Analysis of annular flow disturbance wave frequency in two different installation conditions

H Sun, M Gui
School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, P.R. China
E-mail: sunhongjun@tju.edu.cn

Abstract. The dynamic local liquid film thickness of annular flow was measured with a near infrared (NIR) equipment. Basing on the power spectral density (PSD) to analyze this signal, the frequency of disturbance wave was obtained. The experiment was carried out for both horizontal and vertical annular flow. Considering the effects of flow velocity and gas pressure, the results showed that the wave frequency increases with the increase of flow velocity and gas density in both installation conditions. For the numerical correlation, the frequencies of the vertical is more regular than those of the horizontal.

1. Introduction
Disturbance wave is one of the most important characteristics of annular flow. It has a significant effect on the mass and heat transfer efficiency of the liquid film. When disturbance wave appears, the flow state of the liquid film transforms from layer to turbulent, with which the heat transfer efficiency is greatly improved [1]. Moreover, disturbance wave has direct impact on the safety in production. For example, in the long distance transport process of muti-phase flow material, the gas-liquid interface wave may cause the vibration of pipeline, which will exacerbate the aging of the equipments. And in nuclear reactors, the flooding is believed to be the cause of the coolant accident, which is closely related to the disturbance wave [2].

Frequency is an essential characteristic value of the disturbance wave, which characterizes the intensity and the probability of occurrence of the disturbance wave. To a certain extent, it reflects the influence of the disturbance wave. It is usually calculated from the signal of the dynamic liquid film thickness, by FFT or PSD. Many researchers have measured it by different methods and in different installation conditions. There are A. Ousaka [3], D. Schubring [4], A. Al-Sarkhi [5], A. Setyawan [6] in horizontal annular flow and P. Sawant [7], T. Hazuku [8], D. Schubring [9], Y. Zhao [10] in vertical annular flow (upwards). Generally, the studies of the horizontal and vertical tubes are separate, and few researches focus on the comparison of the two different conditions. Different research conclusions indicate that with different installation conditions, the characteristics of the disturbance wave are not consistent. On the other hand, the effect of the pressure is another problem which requires further study.

In this paper, the disturbance wave was measured by a NIR sensor in both horizontal and vertical annular flow. The wave frequency was calculated by PSD from the experimental signal. The
numerical correlation and the distribution of the disturbance wave frequency are compared under these two conditions. And the influence of gas pressure is also considered.

2. Experimentation

2.1. Flow Device and experimental conditions
The experiment was conducted on a pressure changeable experimental device in Tianjin University Flow Laboratory. The test section could be installed horizontally or vertically. Water and air were injected into the test section tube separately by the valves. Moreover, this device could adjust the pressure of the pipeline from atmospheric pressure to 1.6MPa by the air compressor. The flow of each phase was measured by the standard flow-meters, separately. The involved test section is a pipeline which diameter is 50mm, and is installed horizontally or vertically. The experimental pressure range is from 0.3 to 0.9 MPa for horizontal tube and from 0.2 to 0.9 MPa for vertical tube. And the liquid flow range is from 1.0 to 2.5 m$^3$/h, the gas range is from 90 to 110 m$^3$/h. This corresponds to superficial liquid velocity is from 0.141 to 0.353 m/s, and superficial gas velocity is from 12.732 to 15.562 m/s. There are 70 experiment points for each of the horizontal and vertical conditions. According to the flow pattern maps established by K.J. Bell [11] for horizontal pipe and by G.F. Hewitt [12] for vertical pipe, the flow patterns of the above experimental conditions are annular flow.

2.2. The NIR absorption liquid film measuring system
The schematic of the NIR absorption sensor is as shown in Fig. 1. This equipment is designed with the theory of measuring the laser attenuation when it passes through the medium. The light source emits a laser beam through a light guide pipe which passes through the gas core of the annular flow. The effect of the droplets in the gas core has been almost shielded. Then the laser is irradiated to the liquid film, and the water is the medium which will cause the attenuation of the light intensity. This process follows the Lambert-Beer's law, as which is shown in equation (1). Where $I_0$ is the incident light intensity, $I$ is the exit light intensity, $d$ is the thickness of the medium, and $C, \beta$ is depended on the physical properties of the medium. Finally, the laser passes into the light detector through an organic glass lens. And we can get the information of the dynamic liquid film thickness by analyzing the signal of the exit light intensity.

$$\frac{I}{I_0} = e^{-\beta C d}$$

![Figure 1. Schematic of the NIR absorption sensor](image)

3. Results and Discussion
The test signals of the disturbance wave in horizontal and vertical annular flow is shown in Fig. 2, separately. The comparison of these signals shows that the disturbance wave in the vertical is more regular than it in the horizontal. This phenomenon is also consistent with the numerical results of the power spectral density (PSD) of these signals. A sample of the PSD results is shown in Fig. 3.
Because the amplitude of the disturbance wave is much larger than that of the base film, the peak frequency of the PSD is normally believed to be the characteristic frequency of the disturbance wave. Under the experimental conditions, the frequency of the disturbance wave is no more than 10 Hz. As the results in Fig. 4, the frequency of the disturbance wave increases with the increase of the flow velocity of each phase and the pressure, in general. As the same with Fig. 2, the frequency of
A disturbance wave in the vertical is also more regular than it in the horizontal, especially with different liquid velocities. Because of the gravity, the horizontal annular flow is asymmetric, but the vertical annular flow is relatively uniform. With these circumstances, the horizontal annular liquid film is much thicker than the vertical under the same experimental condition. The thicker liquid film brings greater uncertainty in horizontal tube, so that the frequencies of the disturbance wave are not as regular as those in vertical tube. These results also show that the disturbance wave of annular flow is with great randomness. Moreover, frequencies don’t change in a monotonic manner with the change of liquid velocity, especially in the horizontal tube. This indicates that the thickness of the bottom liquid film has exceeded the critical value. In this case, the main influence factor of the disturbance wave is the gas phase. On the whole, there is a clear trend that the frequency of the disturbance wave increases with the increase of gas velocity and pressure.

Conclusions

In this paper, a NIR absorption liquid film measuring system and the experiment on annular flow disturbance wave is described in detail. The PSD peek is chosen as the characteristic frequency of the test signal. Finally, a total of 140 experiment points of wave frequency for horizontal and vertical conditions were given. In general, the frequency of the disturbance wave increases with the increase of the flow velocity of each phase and the pressure according to the data. Further research is required for the statistical conclusion and numerical law of the disturbance wave frequency.

Acknowledgments

This work is supported by National Natural Science Foundation of China under Grant 50906061.

References

[1] S. Jayanti, G. F. Hewitt. Hydrodynamics and heat transfer in wavy annular gas-liquid flow: a computational fluid dynamics study [J]. International Journal of Heat & Mass Transfer, 1997, 40(10):2445-2460.
[2] G. Karimi, M. Kawaji. Flooding in vertical counter-current annular flow [J]. Nuclear Engineering & Design, 2000, 200(1-2):95-105.
[3] A. Ousaka, I. Morioka, T. Fukano. Air-Water Annular Two-Phase Flow in Horizontal and Near Horizontal Tubes: Disturbance Wave Characteristics and Liquid Transportation [J]. Japanese Journal of Multiphase Flow, 1992, 6(1):80-87.
[4] D. Schubring, T. A. Shedd, Wave behavior in horizontal annular air – water flow [J]. International Journal of Multiphase Flow, 2008, 34(7):636-646.
[5] A. Al-Sarkhi, C. Sarica, K. Magrini. Inclination effects on wave characteristics in annular gas – liquid flows [J]. Aiche Journal, 2012, 58(4):1018-1029.
[6] A. Setyawan, Indarto, Deendarlianto. The effect of the fluid properties on the wave velocity and wave frequency of gas – liquid annular two-phase flow in a horizontal pipe [J]. Experimental Thermal & Fluid Science, 2016, 71:25-41.
[7] P. Sawant, M. Ishii, T. Hazuku. Properties of disturbance waves in vertical annular two-phase flow [J]. Nuclear Engineering & Design, 2008, 238(12):3528-3541.
[8] T. Hazuku, T. Takamasa, Y. Matsumoto. Experimental study on axial development of liquid film in vertical upward annular two-phase flow [J]. International Journal of Multiphase Flow, 2008, 34(2):111-127.
[9] D. Schubring, T. A. Shedd, E. T. Hurlburt. Studying disturbance waves in vertical annular flow with high-speed video [J]. International Journal of Multiphase Flow, 2010, 36(5):385-396.
[10] Y. Zhao, C. N. Markides, O. K. Matar. Disturbance wave development in two-phase gas – liquid upwards vertical annular flow [J]. International Journal of Multiphase Flow, 2013, 55:111-129.
[11] K. J. Bell, J. Taborek, F. Fenoglio. Interpretation of horizontal in-tube condensation heat transfer correlations with a two-phase flow regime map. International Journal of Coal Geology, 1970, 65(1), 51–58.
[12] G.F. Hewitt, D.N. Roberts. Studies of Two-phase Flow Patterns by Simultaneous X-ray and Flash Photography, AERE-M 2159, Harwell, UK, 1969.