The effect of pipe length on the flooding mechanisms in inclined pipes

[1]Deendarlianto, [1]Hermawan
[1]Department of Mechanical & Industrial Engineering, Faculty of Engineering,
Gadjah Mada University, Jalan Grafika No.2, Yogyakarta 55281, Indonesia
E-mail: deendar@hotmail.com, hermawan_ugm@yahoo.com

Abstract-An investigation of the effects of pipe length on flooding during adiabatic air-water counter-current two-phase flow in inclined pipes of 16 mm I.D. was conducted experimentally. A constant electric current method and visual observation were utilized to elucidate the flow mechanisms at the onset of flooding.

As a result, it was found that (1) Upper flooding moves to lower flooding as the pipe length decreases, (2) in the range of pipe length tested, the upper flooding disappeared when the pipe length was 0.5 m, and (3) the onset of flooding decreases as the pipe length increases.

Keywords: loss of coolant accident, flooding, inclined pipes, upper flooding, lower flooding

1. INTRODUCTION

Counter-current flow is an important problem in safety analysis of the loss of coolant accident (LOCA) in a pressurized water reactor (PWR), where the counter-current flow of steam and cold water may take place in an inclined tube when the emergency core cooling (ECC) water is injected into the reactor vessel. The total injected water will reach the reactor core and cool down fuel rods only if the flow condition is far from those for flooding occurrence. The phenomenon of flooding is a considerable technological importance due to a limiting factor in the operation of that equipment.

The flooding has been investigated by a number of researchers, and most of the flooding experiments have been performed in vertical pipes. Very little work has been reported on the effects of pipe length on the flooding phenomena in inclined pipes. The purpose of this study is to examine the influence of pipe length on the flooding phenomena for adiabatic air-water counter-current two-phase flow in inclined pipes.

2. Experimental apparatus & Procedure

The details of the experimental apparatus and procedure used in the present experimental study were described in the previous papers [Deendarlianto et al. (2004, 2005)] and only the main features are presented here. It consisted of four counter-current flow pipes having total lengths of 0.5, 1.1, 2.2 and 5.5 m respectively. They were made of transparent acrylic resin with an inner diameter of 16 mm.

Air was fed from a compressor to the lower end of the inclined pipe and flowed upward through the test section to a separator. Water, measured by a digital flow meter, entered from the porous section and flowed downward in the pipe. The water inlets consisted of a porous tube in order to make the uniform liquid film flow at the entry. The air entrance was made of acrylic resin, providing a conical inlet passage to avoid turbulence effects in this section.

The interfacial behavior of the liquid film was investigated by using two high-speed video cameras at different locations along the pipe, i.e. near the liquid inlet and outlet. Pictures were taken at 240 fps and a shutter speed of 1/10,000 s. The instantaneous local liquid hold-up along the pipe was measured by the constant electric current method (CECM). The output signals from the liquid hold-up sensors were sent respectively through amplifiers with high input impedance to a personal computer via an A/D converter. The liquid hold-up data were acquired at 1.0 kHz. The details of the experimental apparatus, principle and the measurement system can be found in Fukano (1998).

In the present study, the water flow rate was kept constant and the airflow rate was increased by small increment. Next, the liquid hold-up, pressure gradient and discharged liquid flow rate were measured. The onset of flooding was defined as the limit of stability of the counter-current flow, indicated by the maximum airflow rate at which the discharged liquid flow rate is equal to the inlet liquid flow rate.

The experimental conditions were as follows: pipe inclinations; 30°, 45° and 60° from horizontal, the ranges of both superficial velocities; J_L=0.03~0.32 m/s, J_G=0.0~14 m/s, working fluids; air and water.

To simplify the explanation in this paper, we used some abbreviations for the flow characteristics. The abbreviations in this paper are as follows; **W**: wave, **LW**: large wave, and **BW**: breakdown of the wave.

3. RESULTS AND DISCUSSION

3.1. Discharged liquid flow rate

The typical results of flooding curve are shown in Fig.1. The pipe inclination and pipe length were 45º and 1.1 m respectively. In the figure, the abscissa indicates the superficial air velocity J_G and the ordinate the discharged superficial water velocity $J_{L,D}$ at the liquid outlet. The onset of flooding is marked by the arrows.

Figure 1 reveals that the discharged superficial water velocities decrease gradually after the onset of flooding and the shapes of the curves are independent of the inlet liquid flow rate. Next, gas velocities at the onset of flooding tend to decrease with increasing water flow rate as reported for the tests in vertical pipes.

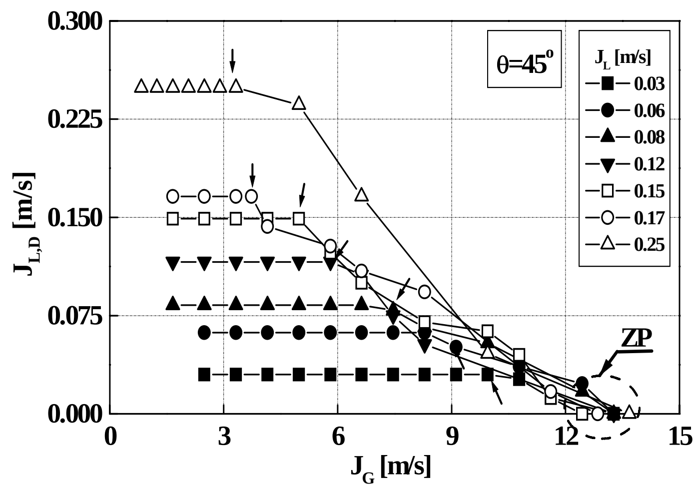


Fig.1 Discharged superficial liquid velocity vs superficial air velocity (L=1.1 m and θ=45º)

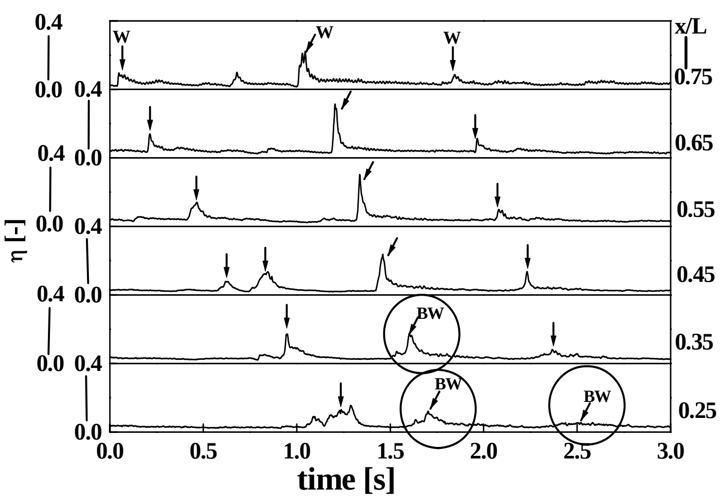
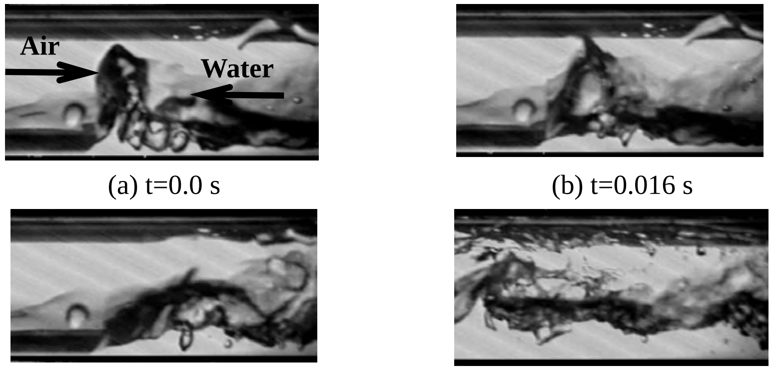


Fig.2 Time variation of liquid hold-up at the onset of flooding (J_L=0.03 m/s, J_G=8.29 m/s, L=1.1 m and θ=30º)



(a) t=0.0 s (b) t=0.016 s

(c) t=0.042 s (d) t=0.137 s

Fig.3 Breakdown of the wave at the onset of flooding obtained at x/L≅0.25 (J_L=0.03 m/s, J_G=8.29 m/s, L=1.1 m and θ=30º).

3.2. Liquid film behavior at the onset of flooding

From visual observations and time variation of liquid hold-up taken by CECM, two mechanisms at the onset of flooding are identified. Those are lower flooding and upper flooding respectively (Deendarlianto et al. (2005)). The terms lower flooding and upper flooding indicate the location where the flooding is initiated at the lower or the upper locus of the test section. The lower flooding occurred at lower liquid flow rate and high pipe inclination angle, and the breakdown of the wave occurs in the lower part of the pipe (x/L ranged from 0.0 to 0.5). It is initiated by the increase of the wave height, in which the wave formation is begun from the upper part of the test pipe (x/L ≅ unity). The wave height increases with the downward movement. It will be broken by the airflow when the wave height reaches a certain wave height in counter-current flow.

The typical result of the time variation of liquid hold-up at the onset of flooding of lower flooding is shown in Fig.2. The flow conditions were J_L=0.03 m/s, J_G=8.29 m/s, L=1.1 m and θ=30º. The occurrence of lower flooding is remarked by the occurrence of **BW** at x/L=0.35 and 0.25. In the present study, the **BW** was decided by comparing the corresponding wave at the time variations of liquid hold-up. It was verified by the visual observation. In addition, the wave shifts to the lower right, indicating that there is upward motion of the wave under this flow condition. Next an example of the breakdown of the wave obtained at x/L≅0.25 is shown in Fig.3.

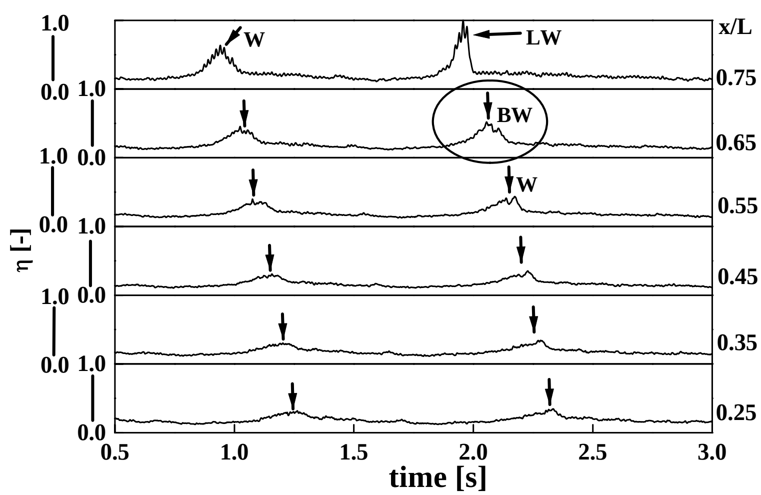
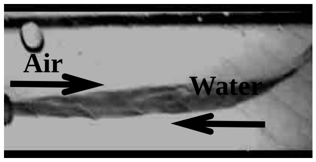


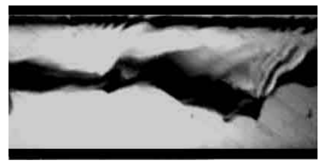
Fig.4 Time variation of liquid hold-up at the onset of flooding (J_L=0.25 m/s, J_G=2.07 m/s, L=1.1 m and θ=30º)



(a) t=0.00 s

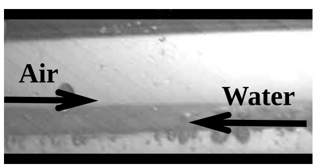
(b) t=0.57 s

(c) t=0.61 s

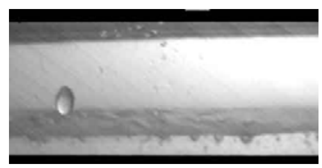


(d) t=0.638 s

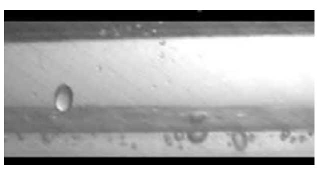
Fig.5 Interfacial of liquid film at the onset of flooding at high liquid flow rate obtained at x/L≅0.90 (J_L=0.25 m/s, J_G=2.07 m/s, L=1.1 m and θ=30º)



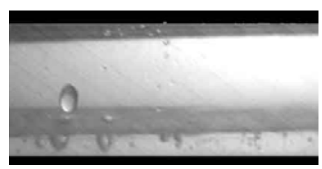
(a) t=0.00 s



(b) t=0.083 s



(c) t=0.116 s



(d) t=0.142 s

Fig.6 Interfacial of liquid film at the onset of flooding at high liquid flow rate obtained at x/L≅0.1 (J_L=0.25 m/s, J_G=2.07 m/s, L=1.1 m and θ=30º)

On the other hand, the upper flooding occurred at higher liquid flow rate and low pipe inclination. It is initiated by the formation of liquid slug in the upper part of the test pipe (x/L≅unity), in which the maximum of liquid hold-up is 1.0. This means that the liquid slug completely blocks the overall cross section of the test pipe. It moves downward for short distance and will be broken by airflow in upper part of the test pipe (x/L from 0.5 to 1.0).The typical result of the time variation of liquid hold-up at the onset of flooding of upper flooding is shown in Fig.4. The flow conditions were J_L=0.25 m/s, J_G=2.07 m/s, L=1.1 m and θ=30º. In this figure, it is clearly shown that the blockage process of liquid film is shown at x/L≅0.75 and t=1.98 s. Next, this large wave is broken-down at x/L≅0.65 and t=2.02 s. In the figure, it is marked as **BW**. The sequence picture of the comparison about the interfacial behavior of liquid film obtained near the inlet and outlet of water are shown in Figs.5 and 6 respectively.

In comparison of Figs.2 and 4, it is noticed that the wave always shifts to the lower right even after the breakdown of the wave. This means that there is no reversal motion of liquid film at the onset of flooding during the occurrence of both lower flooding and upper flooding. The definition of reversal motion, here, does not include the portion of the entrainment of liquid droplet.

The effect of pipe length on the flooding position is shown in Fig.7. In the figure, the lines indicate the transition of flooding mechanisms. The abbreviations of LF and UF represent the terms lower and upper flooding, whereas their positions are in the left and right sides of those transition lines respectively. This figure demonstrates that UF zones increases with pipe length. In the range of the pipe lengths tested, it was found that upper flooding disappeared when the pipe length was 0.5 m.

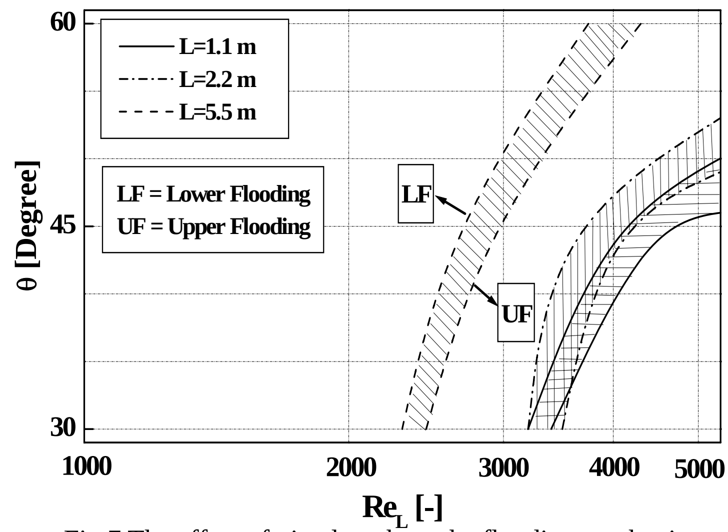


Fig.7 The effect of pipe length on the flooding mechanisms.

3.3. The onset of flooding velocity

Wallis [1969] proposed the dimensionless number, J_K^*, in terms of the gas and liquid superficial velocities to correlate the onset of flooding in vertical pipes. It is defined as follows:

$$J_K^* = J_K \sqrt{\frac{\rho_K}{g\,D\,(\rho_L - \rho_G)}} \tag{1}$$

Where, subscript K indicates gas and liquid phases, ρ the density and D the inner pipe diameter. The correlation is expressed as,

$$\left(J_G^*\right)^{1/2} + m\left(J_L^*\right)^{1/2} = C \tag{2}$$

The constants m and C depend on the conditions of inlet and outlet of liquid phase.

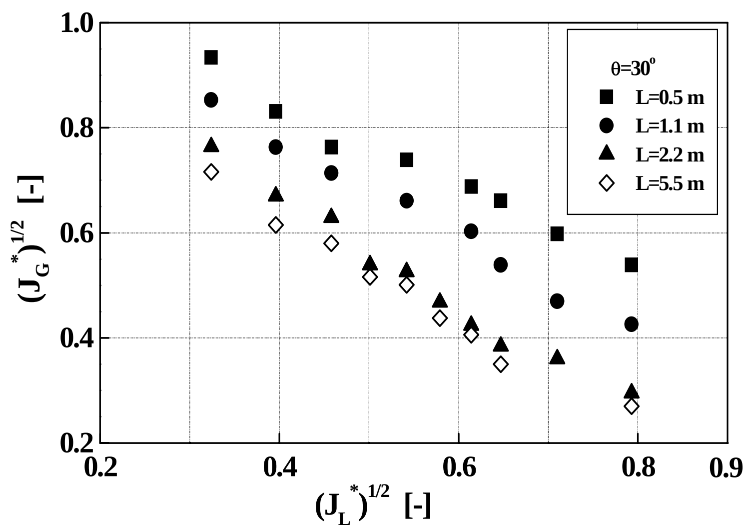


Fig.8 The effect of pipe length on the onset of flooding (θ=30°)

Figure 8 illustrates the effect of the pipe length on the onset of flooding in terms of the Wallis dimensionless number. The Pipe inclination angle is θ=30°, as an example. Close observation of this figure reveals that the onset of flooding velocity is affected by the pipe length for all cases of the examined pipe inclinations. It decreases as the pipe length increases. It can be explained that for a given air flow rate below the onset of flooding, the maximum liquid hold-up increases with downward movement as shown in Fig.9, in which the flow conditions are J_L=0.03 m/s, J_G=7.46 m/s, L=1.1 m and θ=30º. Therefore, an increase in pipe length could be possible to increase the wave height to the certain value at the lower airflow rate. Furthermore the flooding takes place in the lower superficial air velocity. In addition, the effect of pipe length is significant in the range of high liquid flow rate. It accords with the result of Suzuki and Ueda (1977). On the other hand, the obtained phenomena are contradictory to those of Grolmes et al. (1974), Dukler et al. (1984) and Zabaras and Dukler (1988). It can be argued that the differences in the results were due to the using of a sharp exit at the liquid outlet in their experiments, in which it produces a large perturbation near the water outlet that affects the condition of liquid film in the test section. Therefore, the effect of pipe length could not be found in their experiments.

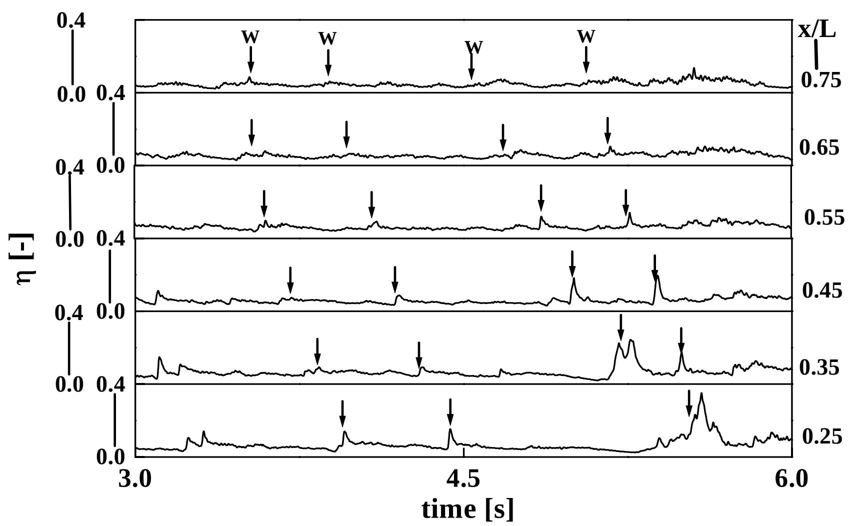


Fig.9 Time variation of liquid hold-up before the onset of flooding (J_L=0.03 m/s, J_G=7.46 m/s, L=1.1 m and θ=30º)

4. CONCLUSIONS

The effects of pipe length on the flooding phenomena in inclined pipes were investigated experimentally. The inner pipe diameter was 16 mm. The pipe lengths were 0.5, 1.1, 2.2 and 5.5 m respectively. The results are summarized as follows:

1. The gas velocity of the onset of flooding decreases as the pipe length increases.
2. Upper flooding moves to lower flooding with the decrease of pipe length, and it does not occur in the short pipe less than about 1.0 m.
3. At the onset of flooding, there is no upward motion of the liquid film. Furthermore, the entrainment plays an important role in the upward transportation of liquid film.

NOMENCLATURE

C	: constant in Eq.(2) (-)
D	: inner diameter (m)
g	: gravitational acceleration (m/s^2)
J_G	: superficial gas velocity (m/s)
J_L	: superficial liquid velocity (m/s)
$J_{L,D}$	: discharged superficial liquid velocity (m/s)

J_K^* : Wallis dimensionless number of superficial velocity (m/s)
L : pipe length (m)
m : constant in Eq.(2) (-)
Re_L : liquid Reynolds number
x : distance from water outlet (m)
t : time (s)

Greek letter

α : void fraction (-)
θ : inclination from horizontal (degree)
η : liquid hold-up (-)
ρ_K : liquid and gas density (kg/m^3)

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