Experimental study of vapor local characteristics in upward low pressure boiling tube

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Abstract Radial distribution of vapor local parameters, including local void fraction, interfacial velocity, bubble size, bubble frequency and interfacial area concentration, are investigated through the measurement in an upward boiling tube using dual-sensor optical probe. In addition, a new local parameter —“local bubble number concentration” is developed on the basis of bubble frequency. The analysis shows that this parameter can reflect bubble number density in space, and has clear physical meaning.

Keywords Two-phase flow, Optical probe, Local parameter

CLC number TL331

1 Introduction

The study of steam-water two-phase flow is significant for the improvement of both safety and economics of reactors. In recent years, two-phase flow models have been developed from initial homogeneous two-phase flow model to multidimensional model. In the calculation of multidimensional two-phase model, vapor local characteristics are very important because the radial distribution of vapor parameters is not homogeneous. At present, experimental data are still far less than enough in spite of the researches into bubble local characteristics in a vertical upward tube.[1-5] Furthermore, the above experiments were performed in adiabatic air-water flow, which is quite different from that of reactor’s steam-water flow.

This paper focuses on the vapor local characteristics in an upward heated tube. Vapor local parameters distribution, including local void fraction, interfacial velocity, bubble size, bubble frequency and interfacial area concentration will be obtained through the radial measurement using dual-sensor optical probe, and the local characteristics will be studied.

2 Dual-sensor optical probe method

2.1 Measurement system

RBI optical probe system, which consists of 5 distinct parts, dual-sensor optical probe, optoelectronic module, acquisition and signal processing, calculation and display software and HP54600B dual-trace oscilloscope, is used in this investigation. Main characteristics of the system are shown as:

Distance between two sensors	1.35 mm
Maximum pressure	3 MPa
Diameter of the sensitive tip	~40 μm

Local void fraction, interfacial velocity and mean bubble diameter can be calculated through this system. For the working principle and signal processing of the system refer to References.[6,7] The accuracy certifying experiment of this system has been described by the author before.[8] The results show that optical probe is very sensitive to the bubble signals and satisfactory surveying results can be achieved.

2.2 Further signal processing

2.2.1 Local bubble frequency and local bubble number concentration

Local bubble frequency f_b is defined as the number of bubbles passing through a local position per unit time. It can be expressed as:

$$f_b = N / T \quad (1)$$

where T and N are the sampling time and number of

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bubbles passing through the probe sensor in the total sampling time respectively.

Most present research considers bubble frequency measurement as the main reflection of the bubble number density, and Eq.(1) is used widely to calculate bubble frequency in two-phase flow measurement using optical or impedance probe. It is easy to see that bubble frequency is a time-domain conception. But space-domain conception has clear physical meaning for two-phase flow, so a new space-domain local interfacial parameter —"local bubble number concentration" is developed on the basis of bubble frequency in this paper. Local bubble number concentration f_{bs} is defined as:

$$f_{bs} = \frac{N}{T \cdot v_b} \tag{2}$$

where v_b is local interfacial velocity. Local bubble number concentration reflects the number of bubbles passing by the probe sensor per unit distance and its unit is m^{-1}. Obviously, f_{bs} reflects bubble number density in space.

2.2.2 Local interfacial area concentration

Interfacial area concentration is defined as the area of two-phase interface per unit volume. It is significant for the calculation of mass, momentum and energy transport between vapor and liquid in two-fluid model.

For local interfacial area concentration measurement using dual-sensor probe, the model developed by Kataoka *et al.*[9] is adopted here:

$$A_i(r) = 4 \cdot f_b \cdot \overline{\frac{1}{|v_b|}} \tag{3}$$

3 Experimental facility and system variables

The experimental flow loop is a high-pressure high-temperature thermal hydraulic test facility. The test section is a 24 mm ID vertical tube, 1304 mm long, and the electrically heating section is 1000 mm long. In the experiment, the surveying results of nearly 1000 spatial local points under 85 system conditions are obtained. The range of system variables covered is as follows:

Pressure	0.13~2.01 MPa
Local equilibrium quality	-5.3%~+1.6%
Heat flux	306~775 $kW \cdot m^{-2}$
Mass flux	266~814 $kg \cdot m^{-2} \cdot s^{-1}$

4 Experimental results

4.1 Local void fraction

Fig.1 shows the typical results for the void fraction radial profiles in different equilibrium quality, in which the units of pressure *P*, mass flux *G*, heat flux *q* and equilibrium quality X_{eq} are MPa, $kg \cdot m^{-2} \cdot s^{-1}$, $kW \cdot m^{-2}$ and % respectively. Radial position *r* is the distance between local point and axis of the tube, and thus radial position 0 and 12 mm denote the center position and tube wall respectively. Local void fraction may decrease to 0 near the center of the tube, owing to the condensation of bubbles in high subcooled states. Fig.1 shows clearly that a greater equilibrium quality results in a higher void fraction, and the lateral profiles of void fraction in the cross-section change from near U shape into saddle and arc ultimately. As the effect of thermodynamic nonequilibrium decreases, void fraction distribution is dominated by bubble dynamics, and there are large bubbles in two-phase flow now, which, relative to small bubbles, tend to migrate to the core region.

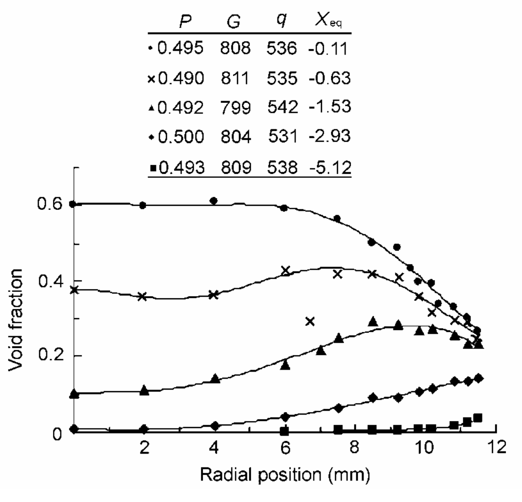

Fig.1 Radial profiles of void fraction.

4.2 Local interfacial velocity

Fig.2 shows that most of the interfacial velocity profiles tend to flatten in the core region, and drop close to the wall. Interfacial velocity increases as the equilibrium quality increases. The lateral profiles of interfacial velocity may take an arc distribution in the cross-section after the interfacial velocity increases to a certain degree, e.g. the profile, of which the equilibrium quality equals –0.11%, as shown in Fig.2. The experiment indicates that this distribution will only occur in the arc shape similar to the distribution of void fraction regimes.

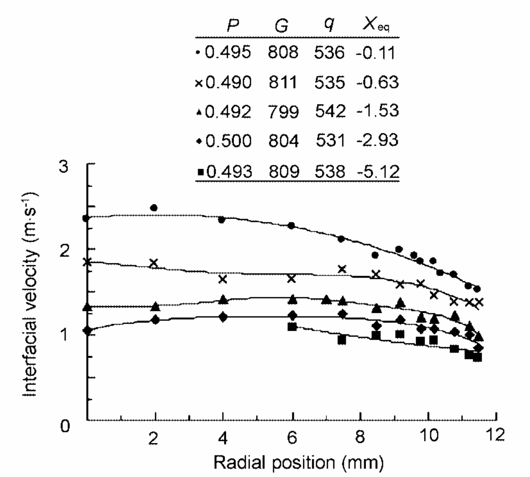

Fig.2 Radial profiles of interfacial velocity.

4.3 Local bubble mean diameter

Fig.3 shows the radial profiles of bubble mean diameter in different equilibrium quality. More bubbles will emerge as equilibrium quality increases, and the bubble size will increase because of the increasing coalescence and bubble detachment size. Bubble size is small in relatively low equilibrium quality states, and the radial profiles of bubble mean diameter tend to flatten in the core region. As the bubble size increases, the profiles will not be so uniform as before, and the lateral profiles will take cosine distribution in the cross-section. It should be mentioned that the measurement results of bubble mean diameter in slug flow can not be used directly because of the limitation of dual-sensor optical probe method.[2, 3] So, flow patterns are given in Fig.3.

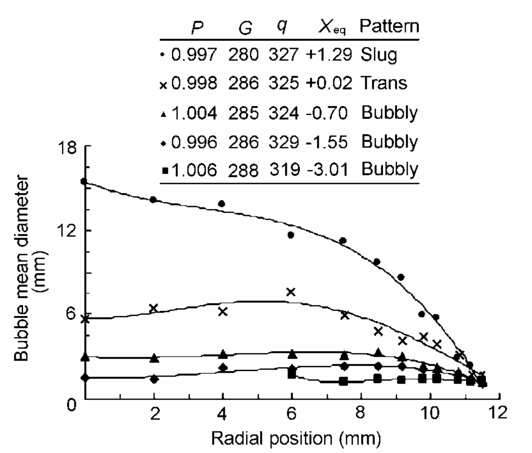

Fig.3 Radial profiles of bubble mean diameter.

4.4 Local bubble frequency and local bubble number concentration

All the experimental results show that local bubble frequency has the maximum value in the region close to the wall, and it decreases as the radial position r decreases, especially in the region near the wall. In the core region, the radial profiles tend to flatten and have the minimum value near the center. So, local bubble frequency takes on the U distribution laterally.

The radial profiles of bubble frequency presented in Fig.4(a) show a general increase with the increase of equilibrium quality.

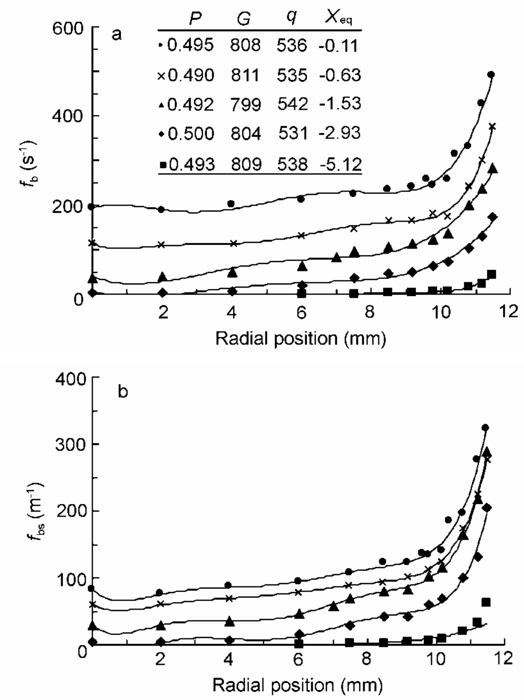

Fig.4 (a) Effect of equilibrium quality on f_b radial profiles; (b) Effect of equilibrium quality on f_{bs} radial profiles.

The radial profiles of local bubble number concentration f_{bs} are shown in Fig.4(b), with the same experiment conditions as in Fig.4(a). It can be observed from Fig.4 that the radial distribution of f_{bs} is similar to that of f_b, however the physical meaning of both is quite different. f_{bs} expresses the bubble number density in space, while f_b is the number of bubbles passing by a certain radial location per unit time. Refer to Fig.4(b), the distribution characteristics of f_{bs} in space can be analyzed as follows.

Increasing the equilibrium quality will increase the bubble number density in space significantly, largely due to the increased void fraction, bubble detached number and decreased subcooling. In relatively high equilibrium quality regime, the increasing degree of f_{bs} is not as significant as before (different from that of f_b), due to the coalescence of bubbles, which increases rapidly as the bubble number density increases.

The experimental results show that f_b increases significantly as the mass flux increases, however, the same tendency is not found for f_{bs}, as shown in Fig.5.

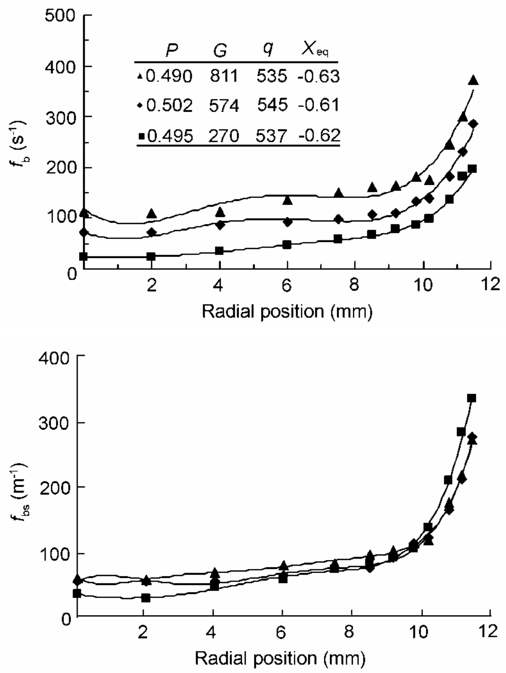

Fig.5 Effect of mass flux on f_b and f_{bs} radial profiles.

It can be observed that local bubble number concentration is different from bubble frequency, not only for the basic physical meaning but also for the influences of system variables. The main purpose of bubble frequency measurement is to reflect the bubble number density. Generally, higher bubble number density corresponds to relatively small bubbles and conversely, lower bubble number density corresponds to relatively large bubbles for a certain average void fraction. However, the analysis of experimental results shows that bubble frequency may not correctly reflect the bubble number density in two-phase flow when interfacial velocities are quite different. As shown in Fig.6, the void fraction that corresponds to the profile dotted by triangles is obviously higher than that of the profile dotted by diamonds, and their bubble sizes almost have the same value, especially in the region near the wall. So, the bubble number density corresponding to the profile dotted by triangles should be higher, especially for the place near the wall. As shown in the figure, f_{bs} (local bubble number concen-

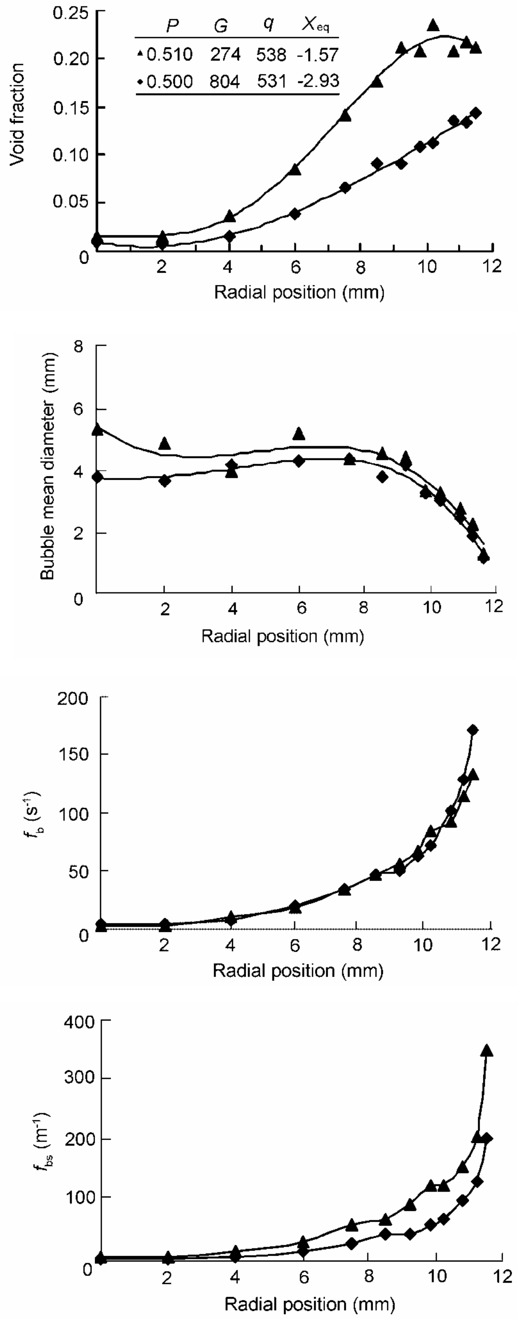

Fig.6 Contrast between f_{bs} and f_b.

tration) reflects this fact correctly, while f_b (local bubble frequency) in two different experiment conditions has almost the same values. This is due to the significant difference in interfacial velocity.

4.5 Local interfacial area concentration

Typical results for the radial profiles of interfacial area concentration are presented in Fig.7. It can be observed that the radial distribution of local interfacial area concentration is similar to that of local bubble frequency and bubble number concentration. It also takes on the U distribution laterally in the cross-section. The figure shows that local interfacial area concentration increases with the increase of equilibrium quality, especially in the core region.

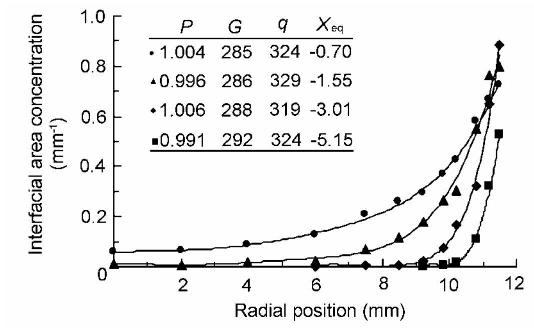

Fig.7 Radial profiles of interfacial area concentration.

The radial distribution of interfacial area concentration indicates that the area of vapor-liquid interfaces is very large in the region near the wall compared to the core region.

5 Conclusion

The following conclusions can be drawn through the study of local interfacial parameters in upward heated tube.

(1) The vapor local characteristics, including local void fraction, interfacial velocity, bubble size, bubble frequency, bubble number concentration and interfacial area concentration, have been investigated. The radial distribution of interfacial parameters are not homogeneous in upward heated tube.

(2) A new space-domain local interfacial parameter —“local bubble number concentration” has been developed. It shows that this parameter reflects bubble number density in space and has clear physical meaning.

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