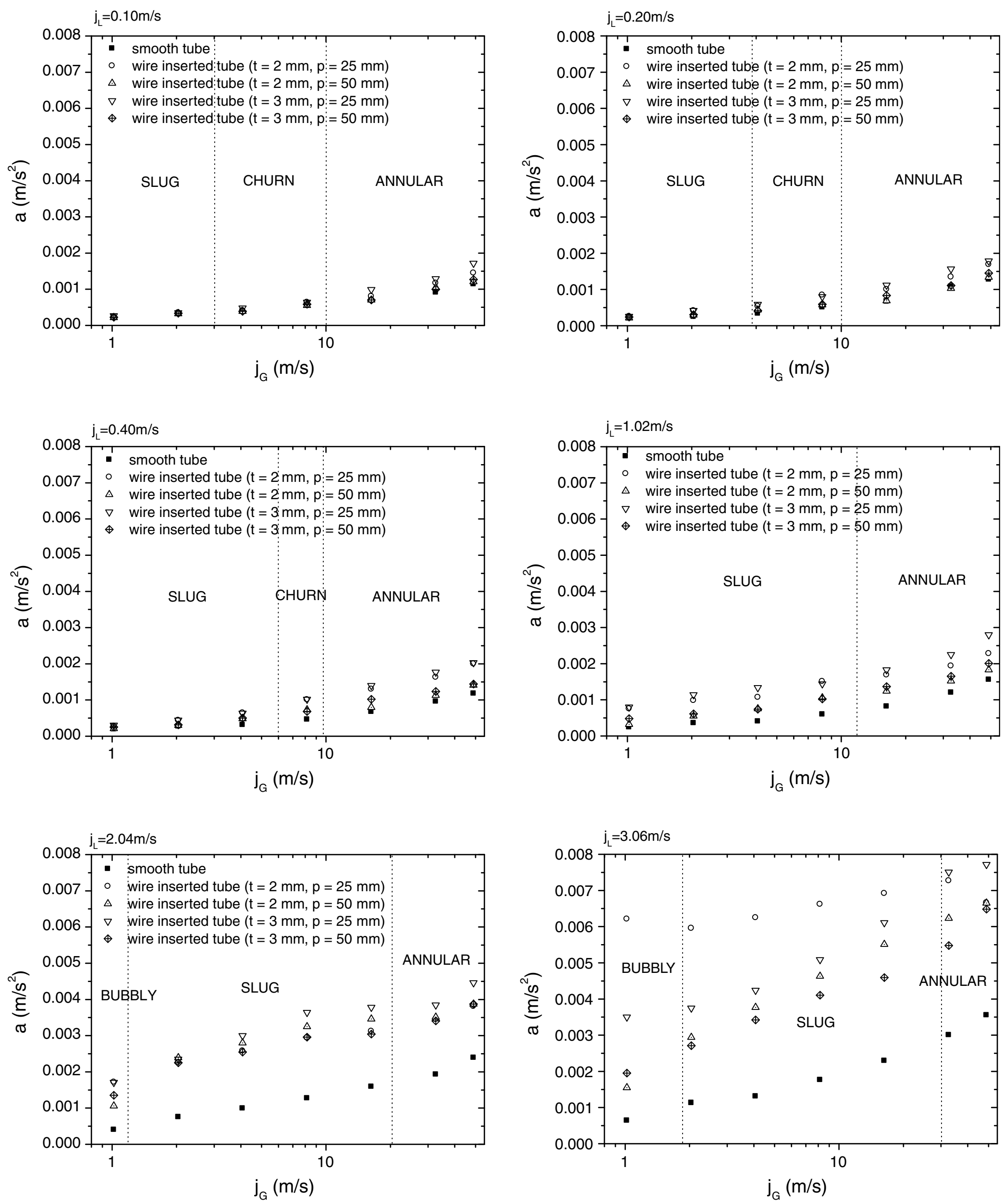


Fig. 6. Mass flux effect on tube vibration in flow pattern map.

Each parameter was compared with resultantly produced vibration acceleration and relative coefficient of correlation was calculated. The most effective parameter on vibration was superficial water velocity. The effect of superficial air velocity and pitch length was included in the correlation. But wire thickness did not show a significant effect on the vibration relatively. ACE algorithm was used for the method of correlation development.

$$a = f(j_L, j_G, p, t) \tag{1}$$

where 'a' means vibration acceleration, 'j_L' means superficial water velocity, 'j_G' means superficial air velocity, 'p' means pitch length of the wire and 't' means thickness of the wire. The resultant correlation is given by

$$a^{0.35} = 0.0247 j_L + 0.0204 \cdot j_G^{0.3} + 0.0006(p)^{-1} \tag{2}$$

The prediction performance of the correlation is shown in Fig. 8. The coefficient of correlation was 0.956. Eq. (2) gives predicted vibration acceleration according to two-phase effect and wire coil insertion effect, yielding an average error of 20.4% and standard deviation of 2.17. The correlation shows successful prediction ability.

5. Conclusions and recommendations

Experimental studies are carried out at atmospheric pressure in vertical round tube under air–water two-phase flow condition with wire coil inserts. FIV was measured at the middle part of the test section changing water mass

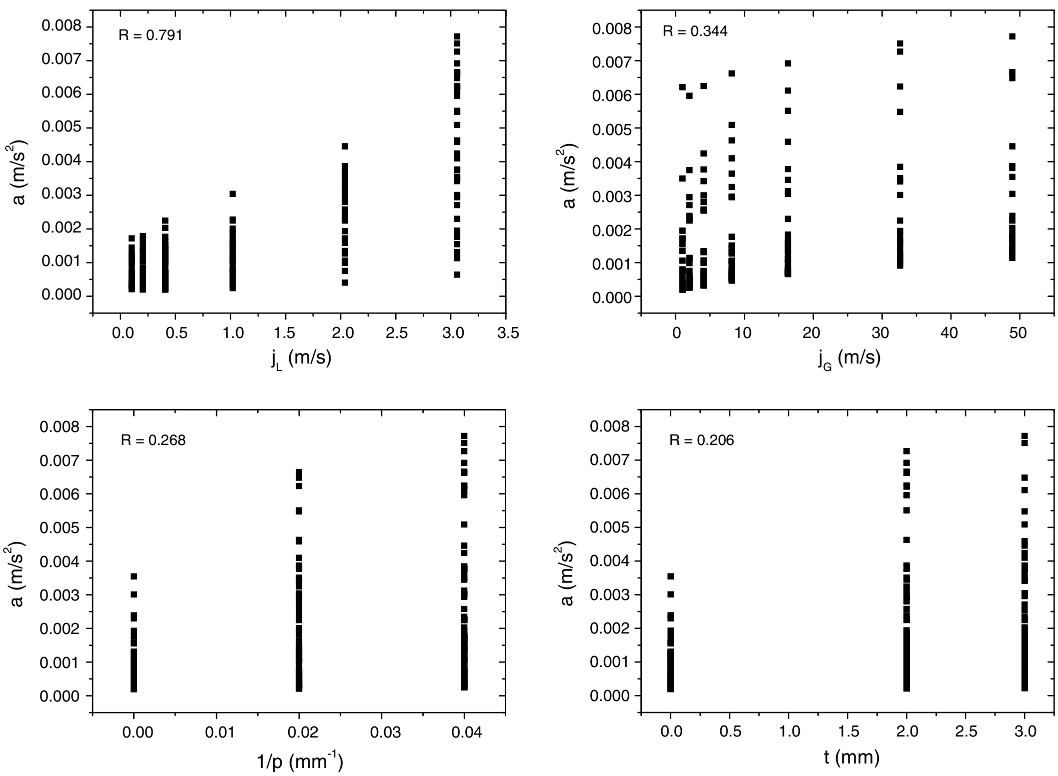


Fig. 7. Parametric coefficients of correlation.

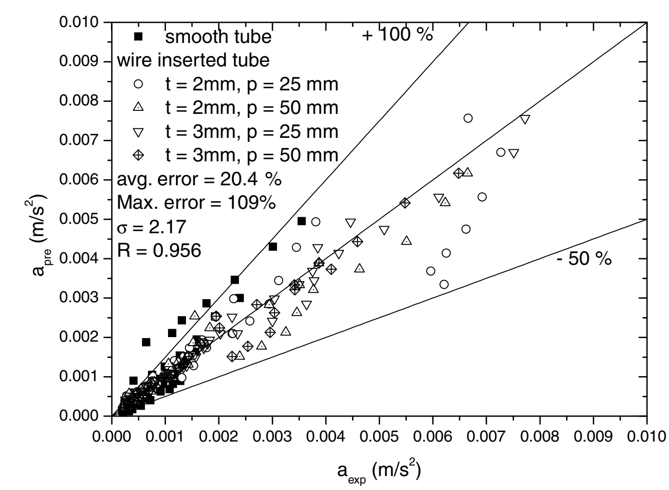


Fig. 8. Prediction performance of the suggested correlation.

flux, air mass flux and wire coil type. The main results obtained are as follows:

(a) FIV was increased along with water mass flux increase. Wire coil insertion promoted the effect of water mass flux on FIV. The wire coil with shorter pitch length produced more vibration by generating more powerful turbulence force and pressure fluctuation.
(b) Air insertion promoted vibration increment especially in low water mass flux condition. Wire coil insertion reduced the effect of air mass flux on FIV especially in high water mass flux condition. It seems that centrifugal force by high turbulence flow, moves air to center core of the tube that reduces the vibration effect of air mass flux on the tube wall.
(c) Vibration increment in slug flow was larger than other flow pattern. Wire coil insertion made early flow pattern changing from bubble to slug. It seems that centrifugal force made bubble to center gathered and made it not easy to disperse bubble making compulsive slug flow.
(d) Based on the experimental results, an FIV prediction correlation was developed after parametric analyses with coefficient of correlation value of 0.956.

Swirl generators can enhance heat transfer and CHF value. But, unexpected FIV can be brought leading to crack or damage of structures. This works can be the basis for optimal design of wire coil heat equipment which can enhance heat transfer and CHF considering FIV production. But, experiments were performed in one tube of 25 mm diameter. The developed correlation is not applicable to the tube with other size and rod bundle. This work is focused only on the flow-induced vibration production by wire coil insertion with various geometric designs. More expended experiments are needed for actual application.

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