Effects of Reduced Surface Tension on Liquid Film Structure in Vertical Upward Gas-Liquid Annular Flows

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Abstract
The purpose of this study is to investigate experimentally the effects of reduced surface tension on the liquid film structure in vertical-upward air-liquid annular flows in a 19.2 mm i.d. and 5.4 m long circular tube. The test liquid was water and/or a dilute water solution of Polyoxyethylene-Lauryl-Ether, and the surface tension of these liquids ranged from 72 to 45 dyne/cm. The liquid film structure was observed by use of both the still photographs and the maps of time and spatial characteristics of peripheral-mean liquid film thickness detected with a series of 63 liquid holdup sensors each axially 15 mm apart in a constant current method. The parameters studied were the wave heights of the liquid film, the passing frequencies of the waves, the mean value and the standard deviation of the wave velocities, each determined from the liquid film thickness signals through a computer program of signal processing. From the observations of still photographs and the maps of time and spatial characteristics of peripheral-mean liquid film thickness, it was cleared that the liquid film structure depends strongly on the surface tension, i.e., the reduction of surface tension makes the passing of the large waves decrease remarkably, the wave height of the large waves lower like small waves, the passing of the small waves more frequent, and the small wave velocity faster.

Key words: Liquid Film Structure, Annular Flow, Liquid Film Thickness

1. Introduction
Gas-liquid annular two-phase flow is the flow which is composed of annular liquid film flowing along the tube wall and a continuous gas core with or without liquid entrainments. Such annular flow is frequently appeared in many types of equipment, e.g., steam generators in power plants, various boilers and air conditioners. The surface tension of high temperature water and/or refrigerant used in these equipments was lower than that of normal temperature water. However, the effects of reduced surface tension on the liquid film flow behavior have never been reported besides Sadatomi et al.(1). In annular flow in general, various waves differing in behavior, velocity and height appear on the liquid film, and spatial distribution of individual wave changes with time, e.g., Fukano et al.(2), Furukawa et al.(3), Al-Sarkhi et al.(4) and Sato et al.(5). The liquid film flow, therefore, shows a very complicated aspect. The structure of liquid film consisting of such complicated waves must affect not only on the interfacial shear stress and the flow mechanism inside the liquid film but also on the heat transfer characteristics of the liquid
film flow.

The objective of this study is to clarify experimentally the effects of reduced surface tension on the liquid film structures, such as the time-spatial distribution of the liquid film thickness, wave height, the mean value of wave velocities and their standard deviation, the passing frequency of the waves.

In the experiments, water and a dilute water solution of Polyoxyethylene-Laury-Ether (PLE for short), having a surface tension of 45 dyne/cm, were used as the test liquids, while air as the test gas. Why the dilute water solution of PLE was used is that it reduces the surface tension but does not induce the drag reduction as reported by Fang et al. The liquid and air at normal temperature and pressure flowed co-currently vertical up in a 19.2 mm i.d. circular tube. The results of such experiments and discussion are presented in this paper.

2. Experimental Apparatus

Figure 1 shows the schematic view of a test rig. The vertical test tube of $D = 19.2$ mm i.d. and about 5.4m long was made of transparent acrylic resin. One of the two test liquids was mixed with air in an air-liquid mixer. The properties of the test liquids are shown in Table 1.

![Fig. 1 Test rig](image)

| Table 1. Physical properties of test liquids at $\theta_L = 21^\circ C$ |
|-----------------|----------------|----------------|
| **Liquid**      | $\nu_L$ | $\rho_L$ | $\sigma_L$ |
| Water (W72)     | 0.980  | 998    | 72         |
| PLE (PLE 45)    | 0.970  | 1000   | 45         |

As can be seen from Table 1, the kinematic viscosity and the density are nearly equal between water and the dilute water solution of PLE, while the surface tension of the dilute water solution of PLE is about 60 % of that of water. These liquids hereafter are abbreviated as W72 and PLE45.

An air-liquid mixer, 7, consisted of 60 mm long concentric annuli, and the inner diameter of the inner tube was the same as that of the test tube. The liquid was injected radially into the air flow through 60 holes of 2 mm i.d. drilled on the inner tube of the annuli. The air-liquid mixture so made flowed upwards through a 3000 mm entrance section, a 930 mm measuring section and a 1460 mm discharge section, and finally flowed into an air-liquid separator, 1. The air separated was discharged into atmosphere, while the liquid was returned back to a liquid storage tank upstream of a liquid circulation pump. In the measuring section, the liquid holdup was measured with the constant current method.
developed by Fukano(7). Calibrations of the constant current method were conducted before and after the measurement in each run by detecting the voltage drop when the test liquid alone flows through the same test channel. The uncertainty in the liquid film measurement is estimated to be within 1 % (8). A summary of the method was also described in Furukawa’s previous paper(9). In the present apparatus, a series of 63 pairs of holdup sensor, each 15 mm apart in axial direction, were arranged over 930 mm. A holdup sensor was composed of 0.5 mm thick and 4.5 mm apart two brass rings embedded flush with the inner surface of the test tube, made from nonconductive acrylic resin of 4.5 mm thick. The output signals from these holdup sensors were converted to time-varying liquid film thickness signals (designated as \( t_f \) signals). Thus, the measured value of the film thickness was a circumferentially averaged value over 4.5 mm in axial length. The time-spatial distribution map, which was required to discuss the liquid film structures in detail, was drawn up using these 63 \( t_f \) signals. Using one \( t_f \) signal or two adjacent \( t_f \) signals among 63 \( t_f \) signals, the wave heights, the mean values of the wave velocity and their standard deviations, and the passing frequency of the waves were calculated by a computer.

The liquid film structures could be visually observed by use of a still camera. The photography section of the flow was located at 2300 mm \((L/D = 120)\) downstream from the air-liquid mixer. According to Furukawa’s previous paper(10) on the flow developing process, \( L/D = 120 \) is enough for the flow to fully develop. The photography section was enclosed within a transparent rectangular vessel full of water in order to minimize the optical distortion of the flow configuration due to the curvature of the tube wall.

The experimental conditions were as follows: A superficial gas velocity, \( j_G \), ranged from 15 to 50 m/s; a superficial liquid velocity, \( j_L \), 0.04 to 0.2 m/s; a system pressure at a middle point of the measuring section 0.110 to 0.128 MPa; an air and liquid temperature 20 to 22 ºC. The surface tension of the test liquid was measured before and after the experiments and the difference between them is within 3 %.

3. Experimental Results and Discussion

3.1 The observations of the liquid film structure

3.1.1 Lower liquid flow rate case Figure 2(A) and (B) shows the typical still photographs and the time-spatial characteristics map (referred to as TS map in this paper) on the liquid film thickness, \( t_f \), respectively for (a) air-W72 and (b) air-PLE45 under the same flow rates condition of \( j_G = 30 \) m/s and \( j_L = 0.04 \) m/s. In TS map, \( t_f \) signals from 63 pair holdup sensor are simultaneously shown on the respective axial distances with the same ordinate scale. The liquid film thickness, \( t_f \), is calculated by substituting the liquid holdup, \( \eta \), data into the following equation:

\[
 t_f = \frac{(D/2)\sqrt{1-\sqrt{1-\eta}}}{12}
\]

The signs “SW” and “LW” in each figure represent the small wave and the large wave. Fukano et al.(11) proposed a model for a liquid film flow in a horizontal air-water annular flow. According to their model, the liquid film flow consists of disturbance wave and a continuous liquid film. The liquid film besides waves is named as a base film, and the ripples formed on the base film are named as a base wave. LW called in the present paper corresponds to the disturbance wave often appeared in air-water flows. The reason why the “LW” is used in the present paper is that the LW in air-PLE45 system as well as in air-liquid with higher viscosity system(9) shows different velocity characteristics from the disturbance wave seen in air-water system, which is clearly confirmed from the spatial distribution of waves. In addition, SW is used as synonymous with the base wave. The discrimination between LW and SW was based upon the trend of TS map as seen in Figs. 2.
and 3, i.e., LW is a clearly discernible large wave which exists more than 0.93 m, being the wave detection zone, while SW is a small wave frequently generated from the rear side of LW and captured and absorbed by the subsequent LW, thus relatively short in existing time.

In Fig. 2 (A), the large wave, LW, is observed at the middle of the photograph for (a) air-W72 system. For (b) air-PLE45 system with a lower surface tension, however, LW disappears and a lot of small wave, SW, appears in comparison with air-W72 system.

The wave characteristics mentioned above is more clearly seen from TS map of Fig. 2 (B) (a-1) and (b-1), respectively for air-W72 and air-PLE45 systems. In Fig. 2 (B), a lot of wave veins of LW or SW, i.e., linear traces formed by individual wave flowing upwards, are observed. The gradient of each wave vein means the velocity of the wave, and steeper the gradient higher the wave velocity. In this paper, LW is defined as the large wave whose wave vein was kept over the measuring section of 0.93 m in TS map. Such LWs exists so much in the TS map of (a-1) W72, while in that of (b-1) PLE45 only one LW exists. SWs with a short lifetime, on the other side, can be scarcely seen in (a-1) W72, while in (b-1) PLE45 a vast amount of SWs appear which have long lifetime and higher wave height than those in (a-1) W72. From this, it is cleared that the magnitude of roughness of gas-liquid interface on the base film increases with decreasing of the surface tension.

Fig. 2(B) (a-2) and (b-2) indicate the scale of $t_f$ in mm and the $t_f$ signals at $L = 0$, the most upstream position in TS map. From a comparison between these $t_f$ signals, the wave characteristics mentioned above become more evident. In addition, it can be seen that the wave height of LW for PLE45 is much lower than that for W72. As can be seen in TS map of (a-1) W72, the wave heights of LW and SW are extremely different. Therefore, it is easy to judge which wave is LW or SW from the $t_f$ signal as shown in (a-2). In TS map of (b-2) PLE45, however, $t_f$ signal differs remarkably from that of W72 in a time-varying aspect, and a SW with the nearly equal wave height to LW sometimes exists. So, in order to surely discriminate LWs from SWs, a lot of $t_f$ signals at different locations have to be
observed. Therefore, the observation of TS map is quite useful to discriminate LW from SW.

3.1.2 Higher liquid flow rate case Figure 3 shows the still photographs and TS maps for (a) W72 and (b) PLE45 at $j_L = 0.1$ m/s and $j_G = 30$ m/s, being equal $j_G$ but 2.5 times higher $j_L$ than that in Fig. 2. From the still photographs of Fig. 3 (A), it is known that with increasing of $j_L$ the interfacial roughness on the base film of (b) PLE45 becomes much rougher than that of (a) W72, and that a huge number of tiny bubbles, smaller than 1 mm o.d., are included in the base film of (b) PLE45, thus the film looked like a ground grass at the gas-liquid interface.

From the observation of TS maps in Fig. 3 (B) (a-1) and (b-1) and the $t_f$ signals at $L = 0$, (a-2) and (b-2), the followings can be clarified: (1) Similarly to Fig. 2, a great number of SW with a long lifetime and a relatively large SWs appear for (b-1) PLE45, comparing with (a-1) W72; (2) As can be seen from the gradient of wave veins of SWs, the wave velocities of SWs for PLE45 become faster than those for W72, meaning that the mean velocity of the base film increases with decreasing of surface tension; (3) From the comparison of the $t_f$ signals in (a-2) and (b-2), the film thickness of PLE45 become thinner than that of W72. This is mainly caused by the increase in the interfacial friction force due to a sharkskin-like interface by a huge number of SW. It is reported that the liquid entrainment to the gas core increases with decreasing of surface tension\(^{(12)}\), thus the film thickness may become somewhat thinner by the entrainment. However, the entrainment rate in PLE45 is considered to be a few since the SW in PLE45 is similar to a ripple wave, being different from a disturbance wave generating the entrainment. In order to confirm the above consideration, we have to measure the entrainment rate in our future study.

In this connection, an example of the experimental data on the base film thickness, $t_fB$, obtained from $t_f$ signals is shown in Fig. 4. The $t_fB$ is very close to the radial distance from tube wall corresponding to the maximum point in $N$ curve, i.e. radial distribution for passing

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(A) Liquid film structures for air-W72 and air-PLE45.

(B) Time-spatial characteristics map of liquid film thickness for air-W72 and air-PLE45.

Fig. 3 Effects of reduced surface tension on liquid film structures and wave behaviors at the same flow rates condition of $j_G = 30$ m/s and $j_L = 0.1$ m/s.
frequency of the wave which was obtained by a computer processing of the \( t_f \) signal (Sekoguchi et al.\textsuperscript{(13)})). In the present study, therefore, Sekoguchi et al.’s method using \( N \) curve was adopted for the determination of \( t_{fb} \). In Fig. 4, the \( t_{fb} \) data are plotted against the superficial gas velocity, \( j_G \), at a fixed liquid velocity of \( j_L = 0.1 \text{ m/s} \). W72 and PLE45 data are shown by circular and triangular symbols, respectively, and the data at the same flow condition as that in Fig. 3 are shown by solid symbols. \( t_{fb} \) of PLE45 is thinner than that of W72, and the difference of \( t_{fb} \) between PLE45 and W72 increases with decreasing of \( j_G \). A comparison of \( t_{fb} \) between the present data and the calculations by Sekoguchi et al.’s correlation\textsuperscript{(14)} showed that the agreement between them is qualitative but not quantitative, and the agreement becomes worse with decreasing of \( j_G \).

### 3.1.3 Comparison between lower and higher liquid flow rate cases and summary of reduced surface tension effects

Again, let us see the TS maps in Figs. 2 and 3. The passing frequency and the height of LW for PLE45 were remarkably lower than those for W72, i.e., the reduction of surface tension lower the passing frequency and the height of LW.

From a comparison of Figs. 2 and 3, the passing frequencies of SW and LW increase with \( j_L \), irrespective of W72 and PLE45. In addition, from TS maps in Fig. 3 (B) (a-2), it is known that the LWs for W72, usually referred to as disturbance waves, have approximately uniform in wave velocity, wave height and axial wave spacing. On the other side, for PLE45 in Fig. 3 (B) (b-2), the uniformity in wave velocity, wave size and axial wave spacing of LWs is deteriorated, being different from the characteristics of disturbance waves for W72 as mentioned earlier.

As discussed above, the liquid film structures strongly depended on the liquid surface tension \( \sigma_L \). In addition, the mechanism of liquid transport depends upon \( \sigma_L \), i.e., as \( \sigma_L \) decreases, the fraction of the liquid flow rate transported by LW decreases, and that by base film increases. These are very important findings because most interfacial shear stress models in annular flow do not account for such a surface tension effects. In addition, the accurate modeling of interfacial shear stress is essential to improve the accuracy of pressure drop and void fraction prediction by a two-phase two-fluid model (e.g., Liles\textsuperscript{(15)}).

### 3.2 Wave height

Figure 5 shows an example of the time fraction data on liquid phase in liquid holdup signal, \( \eta \), for W72 at \( j_G = 15 \text{ m/s} \) and \( j_L = 0.2 \text{ m/s} \). \( \eta \) is given as the ratio of the time occupied by the liquid phase to the total sampling time in the liquid holdup signal. The resulting \( \eta \) data are plotted on a normal probability paper against the distance from the inner wall surface of the test tube, \( y \). Using this kind of figure, the minimum and the maximum film thicknesses, \( t_{f_{\text{max}}} \) and \( t_{f_{\text{min}}} \), was obtained as the \( y \) values at \( \eta = 99 \% \) and 1 \%, respectively, and the wave height, \( h \), was obtained as the difference of these film thicknesses.

Figure 6 (A) shows the relation between the wave height, \( h \), and the superficial gas velocity, \( j_G \) at a fixed condition of \( j_L = 0.1 \text{ m/s} \). Circular and triangular symbols represent...
Fig. 5 Example of time fraction data on liquid phase in liquid holdup signal, $\eta_t$, and determination of the maximum and the minimum liquid film thicknesses, $t_{f_{\text{max}}}$ and $t_{f_{\text{min}}}$, and wave height, $h$.

Fig. 6 Effects of reduced surface tension on wave height, $h$.

W72 and PLE45 data, respectively. $h$ for W72 remarkably decreases with increasing of $j_G$, while $h$ for PLE45 the decrease is gradual. Accordingly, $h$ for W72 in a low $j_L$ region indicates about three times higher than that of PLE45, but with increasing of $j_G$, the difference of $h$ between PLE45 and W72 becomes smaller, and $h$ for both cases becomes similar at about $j_G = 50$ m/s. Similar tendency was also appeared at other $j_L$ conditions, namely $j_L = 0.04, 0.06, 0.2$ m/s.

Figure 6 (B) shows an example of $h$ data against $j_L$ at a fixed condition of $j_G = 30$ m/s. $h$ increases with $j_L$ for both W72 and PLE45 cases, and $h$ for W72 is about twice larger than that for PLE45. Similar tendency was also seen at other $j_G$ conditions, namely at $j_G = 15, 20$ and 40 m/s.

3.3 Mean velocities of waves and its standard deviation, and passing frequencies of waves

3.3.1 Calculation of wave velocities  

The velocities of waves were determined by the following computer-aided-processing method using the $t_f$ signals obtained from arbitrary two adjacent holdup sensors ($L_P = 15$ mm apart) among 63 holdup sensors.

Figure 7 shows two $t_f$ signals from two adjacent axial positions, namely the upstream $t_f$ signal (denoted as Up) and the downstream $t_f$ signal (Down) in its upper part, while in its lower part the calculated velocities of the respective waves $u_w$ for W72 at $j_G = 30$ m/s and $j_L = 0.1$ m/s. Solid and open circle symbols represent the velocities for SW and LW, respectively. The distinction between SW and LW was done by the observation of TS map.

In calculation of $u_w$, as indicated in Fig. 7, the residence zones of individual waves which appear on the upstream $t_f$ signal are first determined. Next, the transit time between corresponding waves, for example, a wave A on the upstream $t_f$ signal and a wave A' on the downstream $t_f$ signal, is calculated from a cross-correlation of two signals as the delay time,
The velocities of the respective waves which appear in a sampling time of 8 to 10 sec are calculated by the same manner as mentioned above. From the calculated result, the mean values of wave velocities \( \bar{L}_W \) and \( \bar{S}_W \) and their standard deviations \( \sigma_{LW} \) and \( \sigma_{SW} \), and passing frequencies \( N_{LW}, N_{SW} \) for LW and SW are obtained by

\[
\bar{L}_W = \frac{\sum u_{LW}}{n_{LW}} \quad \bar{S}_W = \frac{\sum u_{SW}}{n_{SW}} \tag{3, 4}
\]

\[
\sigma_{LW} = \sqrt{\frac{\sum (u_{LW} - \bar{L}_W)^2}{n_{LW}}}, \quad \sigma_{SW} = \sqrt{\frac{\sum (u_{SW} - \bar{S}_W)^2}{n_{SW}}} \tag{5, 6}
\]

\[
N_{LW} = \frac{n_{LW}}{ST}, \quad N_{SW} = \frac{n_{SW}}{ST} \tag{7, 8}
\]

Here, \( u_{LW} \) and \( u_{SW} \) are the velocities for LW and SW, ST is the sampling time, and \( n_{LW} \) and \( n_{SW} \) are the numbers of LW and SW which appear within \( ST \).

### 3.3.2 Mean values of wave velocities and their standard deviations, and passing frequencies for LW and SW

Figure 8(a) shows the experimental data on the mean wave velocities, \( \bar{L}_W \) and \( \bar{S}_W \), respectively for large waves, LW, and small waves, SW. Fig. 8(b) shows the ratios of the standard deviation to the mean value, \( \sigma_{LW} / \bar{L}_W \) and \( \sigma_{SW} / \bar{S}_W \), and Fig. 8(c) shows the passing frequencies, \( N_{LW} \) and \( N_{SW} \). Figs. (A) and (B) indicate their variation against \( j_G \) at a fixed \( j_L \) of 0.04 m/s and 0.1 m/s, respectively. Open symbols represent the data for LW and solid symbols for SW. In addition, Nakasatomi’s data\(^{16}\) are also plotted for reference. Their data were obtained for air-water flows in a 25.0 mm i.d. vertical tube at a fixed water temperature of 18 °C.

From Fig. 8 (B) (a), the followings can be seen: Both \( \bar{L}_W \) and \( \bar{S}_W \) increase with \( j_G \), independent of the surface tension value; \( \bar{S}_W \) for PLE45 become larger than that for W72 at the same \( j_G \); In the case of \( \bar{L}_W \), however, the difference of \( \bar{L}_W \) between PLE45 and W72 is little irrespective of \( j_G \); the present \( \bar{L}_W \) values are nearly the same as Nakasatomi’s in spite of the difference in tube diameter. From a comparison of \( \bar{L}_W \) and \( \bar{S}_W \) for PLE45 and W72, we found that the relative velocity of LW to SW for W72 is higher than that for PLE45. A similar trend is also seen in Fig. 8 (A) (a). The cause of this seems that the drag force by air flow on LW flowing on the base film is larger for W72 than PLE45 depending on their difference in roughness on the base film as mentioned at section 3.1. A comparison of \( u_{LW} \) between the present data and the calculations by Sekoguchi et al.’s correlation\(^{14}\) showed that the calculations agrees quite well for W72, but doesn’t agree qualitatively for PLE45.
Fig. 8 Mean wave velocities, ratios of standard deviation to the mean value and passing frequencies, respectively for large waves, LW, and small waves, SW.

Fig. 8 (A)(B)(b) shows $\sigma_{LW}/u_{LW}$ and $\sigma_{SW}/u_{SW}$ data representing the scatters of $u_{LW}$ and $u_{SW}$. Generally, these values for both PLE45 and W72 slightly decrease as $j_G$ is increased. $\sigma_{SW}/u_{SW}$ for PLE45 is quite similar to that for W72, showing little surface tension effects. On the other hand, $\sigma_{LW}/u_{LW}$ for PLE45 is extremely larger than that for W72. The reason of this is presumably that the uniformity in LW size for PLE45 is deteriorated as described in section 3.1.

Fig. 8 (A) (B) (c) indicates the passing frequencies of LW and SW. At both $j_L = 0.04$ m/s and 0.1 m/s, $N_{LW}$ is larger than $N_{SW}$ for W72, while for PLE45 $N_{LW}$ is smaller than $N_{SW}$. For example, as can be seen in Fig. 8 (A) (c), for W72 SW disappears and LW alone appears when $j_G$ reaches to 40 m/s, while for PLE45 LW disappears and SW alone appears. Thus, $N_{SW}$ of PLE45 is remarkably larger than that of W72, while $N_{LW}$ of PLE45 is smaller than that of W72, and the difference of $N_{LW}$ between W72 and PLE45 increases with $j_G$. A comparison of $N_{LW}$ between the present data and the calculations by Sekoguchi et al.’s correlation\(^{(14)}\) showed that the agreement between them is good for W72, but is qualitatively poor for PLE45. The cause of this seems that the correlation by Sekoguchi et al. was based only on the experimental data in air-water system despite the correlation contains a surface tension term.

As a summary, it is found that the effects of reduced surface tension are extremely large on the characteristics of velocity and passing frequency of LW and SW.

4. Conclusions

The effects of reduced surface tension upon the liquid film structures in isothermal annular two-phase upwards flows in a 19.2 mm i.d. vertical tube were experimentally investigated. In the experiments, in order to study the reduced surface tension effects, water (72 dyne/cm in surface tension, thus W72 for short) and a dilute water solution of...
Polyoxyethylene-Lauryl-Ether (45 dyne/cm, PLE 45) were used as the working liquids. Several new findings were obtained from the experiments and are summarized as follows:

- Still photographs and the time-spatial characteristic maps of liquid film thickness showed that the liquid film structures, such as spatial distribution, behaviors, wave height, passing frequency for large wave “LW” and small wave “SW” for PLE45 differed extremely from that for W72 due to the reduced surface tension effects.
- The mean velocities of LW were little affected by the reduced surface tension. Those of SW, however, increased with decreasing of the reduced surface tension.
- The uniformities in velocity, size and axial spacing of LW are deteriorated due to the reduced surface tension effects.
- By the reduction of liquid surface tension, the passing frequency of LW decreased, while that of SW extremely increased. Therefore, the roughness on the base film of PLE45 was noticeably rougher than that of W72.

Acknowledgements

The authors would like to express their appreciation to H. Yamazoe, J. Hirose, Y. Miyata and S. Yoshihara, students in those days at Sasebo National College of Technology, for their cooperation in the experiments.

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