Studies on the Turbulence Modification Affected by the Wavy Interface on Liquid Film in Vertical Upward Annular Flow

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Experimental and numerical studies were performed to investigate the gas-phase turbulence modification affected by the wavy interface on liquid film in vertical upward annular flow. By using the constant temperature hot-wire anemometer, time-series of axial velocity profiles of gas-phase flow were precisely measured. For the liquid film flowing on the pipe wall, direct observations by using high-speed video camera and the measurement for liquid film thickness by using point-electrode probe was also carried out to make clear the interfacial velocity of gas-liquid wavy interface and the wave height. Numerical simulation for gas-phase turbulence in annular flow considering the effect of wavy interface on liquid film flow was also carried out. The measured interfacial wave velocity and wave height were applied as the boundary condition for the present numerical analysis. Time-averaged velocity profiles and fluctuation velocity profiles were calculated with standard \( k-\varepsilon \) model. Numerical results were consistent with the experimental results obtained in the present study.

KEYWORDS: Annular Flow, Turbulence Modification, Gas-Liquid Interface, Turbulence Structure

I. Introduction

Turbulence in multiphase flow is supposed to be affected and modified by a second phase compared with single-phase flow. The turbulence in annular dispersed two-phase flow has attracted research attention, because the investigating of turbulence structure, characteristics and modification mechanism that occurs in annular flow is useful for the accurate prediction for annular dispersed two-phase flow. Some published literatures reported on the turbulence of the gas-core in annular flow. Azzopardi and Teixeira¹,² measured two simultaneous components of gas-core velocity in annular flow. They measure the velocity of 1mm polystyrene tracer particles injected into the gas flow by using a LDV system, and also measured the sizes and velocity of droplets using the PDA system. Fore and Dukler³ measured the droplets size and velocity distribution in gas-liquid annular up flow using PDA system. Turbulence intensity for annular gas-liquid flow were examined and contrasted with values from gas-solids flow by Azzopardi⁴. He suggested that the rough wavy interface of the liquid film and droplets, which are slow moving just after their creation from the liquid film should be the contributions of turbulence augmentation in annular flow.

In this paper, experimental and numerical studies were made to investigate the effects of liquid film on gas-phase turbulence modification on air-water annular flow in a vertically arranged round tube. The time-averaged axial velocity profiles, turbulence fluctuation velocity profile, energy spectrum, and auto-correlation coefficient of gas-phase axial velocity component were precisely measured by using the constant temperature hot-wire anemometer. Measurement of liquid film thickness was added by using point-electrode resistivity prove to make clear the time-averaged liquid film thickness and height of the wave moving on the gas-liquid interface. Direct observations using high-speed video camera were also added to make clear the interfacial velocity of ripple or disturbance waves moving on liquid film. The experimental conditions were set to be the ripple region or disturbance wave region, where the entrainments from the liquid film do not occur, to make clear the effect of wavy interface on liquid film to the turbulence modification of gas-phase flow.

Numerical simulations for gas-phase turbulence structures considering the effect of wavy interface on liquid film flow were also carried out. The liquid film was modeled to be the surface roughness of interfacial wave height moving with the interfacial velocity of liquid film by using the wall function for turbulent model. The roughness and interfacial velocity of the modeled liquid film for computational condition was provided by the present experimental results. Time-averaged velocity profiles and fluctuation velocity profiles were calculated with standard \( k-\varepsilon \) model. The comparisons of experimental results and numerical results are carried out to make the confirmation of the consistency of the computations with experimental results.

II. Experimental Apparatus and Experimental Condition

The schematic drawing of the experimental flow loop is shown in fig.1. The test section is a vertical arranged clear acrylic circular pipe of 20.03mm inner diameter, and 7.6m lengths. The symbols in fig.1, “T”, “DP”, “P” and “F” indicate the thermocouples, differential pressure gauge,
pressure gauge and flow meter, respectively. Dried air and filtered water under the normal temperature are used as the working fluids. The air-water mixer is attached at the bottom part of the test sectional pipe. Dry air supplied from the scroll compressor is once stored in the pressure tank to keep from the flow rate surging, and introduced into the air-water mixer. Water from the head tank is introduced to the air-water mixer and injected into the test sectional pipe through the eight pinholes of 2.0mm I.D. pricked on the pipe wall of mixer section. Beyond the test section, the two-phase mixture is separated; air is released to the atmosphere while the water is returned to the water tank. Before mixing the air and water, the flow rate of air and water are measured by the variable area meter and the ultrasonic flow meter, respectively.

Velocity measurement was made by using constant temperature hot-wire anemometer system. Hot-wire probe was inserted at 4.87m height of test section, which is about 240 diameters height from the air-water mixer section. Pressure drop measurement was made by electrical differential pressure transducer (Validyne DP15-32) attached at 1.67m and 2.74m height of test section, that are about 80 and 130 diameters from the mixer. For the range of flow rates employed in this study, these lengths were sufficient for annular flow to reasonably reach to the equilibrium state.

1. Gas-phase Velocity Measurement

The schematic drawing of the measurement station for gas-phase velocity profile measurement is shown in fig.2. Gas-phase velocity measurement was made by using constant temperature hot-wire anemometer (CTA). Velocity measurement by using hot-wire anemometer has some advantages in the point of the direct measuring of the gas-phase velocity field without injecting the tracer particle into the gas-flow. In another velocity measurement techniques like LDV, PDA, or PIV, in which the tracer particles are seeded in the flow, the tracer particles might cause the obstruction source for the gas-phase turbulence or contamination source of gas-liquid interface. Otherwise, the velocity measurement using hot-wire anemometer makes it possible to analyze the turbulence energy spectrum accurately, because of the time-series of velocity data can be acquired continuously. U-type hot-wire probe (KANOMAX 0248-T5, \( \phi = 5 \mu m, l = 1.0 mm \)) made of tungsten wire is inserted into the test sectional pipe as shown in fig. 2. The over heating ratio for hot-wire was set to be 1.5, which is enough for CTA system to respond precisely to the turbulence fluctuation of gas-core flow. CTA system (KANOMAX CTA System 7000) consists of a CTA unit, a linearizer unit, and a temperature compensation unit. The linearizer unit makes the CTA voltage signal to be the directly proportional to real velocity. The temperature compensation unit allows the velocity measurement under the gentle temperature decreasing due to the slight water vaporization. The hot-wire probe was set up to be able to traverse on radial direction and can be fixed at any radial position by using micrometer. In the case of pipe flow like this study, where the main stream direction is the same with
central axis and fluctuation velocity is relatively small, U-type hot-wire probe can measure the instantaneous axial velocity component \( u \) by setting the hot-wire perpendicular direction against the main stream direction. From the acquired time-series of axial velocity information, we can calculate the turbulent structural parameter such as time-averaged axial velocity profiles, fluctuation velocity profiles, energy spectrum, and auto-correlation coefficient of the fluctuation velocity component. The velocity signals from CTA system were acquired by Analog-Digital converter (PCI-MIO-16E-1, National Instruments). The sampling frequency of data acquisition was set to be 100kHz, which is enough to capture the turbulence fluctuation\(^3\). The data analyses were performed by using data analysis software (LabVIEW6i, National Instruments). The data-sampling period was set to 40 seconds for each case.

2. Liquid Film Measurement

To make clear the effect of the wavy interface moving on the liquid film flow on the gas-phase turbulence modification, the liquid film thickness was also measured by using point electrode resistivity probe. Figure 3 shows the schematic drawing of measurement station for liquid film thickness measurements. Measuring setup is nearly the same as shown in fig.2, which is for the measurement of gas-phase velocity profile. For the film thickness measurements, the hot-wire probe shown in fig.2 was replaced by point resistivity probe on the opposite side on the inner surface of the acrylic pipe, minus electrode, which is grounded, was buried in the pipe wall. The surface of minus electrode is polished to make the electrode and pipe wall smooth and not to make the difference in height level each other. A point electrode probe is made of stainless steel wire with a diameter of 0.2mm. The stainless wire was inserted into Teflon-insulated tube of 0.36mm diameter. The wire was coated with insulating enamel except for the tip, and it was dried up to ensure a well insulation at 200 degree centigrade. This wire was inserted into another sheath stainless steel tube. The electrode probe was mounted on traverse system with micrometer and can be fixed at any radial position from the inner surface of the pipe wall in micron-meter precision. The tip of wire is can be moved into the liquid film flows. As the tip of the wire was moved, the time fraction contacting with the liquid takes place is detected, and is the probability that the film thickness is greater than the distance between the tip of wire and pipe wall. This measurement can provide the information of the minimum, maximum, time-averaged mean thickness, and interfacial wave height of liquid film with reasonable reliability. The electric signal from the electrode probe was acquired by using Analog-Digital converter (PCI-MIO-16E-1, National Instruments). Sampling frequency of data acquisition was set to be 10kHz. The data analyses were performed by using data analysis software (LabVIEW6i, National Instruments). The data-sampling period was set to 60 seconds for each case.

The direct observations of liquid film behavior by using high speed-video camera (Photoron, FastCAM-Net) was also carried out to make visually clear the dynamic behavior and propagating velocity of interfacial waves. The dynamic behavior and structure of ripple or disturbance wave on gas-liquid interface were visually made clear through backlight image. The viewing section locates just below of the measurement station shown in fig1. The shutter speed and flame rate of high-speed video camera were set to 1/5000 sec and 1000 frame per second, respectively.

3. Experimental Condition

The experiments were carried out for the cases changing the superficial velocities of gas and liquid phase, \( j_G \) and \( j_L \), respectively. In this study, the superficial velocity of gas-phase was changed from 15.5 m/s to 26.5 m/s. The superficial velocity of liquid-phase was changed from 0.75 cm/s to 1.25 cm/s.

Figure 4 shows the flow pattern diagram for air-water annular flow indicating the experimental condition.

![Fig.4 Flow pattern diagram of air-water annular flow](image)

4. Experimental Results

1. Time-Averaged and Fluctuation Velocity Profiles

Figure 5 shows the measured time-averaged gas-phase velocity profiles in annular flow. The horizontal axis represents the non-dimensional radial position, and the
vertical axis means the time-averaged axial velocity non-dimensionalized by the superficial gas velocity. The vertical axis of $r/R = 0$ indicates the central axis of the pipe. The result for the case of single-phase flow ($j_L = 0.0 \text{cm/s}$) was also measured and plotted.

In the case for single-phase flow, the measured velocity profiles has a good agreement with Laufer's data \cite{10}, which is the well known accurate data for the single-phase turbulence flow in circular tube. This can make a confirmation that the velocity measurement in present experiments were precisely performed and has a good accuracy. In the case for the annular flow, the velocity profiles are modified to sharpened shape. The velocity near the central axis increases, and the velocity near the pipe wall decreases. This modification becomes significant as the flow rate of the liquid film becomes larger.

Figure 6 shows the measured fluctuation velocity profiles. The experimental data for the single-phase flow and the annular flow are plotted in fig.6. The published data for single phase flow measured by Laufer\cite{10} is also drawn. In the case for single-phase flow, the experimental data has a good agreement with Laufer's data. The fluctuation velocity profiles of core region were well confirmed to be measured accurately. In the case for the annular flow, the fluctuation velocity becomes larger than that of the single-phase flow through the all-radial position. This enhancement of gas-phase turbulence fluctuation becomes significant as the flow rate of liquid film becomes larger. In the case of $j_L = 0.50 \text{cm/s}$, the fluctuation enhancement is about 13 ~ 15% relative to single-phase flow, 28 ~ 30% in $j_L = 1.00 \text{cm/s}$, respectively.

In general, the increase of the turbulence fluctuation makes the velocity profile flatten, e.g. at progressively higher Reynolds number values, the power dependence $1/7$ on time-averaged velocity profile must becomes $1/8$, $1/9$, or $1/10$ in single-phase flow. However, the velocity profiles in annular flow shown in fig.5 are modified to the sharpened shape: this means the power dependence increases in spite of the enhancement of the turbulence fluctuation as shown in fig.6.

2. Energy Spectrum for Fluctuation

Figure 7 shows the one-dimensional energy-spectrum density function for the fluctuation velocity component.
one-dimensional energy spectrum density function for the fluctuation component. The one-dimensional energy spectrum density function for the fluctuation velocity component, \( e(f) \), is defined mathematically as following equation.

\[
e(f) = \lim_{T \to \infty} \frac{1}{T} \left[ \hat{u}'(f) \right]^2
\]  

(1)

Where, \( \hat{u}'(f) \) indicates the Fourier transform for time series of fluctuation velocity component in axial direction, \( u'(t) \), and \( T \) means the sampling time for data acquisition. FFT algorithm was used to evaluate the energy-spectrum density function from the original fluctuation velocity data, which was acquired on the central axis of the pipe.

The typical two cases for annular flow \( (j_G = 21.0 \text{ m/s}, j_L = 1.25 \text{ cm/s}) \) and single-phase flow \( (j_G = 21.6 \text{ m/s}, j_L = 0.00 \text{ cm/s}) \) were plotted. For each case, superficial velocities of gas-phase were set to nearly the same condition. From fig.8, it is noted that the auto-correlation coefficient for the fluctuation velocity component, which was non-dimensionalized auto correlation function by mean square of the fluctuation velocity, becomes larger in the whole spectrum range compared with single-phase flow in the range of \( z > 0.005 \text{ m} \). As the superficial velocity of liquid-phase increased, this tendency becomes significant. This indicates that the integral scale (macro scale) of turbulence vortex becomes larger in the annular flow compared with the single-phase flow. It is also noted that the gas-phase turbulence in annular flow is modified and has a coherency in the range of \( z > 0.005 \text{ m} \). This should be affected by gas-liquid wavy interface that is periodically moving on the liquid film flow.

4. Direct Observation for Dynamic Behavior of Gas-Liquid Interface

Figure 9 shows the direct photograph of the dynamic behavior of wavy interface on the liquid film flow. Photographs of (a) to (f) represent the photos for the cases changing the superficial velocities of liquid-phase and gas-phase. We have the motion movies of the dynamic behavior of gas-liquid wavy interface for each case taken by using high-speed video camera system, but only the instantaneous captured photographs are printed on present paper. The shutter speed of the high-speed video camera was set to 1/5000 sec, which was short enough to capture clearly the motion and shapes of the ripple or disturbance waves propagation on the liquid film.

In these figures, (a) and (b) show the cases with keeping the superficial gas velocity \( j_G \) on 15.5 m/s, but changing the superficial liquid velocity \( j_L \) on 0.75 or 1.00 cm/s, respectively. The case of (c) and (d) show the cases of keeping \( j_G \) about 20.8 m/s, and (e) and (f) represent the cases of \( j_G \) fixed at about 26.4 m/s, but changing the \( j_L \) on 0.75 or 1.25 cm/s, respectively.

As shown in fig.9 (b) and (d), it is noted that the pulse of disturbance wave, which has very complicated wrinkle structure and large-propagating velocity, were observed at rare intervals on the liquid film flow. The disturbance waves
occur periodically like the pulses in the frequency of about 0.3 ~ 2 Hz in these cases.

From the image processing method, it was noted that the propagation velocities of the disturbance waves reach up to 3 ~ 10 times of that of the ripple waves and overtakes the ripple waves, while the ripple waves propagate with the velocities about 1.1 ~ 2.1 times of the mean velocity of the liquid film. The disturbance wave appears in the condition of relatively high superficial liquid velocity and low superficial gas velocity. In the case of (f), disturbance waves rarely occur, even though the superficial liquid velocity is the same with cases of (b) and (d). In the cases of (c) and (e), in which the superficial liquid velocity is relatively lower, only ripple wave was observed on liquid film flow. It is also noted from figs of (a), (c) and (e), the ripple waves become minute structure as the superficial gas velocities becomes larger.

Table 1 Appearance of the pulse of disturbance waves

<table>
<thead>
<tr>
<th>$j_L$ cm/s</th>
<th>15.5</th>
<th>21.0</th>
<th>26.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>○</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>1.00</td>
<td>○</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>1.25</td>
<td>○</td>
<td>○</td>
<td>×</td>
</tr>
</tbody>
</table>

Fig.9 Direct photograph of dynamic behavior of wavy interface on liquid film flow

Fig.10 Void fraction data for liquid film measured by the point-electrode probe

Fig.11 Experimental results for liquid film thickness

The appearance of disturbance wave is summarized in table 1. In the table 1, “○” indicate the appearance of disturbance waves, and “×” indicate the conditions where the disturbance waves do not appear.

4. Measurement for Liquid Film Thickness
Figure 10 shows the experimental results for the void fraction data for liquid film thickness measured by the point-electrode probe shown in the section II-2. The horizontal axis means the distance between the tip of the point electrode probe and the pipe wall. The vertical axis means the measured time-averaged void fraction, which indicates the fraction of time period in which the probe tip contacts with the water takes place. The mean thickness of the liquid film was determined as the distance from the pipe wall where the time-averaged void fraction becomes 50%. The thickness of the base film was determined as the distance where the void fraction just rises up from zero. The maximum thickness of the liquid film was determined as the distance from the wall where just below of the void fraction reaches up to 100%.

From fig.10, it is noted that the gradient of curves indicating the void fraction tends to decrease. Especially, it becomes significant in the region where the void fraction is near 100%; the maximum thickness of liquid film increases radically. This tendency corresponds to the appearance of disturbance wave on liquid film flow. The disturbance wave height might be 5 ~ 10 times of mean thickness of liquid film. Meanwhile, the thickness of base film or mean thickness does not change so much even though the disturbance wave appears.

Figure 11 shows the summarized experimental results for liquid film thickness for each case. The maximum, mean and base-film thickness is plotted for each case. It is noted that the mean thickness of the liquid film decreases as the flow rate of gas-phase decreases. It is also noted that the mean thickness of the liquid film mainly depends on gas flow rate but liquid flow rate: the mean thickness has nearly the same value when the gas flow rates were the same conditions. On the other hand, minimum or maximum thickness of liquid film changes as the liquid flow rate changes.

### III. Numerical Analysis

Numerical analysis was carried out to predict the gas-phase turbulence modification in annular flow. Gas-core turbulence modification by the effects of liquid film flow, which has wavy interface, are assessed by employing the turbulence modification by the effects of liquid film flow, gas-phase turbulence modification in annular flow. Gas-core liquid film changes as the liquid flow rate changes. On the other hand, minimum or maximum thickness of liquid film mainly depends on gas flow rate. The mean thickness of the liquid film decreases as the flow rate of gas-phase decreases. It is noted that for the time-averaged velocity profiles calculated by the numerical method.

The liquid film has a wavy interface. In this paper, we adopted the idea of rough wall function on moving wall as a liquid film boundary condition. A wall function for a rough surface can be presented as the following formula, which has modified form in the second term of the right hand term compared with popular wall function used in the standard k-ε model:

\[ u^+ = \frac{1}{k} \ln y^+ + B \frac{1}{k} \ln \left( 1 + 0.3 \Delta k^+ \right) \]

Where

\[ u^+ = \frac{u^*}{\nu}, \quad y^+ = \frac{y^*}{\nu}, \quad \kappa = 0.41, \quad B = 5.5, \quad \Delta k^+ = \frac{u^* \Delta k}{\nu} \]

\[ u^* \] is the gas velocity, \( u^+ \) is the non-dimensional velocity, \( u^+ \) is the friction velocity, \( y^+ \) is the distance from wall surface, \( \nu \) is the kinematical viscosity, \( \kappa \) is Kalman constant, \( \Delta k \) is roughness and \( \Delta k^+ \) is the non-dimensional roughness, respectively. The height of ripple waves, \( \Delta h \), was employed instead of \( \Delta k \), as a liquid film boundary condition. The interfacial wave heights were estimated from the experimental data shown in fig.11, that was calculated by subtracting the base-film thickness from the maximum film thickness, where the void fraction is 99.9% in ripple wave regions, or 99.5% in ripple with disturbance wave regions for each case as shown in flow pattern diagram of fig.4.

In this computation, the propagating velocities of ripple waves shown in table 2, which are not the disturbance waves, were employed as the interfacial velocities for the boundary condition, because if the disturbance wave occurred, the frequency of appearance of disturbance waves were extremely rare intervals as 0.3 ~ 2 Hz, so the effects of disturbance waves on the time-averaged turbulence velocity can be thought to small. The propagating velocity of ripple waves were about 1.1 ~ 2.1 times of the mean velocity of the liquid film.

### 2. Numerical Results

Figure 12 shows the numerical results of time-averaged velocity profiles for the typical cases, and fig.13 shows the fluctuation velocity profiles calculated by the numerical code as described above. The lines with symbols indicate the experimental results in the present studies, and without symbols are the numerical results. The flow conditions for numerical analysis were set to be the same of the present experiments. The results for single-phase flow are also shown as the reference data.

From fig.12, it is noted that for the time-averaged velocity profiles, the numerical results are as a whole consistent with experimental data for the both cases of single-phase flow and annular flow, but for the slight under-estimation near the central axis.

From fig.13, followings were noted. In the case for single-phase flow, a certain amount of agreement with
IV. Conclusions

Under-estimations were observed in the region of but over-estimations were occurred near the central axis and the overall tendency was consistent with experimental data, observed near the central axis. In the cases for annular flows, experimental data was confirmed, but over-estimation was more accurate prediction.

Improvements are needed for the liquid film modeling for qualitatively the experimental results. Some more using the wall function as boundary condition can simulate interfacial velocity and interfacial roughness modeled by turbulence by numerical analysis taking into account the interfacial waves by the modeling using the wall function for rough moving wall as the boundary condition. Followings are noted from the experimental and numerical results. (1) In annular flow, time-averaged velocity profiles are modified to sharpened shape compared with single-phase flow. (2) Fluctuation velocity in axial direction becomes larger than that of single-phase flow through the all-radial position. (3) Turbulence in annular flow is modified to coherent structure in relatively low-frequency region, which should be affected by gas-liquid periodically moving wavy interface. (4) Numerical simulation considering the effects of interfacial wave height and interfacial velocity on liquid film flow were generally consistent with the experimental results. But some more improvements for the film-flow modeling and the understanding the interaction between the droplets and gas-phase turbulence or droplets and film flow should be performed for a good prediction of annular dispersed flow.

References

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