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Experimental study of water–air countercurrent flow characteristics in large scale rectangular channel

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ABSTRACT

Water–air countercurrent flow in a rectangular channel is studied experimentally in this study. The experiment is carried out in a large scale facility that consists of a large scale flow channel and a rotatable operating platform which provides different inclination conditions. This paper focuses on the study of film behavior, such as film thickness and surface wave, in countercurrent flow. Optical thickness probe, hot wire anemometry and high speed camera are applied to perform the data measurement. The results show that the film thickness variation in the large scale channel under countercurrent flow condition is different from the results from small scale tests. The critical air velocity, which is usually considered as the proof of flooding onset, is discussed for different film Reynolds numbers. Moreover, the droplet entrainment plays an important role under high speed air flow conditions. The observation of the surface wave is also conducted to supplement the analysis of film surface variation.

1. Introduction

Facility cooling is one of the most important problems interested in industry. Film cooling is widely concerned in recent years due to its advantages, such as simple schematics, high heat transfer efficiency and low energy demand. Thus, the film cooling is applied in advanced pressure water reactor (PWR) AP1000 to remove the heat of passive containment cooling system (PCCS) during severe accident. Since the countercurrent flow happened in film cooling of PCCS under hypothetical severe accident, the study of film – air countercurrent flow attracts more and more attentions. Most of the studies are carried out in unheated condition to analyze the film thickness variation, surface wave behavior and the onset of flooding (droplet tearing from film surface) which are often related to the heat transfer.

The studies of film flow in tube and on plate were started years ago. With the development of measurement methods and analysis techniques, some mechanisms of the film flow are revealed and some empirical relations constructed. Karapantsios (Karapantsios and Karabelas, 1995) studied the average, maximum and minimum film thickness, the transition of surface wave pattern, as well as the judgment of fully development. Ambrosini (Ambrosini et al., 2002) studied the film behavior on different inclined plate, Re and film temperature (assumes no evaporation). Karimi (Karimi and Kawaji, 1998) used the laser-induced photochromic dye tracer technique to study the hydrodynamic characteristics of water flow in tubes, such as the velocity distribution across the film. In addition, they also investigated the flow pattern with and without countercurrent flow (Karimi and Kawaji, 1999). Wallis (1969) and Kutateladze (1972) gave the correlations for prediction of flooding onset in countercurrent flow. The two correlations are usually adopted in theoretical analysis. Drosos et al. (2003) and Vlachos et al. (2001) investigated the variation of air–water countercurrent flow in small scale rectangular channel, and concluded that the large air velocity could induce the droplet entrainment and increase the surface wave height. In addition, Jayanti et al. (1996) and Stephan and Mayinger (1992) studied the countercurrent flow limitation of flooding in tubes theoretically and experimentally, and identified the usage condition of some correlations. The droplet entrainment phenomenon, usually occurring in flooding, is carefully observed and described in small scale test (Roy and Jain, 1989). The top flooding in thin rectangular channel is studied experimentally to solve the nuclear engineering problems (Osakabe and Kawasaki, 1989). With small scale facility, flooding affected by the duct geometry and fluid property is analyzed (Zapke and Kroeger, 2000). Countercurrent flow is also studied by Ghiaasiaan with a series of works (Ghiaasiaan et al., 1996, 1997). Some researchers have studied the film behavior under countercurrent flow theoretically and numerically. The integral approach is used to obtain the two-wave equation for weakly nonlinear long waves on a liquid film flowing along an inclined plate in countercurrent

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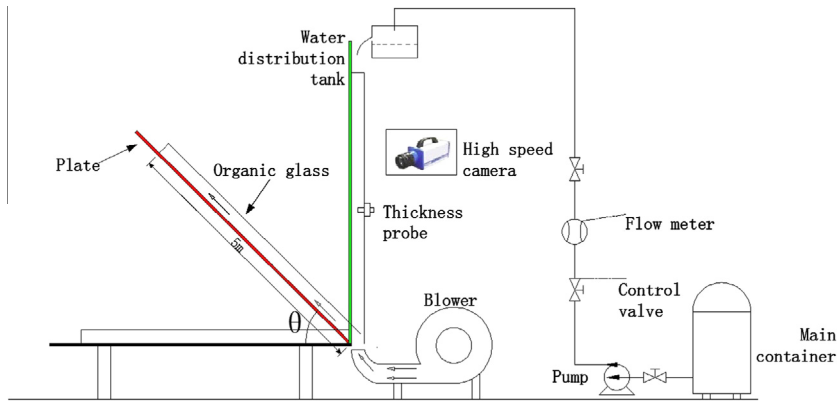

Fig. 1. Schematic of the experimental setup.

flow (Alekseenko and Nakoryakov, 1995). The investigation of the standing wave due to gas blowing upwards over a liquid film is also studied, and the prediction theory of flooding is established (Shearer and Davidson, 1964).

However, study of large scale countercurrent flow experiment has not been conducted yet. The existing experiment data mostly are from small scale channel or tubes. Therefore, this paper focuses on study of characteristics of air–water countercurrent flow on large scale rectangular channel. Specifically, the film thickness variation, surface wave behavior and onset of flooding are investigated.

2. Experimental setup

The facility consists of test section, water supply system, air supply system and measurement system. And the schematic is shown in Fig. 1. The test section is a channel constituted by steel flat plate and organic glass. The steel plate is 5.0 m long, 1.2 m wide and installed on a deck. It could be rotated from 0 to 90°. The cross section size of the channel is 1.2 m wide and 0.3 m height. The water supply system uses motorized valves to control the water flow, and electromagnetic flowmeter to measure the flow rate. The basic component of the air supply system is the centrifugal blower with a maximum air flow rate of 20,000 m^3/h. The air flow generated in the blower part goes through the air duct and test section.

The hot wire anemometer is applied in this experiment to obtain the air flow velocity. In the previous countercurrent flow experiment, air velocity is easily to be measured because of the small facility size. However, the air velocity distribution should be concerned in the 1.2×0.3 m size cross section. The 1.2×0.3 m size pore plate is used to adjust the air velocity distribution. Nearly 300 circular holes uniformly located on the pore plate, and the diameter of circular hole is 20.0 mm. By using of the pore plate, the verification test result shows a more uniform distribution of the air velocity. The optical confocal probe is applied in the experiment to measure the film thickness. Compared with capacitance probe, dye tracer technical or other method, the optical confocal probe has the advantages such as high accuracy (error provided by factory is less than 0.33%), insensitivity to the environment, and no affection to the fluid. The high speed camera is adopted to observe the surface wave of the film flow with frequency of 1000 frame per second. All the measuring equipments mentioned above are calibrated. Due to the importance of the film thickness measurement in this study, the calibration of optical confocal probe is described specially. A plane optical flat produced by Shanghai instituted of optics and fine mechanics is used in calibration. According to the factory parameter table, the plane optical flat is 5.00 ± 0.02 mm thick. We use the optical confocal probe to measure the optical flat thickness several times, and the results in Fig. 2 shows than the error is less than 0.6%.

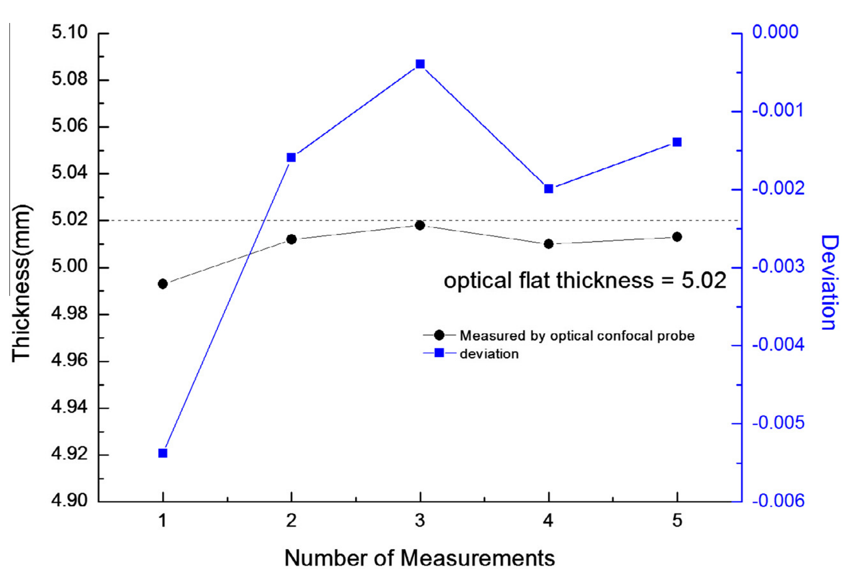

Fig. 2. Calibration of optical confocal probe.