Liquid holdup distribution and disturbance wave parameters in air-water horizontal annular flow

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ABSTRACT

Annular flow is one of the important flow regimes commonly found in process, power plant, geothermal, nuclear, air conditioning, and other industries employing two-phase flow. It is characterized by liquid film flowing on the wall and a gas core containing liquid droplets. Liquid holdup and disturbance wave are key parameters in such flow. Therefore, it is useful to observe its behavior for analyzing other parameters in horizontal annular flow.
The liquid holdup and wave parameters of horizontal air-water annular flow in 26 and 16-mm-diameter pipe were determined using two flush-mounted CECM sensors, spaced 215 mm apart. The air and water superficial velocities were varied from 12 to 40 m/s and 0.05 to 0.2 m/s, respectively, and its effects were observed. The common phenomena of annular flow such as the disturbance wave, ripple wave, wave velocity, wave number, wave coalescence, and wave deformation could be observed. The mean liquid holdup was in the range of 0.04 to 0.15, indicating the *gas dominant* flow. It is also found that wave velocity increase as the air and water superficial velocity increase. Similar to those of wave velocity, the wave number also increases when the air and water superficial velocity increase.

Keywords
Annular flow, liquid holdup, wave velocity, wave number, CECM

1. INTRODUCTION

Annular two-phase flow is easily found in many industrial applications involving phase-change. This flow regime is quite complex, for both vertical and horizontal orientation, and it is characterized by liquid film on the wall and a gas core containing liquid droplets. For horizontal orientation, annular flow is characterized by the asymmetric distribution of liquid film with thicker liquid flows along the bottom of a tube than on the top, although the degree of asymmetry is dependent on the mass flow rates of liquid and vapor [1]. The effect of gravity-induced drainage increases the thickness of the liquid film on the bottom surface while reducing it on the top surface. Similarly, the drops concentration will be higher in the bottom part than in the top of the pipe.

Considerable researches have been carried out over decades on horizontal annular flow. However, theoretical modeling of horizontal annular flow is generally less successful than in those of vertical flow [2]. Few investigations have been done on the flow mechanism of the annular flow in pipelines and even the fundamental data is still lacking. As a result, many important questions remain unanswered. Perhaps the most significant issue associated with horizontal annular flow is the mechanism by which the liquid film forms on the walls of the conduit, especially on the upper surface of pipe [3]. The main goal of this paper is, therefore, to contribute the fundamental data concerning to the liquid holdup and wave parameters in air-water horizontal annular flow as important variables for determining annular flow mechanism.

1.1 Models for Annular Flow

Several models have been proposed, and the most credible and important among these are *secondary flow*, *entrainment and redeposition of droplets*, *wave spreading,* and *pumping action* due to disturbance wave.
The secondary flow mechanism [4] assumes that the circumferential variation of the film thickness and disturbance waves produces gas-liquid interfacial roughness gradient around the circumference of the tube. As a result, a two-vortex secondary flow in the gas phase normal to the tube axis is created, which drives the liquid up along the wall. Other experiments have also shown the existence of such flows, [5,6,7]. However, the role of these flows in liquid film circumferential distribution is still debated. **Entrainment and redeposition mechanism** [8], suggests that the drained liquid film on the upper wall is continuously replenished by impacting liquid droplets from the vapor core. The entrainment of droplets from the bottom to the top of the tube is created by the variation in the film thickness. **Wave spreading mechanism** [9], suggests that when a disturbance wave travels through the tube, it brings the liquid film in front of the wave up the

tube walls, thus maintaining the film on the top of the tube. The idea is that the disturbance waves travel faster along the bottom of the tube than along the top. This will create a plowing effect that drives liquid film upward immediately in front of the wave. **Pumping action** due to a disturbance wave [10], states that the gas flow over a disturbance wave will produce a circumferential pressure gradient caused by the variation of the wave height.

1.2 Liquid Holdup

Liquid holdup is defined as the fraction of an element of pipe which is occupied by liquid

$$\eta = \frac{A_L}{A} \quad (1)$$

In two-phase flow, it is necessary to be able to determine liquid holdup to calculate such things as mixture density, actual gas and liquid viscosities, effective viscosity and heat transfer. The value of liquid holdup varies from zero for single-phase gas flow to one for single phase liquid flow. Liquid holdup may be measured experimentally by several methods, such as resistivity or capacitance.
The relative volume of liquid and gas is sometimes expressed in terms of the volume fraction occupied by gas, called gas holdup or void fraction. It is expressed as:

$$\alpha = \frac{A_G}{A} = \frac{A - A_L}{A} = 1 - \eta \quad (2)$$

The value for liquid holdup is difficult to be calculated analytically. It must be determined from empirical correlations and is a function of variables such as gas and liquid properties, flow pattern, pipe diameter, and inclination. Liquid holdup equations are functions of dimensionless liquid and gas velocity numbers in addition to liquid viscosity number and angle of inclination.

2. CECM FOR HOLDUP MEASUREMENT

For measuring the liquid holdup, Fukano has developed a constant electric current method (CECM) [11], in which the constant electric current is applied from a pair of electrodes, which will be referred to as the power electrodes, as shown in Figure 1.

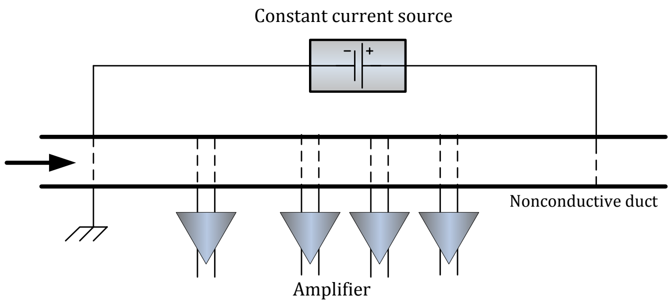


Figure 1: Basic idea of CECM.

The method was developed based on the conductance method. It has been used for measuring liquid holdup and film thickness in air-water annular flow in near horizontal pipe [12].

The output of the conventional conductance method is asymptotically increases with the increase in the film thickness up to a certain value which is considerably small compared with the distance between the sensor electrodes. On the other hand, in the constant electric current method, the output is fundamentally improved, and the distribution of the electric current is uniform independent of the film thickness and a quite good linearity of the output with the film thickness is obtained.

The voltage drop at the sensor electrodes is fed to a high-input amplifier, so that the constant current is not affected by the presence of the sensor electrodes. The increase in voltage drop with the increase in electrical resistance due to the existence of gas phase is independent of the location of gas in the pipe cross section. If the film thickness is very thin, the electric resistance will be high with the current source is kept at a constant value. It results in large voltage drop. Therefore, the thinner the film, the larger the voltage drop, the higher the sensor sensitivity, and the more accurate the holdup measurement.
The interaction among sensor electrodes could be neglected as the outputs are fed to high impedance amplifier. It means that multiple sensors could be installed in a short distance for simultaneous measurement of liquid holdup at any different axially locations. In this case, only single power source is needed. The other advantage of CECM is that the sensors could be flush-mounted in duct or pipe. Therefore, the two-phase flow is not disturbed by the existence of the sensor electrodes.

3. WORKING PRINCIPLE

Due to the difference in conductivity of each component in two-phase flow, the sensor will give combined conductance of liquid and gas flowing in the pipe which can be converted into liquid volume fraction in electric voltage.

The basic idea in designing the sensor is as follows: The electric resistance of two-phase flow, R_{TP}, in a unit length of the channel is expressed as,

$$\frac{1}{R_{TP}} = \frac{1-\eta}{R_G} + \frac{1}{R_L} \quad (3)$$

where R_G and R_L are the electric resistance of gas phase and liquid phase alone occupies the whole cross-section of the tube. The two-phase voltage drop is expressed in the unit length (V_{TP}) when a constant current I_0 is supplied. As $R_G >> R_L$, the holdup could be expressed as

$$\eta = \frac{R_L}{R_{TP}} = \frac{I_0 R_L}{I_0 R_{TP}} = \frac{V_L}{V_{TP}} \quad (4)$$

where V_L is the voltage drop when the liquid alone flows with occupying the whole cross-section of the tube. If the electrical resistance and voltage drop are expressed as R_{TP0} and V_{TP0} when the liquid holdup has the value of η_0 and the electric current has the same value as in (4), then the following equation could be obtained:

$$\eta_0 = \frac{I_0 R_L}{I_0 R_{TP0}} = \frac{V_L}{V_{TP0}} \qquad (5)$$

Eliminating V_L in equations (4) and (5) results in

$$\eta_{TP} = \frac{I_0 R_{TP0}}{I_0 R_{TP}} \eta_0 = \frac{V_{TP0}}{V_{TP}} \eta_0 \qquad (6)$$

If V_{TP} is measured under the condition of known values of η_0, V_L and V_{TP0}, then the liquid holdup, η, could be calculated with equation (6).

4. LIQUID HOLDUP AND WAVE INVESTIGATIONS

The measurements of liquid holdup were carried out in the air-water horizontal flow rig shown schematically in Figure 2.

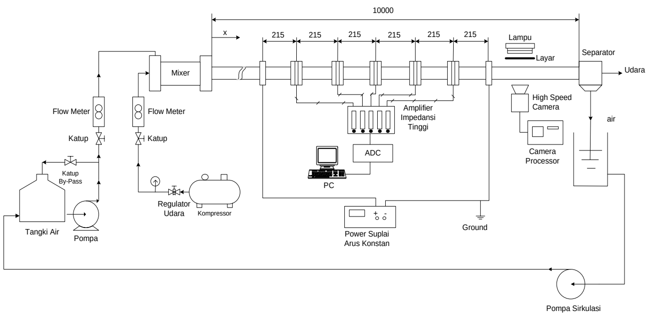


Figure 2: Experimental rig.

The test section is a 10 m long acrylic resin tube of 26 mm ID. Air enters the test section at one end from a compressed air supply. Water is injected through a porous tube wall section. The liquid holdup was measured at a distance of 5.5 m from the porous mixer, thus giving a developing length of 200 tube diameters. In view of the fact that water entered through a porous wall section, it was felt that this length was sufficient for the flow to be fully developed [5]. The range of liquid and gas superficial velocities are 0.05 to 0.2 m/s and 12 to 40 m/s, respectively. Under the combinations of gas and liquid superficial velocities, the flow regimes observed in this research are annular and transition from wavy to annular if plotted in Mandhane map (Figure 3).

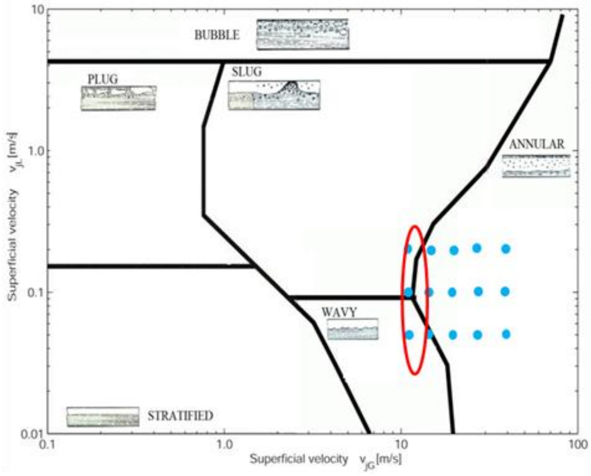


Figure 3: Experimental matrix plotted in Mandhane map.

4. RESULTS AND DISCUSSION

The measurement of liquid holdup using CECM could be used for analyzing some behaviors of annular flow. The observed disturbance wave, ripple wave, wave development, entrainment, wave breakup, and coalescence are indications that the annular flow has been established successfully.

4.1. Disturbance Wave and Ripple Wave

One of them is the existence of disturbance wave and ripple wave in annular flow. Figure 4 shows such phenomena compared to the visual observation using video camera.

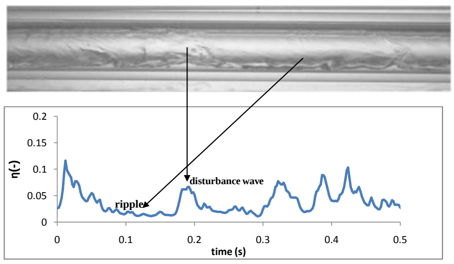


Figure 4: Disturbance and ripple waves.

The ripple wave shown in Figure 4 could be captured by CECM sensor as well as large disturbance wave. The wave is identified when a liquid wave with high amplitude flows through the sensor.

4.2 Wave Development and Entrainment

Other phenomenon observed in this experiment is wave development and entrainment, as shown in Figure 5. The transport of liquid film in the pipe wall could be traced from the holdup signal. Figure 5 shows the change of wave height measured by sensor 1 and 2. The peak of the wave when sensed by sensor 2 is higher than those of sensor 1. It means that the wave "grows" and the phenomenon is called "wave development". The reduction of wave height when it is sensed by sensor 2 and then sensor 2 is a phenomenon called "entrainment", in which a portion of liquid in the wave crest is entrained when high velocity of gas flows and shear the gas-liquid interface at wave crest.

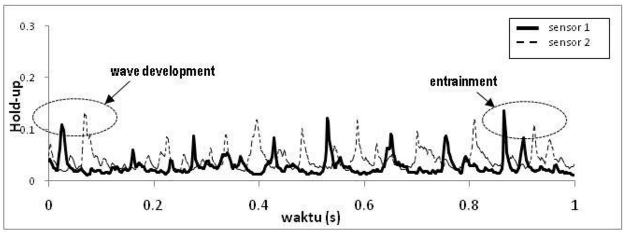


Figure 5: Wave development and entrainment.

4.3 Wave Coalescence and Breakup

It has been observed that disturbance waves tend to move with constant velocity and that if faster wave overtakes a slower wave, then the two waves coalesce and usually continue with the speed of the faster wave. This phenomenon is called wave coalescence. In the other hand, the break of a large wave into smaller waves is also observed in this experiment. This phenomenon is called wave breakup. The coalescence and breakup of wave is illustrated in Figure 6.

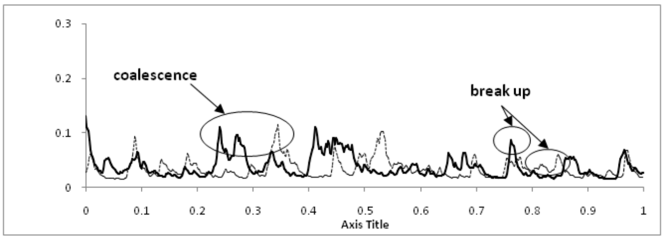


Figure 6: Wave coalescence and break up.

4.4. Wave Velocity

The signal sensed by the downstream sensor (sensor 2) is delayed by several milliseconds compared to those of sensor 1, depends on the velocity of the wave. If the time delay and the distance between the sensors are known, then the wave velocity could be calculated. To determine the time delay, a cross correlation function is used. Figure 7 shows the result of cross-correlation function of holdup signal sensed by sensor 1 and 2 for gas superficial velocity, J_G, of 12 m/s and liquid superficial velocity, J_L, of 0.05 m/s.

From Figure 7, the cross correlation shows that time lag for the holdup signal sensed by sensor 1 and 2 is 0.14 s. With the sensors spaced 21.5 mm apart, then the wave velocity is 1.5 m/s. The wave velocity increases with the increasing of gas superficial velocity. It could be described as follows: at the higher the air velocity, the force that shear the gas-liquid interface is also higher, resulting in higher liquid film flowing in the pipe.

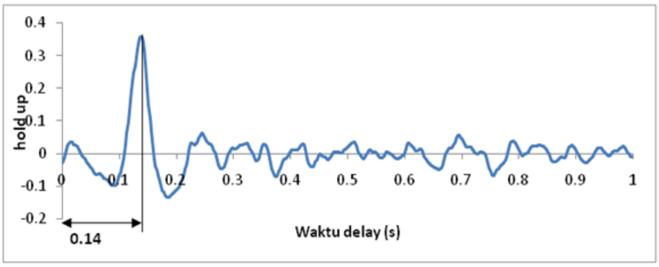


Figure 7: Cross-correlation function of holdup signal J_G = 12 m/s and J_L = 0.05 m/s.

The experiment of Jayanti et al. [5] with 32 mm ID pipe showed that the wave velocity ranged from 1.9 to 4.5 m/s for liquid superficial velocity of 0.08 – 0.145 m/s and gas superficial velocity of 14 – 26 m/s. Using 50.8 mm ID pipe, Paras and Karabelas [6] showed that the wave velocity was in the range of 1.6 to 3.6 m/s for liquid superficial velocity of 0.02 – 0.06 m/s and gas superficial velocity of 31 – 66 m/s. Figure 8 shows the comparison of wave velocity obtained from this work and those obtained by [5] and [6].

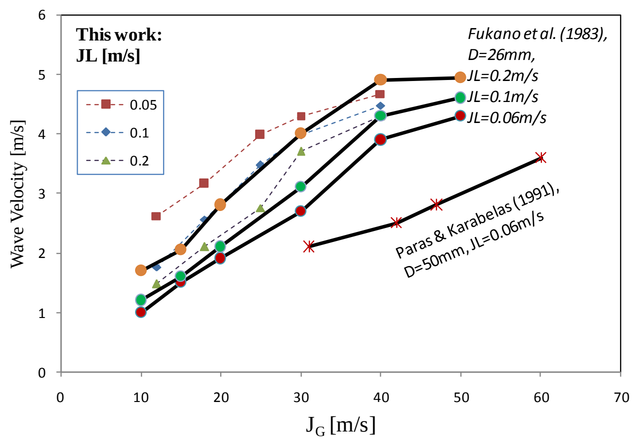


Figure 8: Comparison of wave velocity obtained from this work and those obtained by Fukano et al. (1983) and Paras and Karabelas (1991).

Scubring and Shedd [13] have reported that the wave velocity for horizontal annular flow is 2.4 to 6 m/s for their experiment with 26.3 mm ID pipe using liquid superficial velocity of 0.04 to 0.39 m/s and 32 to 91 m/s. For the smaller pipe (8.8 and 15.1 mm), the wave velocities will be higher.

4.5 Wave Frequency/Wave Number

The wave frequency or wave number could be determined from the frequency corresponding to the largest peak of power spectral density function. From Figure 9, it is shown that wave frequency increases with increasing of gas superficial velocity.

Paras and Karabelas [6] also stated that the higher gas superficial velocity, the higher the wave number. However, they showed that the wave number decreases with the increasing of liquid superficial velocity. This is different from the results of this work, in which the wave number increases with the increase of liquid superficial velocity.

The effect of diameter on the wave frequency has also been observed in this experiment. The pipe diameter has a significant effect on the wave number, as could be seen in Figure 10. It is shown that the smaller pipe gives the larger wave number.

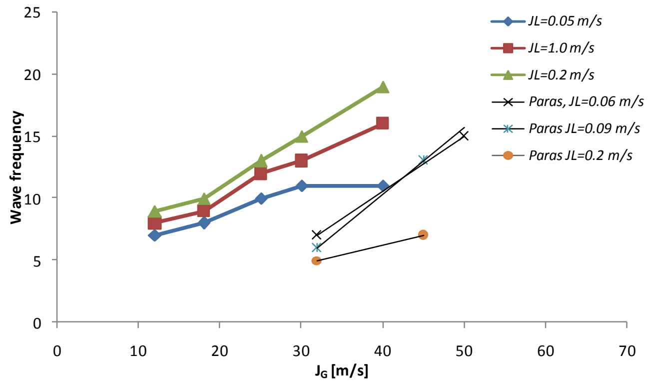
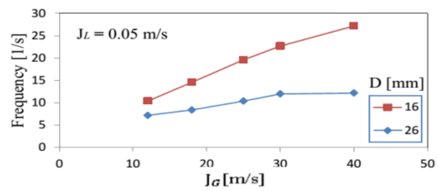
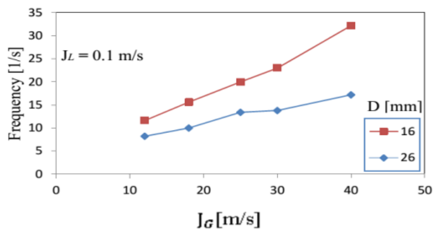


Figure 9: Wave frequency vs gas superficial velocity.



(a)



(b)

Figure 10: Effects of diameter and J_G on the wave number.

Schubring and Shedd [14] reported that for pipe diameter 26.3 mm, the wave frequency ranges from 10 to 15 for the same range of gas superficial velocity. However, when the gas velocity is increased to 70 m/s, the wave number could reach 40. For pipe diameter of 15.1 mm and the same range of gas superficial velocity, the wave number ranges from 15-30, similar to those obtained from this work.

4.6 Liquid Holdup

The effect of diameter and gas superficial velocity on the liquid holdup of horizontal annular flow is presented in Figure 11. For liquid superficial velocity of 0.05 m/s and pipe diameter of 16 mm, the liquid holdup ranges from 0.038 to 0.079. For 26 mm pipe, the liquid holdup ranges from 0.011 to 0.041. Therefore, for the larger the diameter, the liquid holdup will be smaller. If the liquid superficial velocity is increased to 0.01 m/s, the maximum liquid holdup for 16 mm and 26 mm pipes are 0.11 and 0.06, respectively. If the liquid superficial velocity is further increased to 0.2 m/s, the maximum liquid holdup are 0.15 and 0.09 for pipe diameter of 16 and 26 mm, respectively.

From the detail observation of Figure 11 it is shown that the liquid superficial velocity affects the liquid holdup significantly. For both diameters observed, the effect of liquid superficial velocity is very clear at low gas superficial velocity for 16 mm pipe. However, for 26 mm pipe the strong correlation of liquid holdup and liquid superficial velocity could be found in all range of gas superficial velocity.

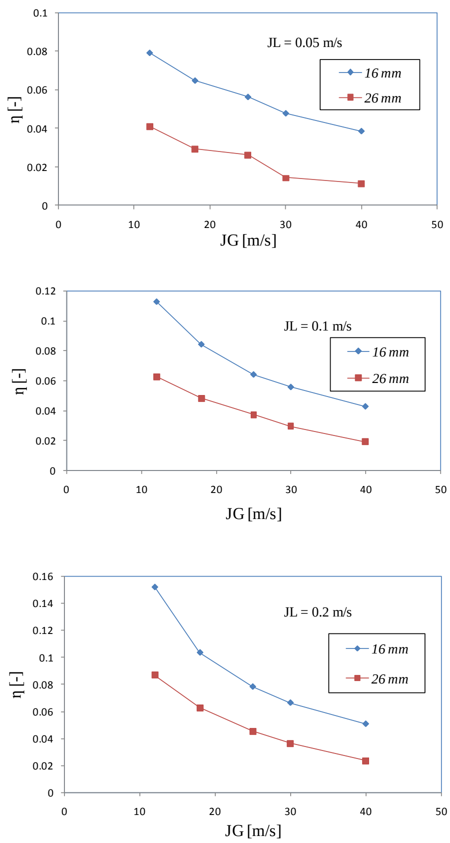


Figure 11: The effect of diameter and J_G on the liquid holdup.

4.7 Visual Observations

The visual observations for this experiment were conducted using Canon PowerShot 100 with recording speed of 250 frames per second and a resolution of 640 x 480 pixels. The results of the visual observation are presented in figure 12 and 13.

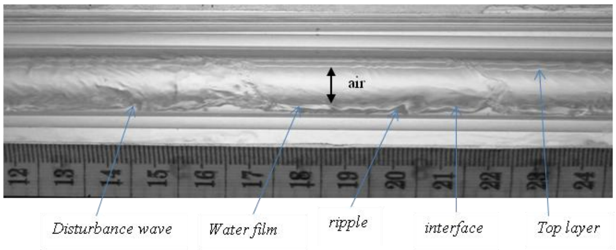
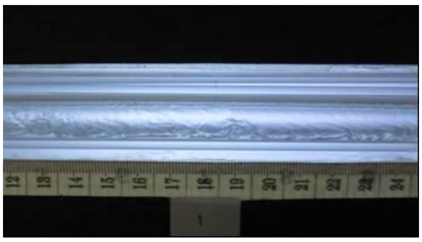
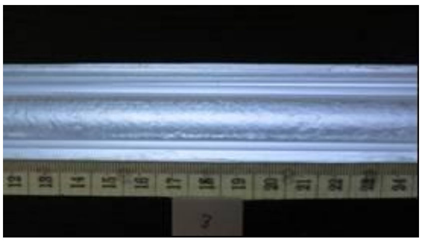


Figure 12: Visual observation annular flow.

To observe the detailed behavior of annular flow through visual observation, comparisons to other flow conditions are needed. From Figure 12, the annular flow could be observed through the existence of asymmetric liquid film due to gravity effect flowing in the pipe wall, disturbance wave, ripple wave, top layer of liquid film, and gas core flowing in the center of pipe.

At low gas and liquid superficial velocity (J_G = 12 m/s and J_L = 0.05 m/s), the liquid film flows in a relative low velocity (Figure 13, top) and the interface of gas and liquid is rough. If the gas superficial velocity is increased to 25 m/s, the interface will be smoother (middle). Further increase of gas superficial velocity to 40 m/s will give the much smoother interface (bottom).





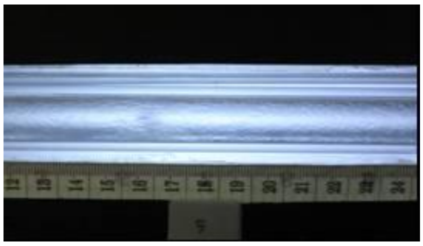


Figure 13: Flow at J_L = 0.05 and J_G = 12 (top), J_G = 25 m/s (middle), J_G = 40 (bottom)

It indicates that the thickness of liquid film will be thinner for the higher gas superficial velocity. The same phenomenon is also observed for the disturbance wave, in which the amplitude decreases with the increasing of gas superficial velocity.

5. CONCLUSIONS

From the conducted experiment, it could be concluded that:

- The annular regime has been established successfully.
- The common phenomena of annular flow such as ripple waves, disturbance waves, gas core, gas-liquid interface, and asymmetric liquid film due to gravity effect could be observed both visually and using liquid holdup signal.
- The wave velocity and wave number increase with the increasing of gas superficial velocity.
- Liquid holdup increases with the increasing of liquid superficial velocity and decreasing of gas superficial velocity.

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