Progress in Nuclear Energy 105 (2018) 1–7

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Film thickness of free falling water flow on a large-scale ellipsoidal surface

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ARTICLE INFO

Keywords:
Film thickness
Free falling film flow
Curved surface
Inclined angle
Extend angle

ABSTRACT

Falling water film flow on large-scale curved dome of passive containment, of which the data is very scarce, plays a crucial role for the thermal-hydraulic behaviors of passive containment cooling system (PCCS) in advanced nuclear power plant. It exhibits a developing phenomenon in nature because of continuous changes of the inclined angle, the width and the extend angle of the flow channel in the longitudinal direction. In order to examine the influences of these continuously varying factors on the flow characteristics, the film thickness of free falling water flow on a large-scale ellipsoidal surface with continuously varying inclined angle and extend angle has been measured experimentally. The working fluid is the low hardness municipal water, of which the inlet temperature is the same as ambient environment. Capacitive non-contact displacement transducers, Micro-Epsilon capaNCDT-CS10 sensors, are used to measure the film thickness at different locations with inclined angle ranging from 18° to 76°. The range of the film Reynolds number is from 360 to 2175. Detailed analyses on the relationship between the dimensionless film thickness and the film Reynolds number at different longitudinal positions on the dome surface are carried out. No obvious influence on the evolution of falling film caused by the continuous changes of the inclined angle, the width and the extend angle of flow channel on the dome can be observed. A new empirical correlation of film thickness on the ellipsoid dome surface is suggested based on the data obtained in the present experiments. Most of experimental data points fall in the range of ± 15% around its prediction. Comparisons are also made between the suggested correlation with other theoretical or empirical correlations of film thickness in straight channels reported in the literature, as well as the numerical results on curved surface by computational fluid dynamics software COMMIX and GASFLOW-MPI. Fairly good agreements are observed, proving that the suggested correlation can predict the film thickness on the curved dome surface of PCCS with much accuracy and then provide a more reliable basis for further analysis of the conjugate heat and mass transfer of PCCS.

1. Introduction

Passive containment cooling system (PCCS) has been utilized in advanced pressurized water reactors, such as AP1000 and CAP1400 to build the natural circulation and to remove the heat released inside the containment under postulated design-base accidents (DBAs), such as loss of coolant accident (LOCA) (Schulz, 2006; Wang et al., 2016). During a DBA, heat is released to the interior of the steel containment vessel. The flooding water from the top of the ellipsoidal dome forms thin water film on external surface of the containment vessel. The falling water film cools down the hot wall of the steel vessel which leads to steam condensation on the internal surface and pressure decrease inside the vessel. Due to its small heat resistance, water film is able to remove the heat and restrict the peak pressure inside containment. The thickness of falling film, among many other parameters, plays an important role on mass and heat transfer of falling film evaporation. Accurate modeling of film thickness is crucial for the predictions of conjugate heat and mass transfer between the space inside the steel containment, water film flow on the surface of steel containment, and the annular space between the steel and concrete containments.

Up to now, a number of studies in this field have been carried out by many researchers. Among them, the classical analytical study was conducted firstly by Nusselt (1916). After that, some theoretical studies are carried out to loose some restricts in Nusselt model, and to enlarge their application ranges (Rohsenow, 1970). Due to the complexity of the film flow, theoretical models are usually verified and validated using empirical data obtained from elaborate-designed experiments. On the other hand, a lot of experimental works have also been conducted to collect experimental data and then to construct directly empirical correlations for practical applications. For the sake of simplicity, only typical experimental studies relevant directly with the thickness of falling films are reviewed here, of which the details about the test sections, the working fluids and the ranges of the film Reynolds number are summarized in Table 1.

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https://doi.org/10.1016/j.pnucene.2017.12.007
Received 22 July 2017; Received in revised form 14 November 2017; Accepted 25 December 2017

Table 1
Detailed information of some experiments on falling liquid film flow.

Authors	Test section				Working fluid	Reynolds number
	Size (mm)	Inclined angle (°)	Material	Shape		
Karapantsios and Karabelas (1995)	1400 × 50	90	Plexiglas	Pipe	deaerated tap water	370–11020
Moran et al. (2002)	1920 × 80	45	Polished copper	Plate	20 cS silicone oil	11–220
Ambrosini et al. (2002)	2000 × 600	0–45	Stainless steel	Plate	Water	170–3300
Zhou et al. (2009)	622 × 150	49–90	Stainless steel	Plate	Distilled water	317–2064
Yu and Cheng (2014)	5000 × 2000	90	Stainless steel	Plate	Water	50–900
	5000 × 400	30–80				200–3600
Fuchs et al. (2015)	300 × 100	30–90	Stainless steel	Plate	Deionised water	1190–3110
Huang et al. (2014)	1200 × 500	0–90	Stainless steel	Plate	Water	103–1595

Karapantsios and Karabelas (1995) studied film thickness characteristics over a range of Reynolds number from 370 to 11020. The data of the mean and minimum film thickness, the standard deviation, as well as the dominant wave velocity were reported. They also provided the judgment of fully development by analyzing the tendencies of the film statistical characteristics with longitudinal distance. Small variation of these quantities suggested that the flow may not be fully developed over the distances examined though relatively long distances from liquid entry were used in their experiments.

Moran et al. (2002) conducted experiments on instantaneous hydrodynamic characteristics of laminar falling films on an inclined plate using a photochromic dye activation technique and high-speed video photography over a range of Reynolds number from 11 to 220. Experimental data indicated that the time-averaged mean and maximum velocity data are significantly over-predicted by Nusselt model, while the time-averaged film thickness data are slightly under-predicted.

Ambrosini et al. (2002) studied the statistical characteristics of water film falling freely down a vertical or inclined flat plate at different temperature (assumes no evaporation). The range of Reynolds numbers includes the classical threshold for the transition between the laminar-wavy and the turbulent regimes. Data on mean, minimum and maximum film thickness as well as standard deviation and wave velocity were reported.

Using confocal chromatic sensoring technique, Zhou et al. (2009) studied the instantaneous and statistical characteristics of wavy water film falling down a flat plate at different liquid feed mode, Reynolds number and plate inclination angle. The time-average film thickness data was compared with other experimental and theoretical results showing a good agreement. A new correlation for the average film thickness was also suggested.

Yu and Cheng (2014) carried out experiments on free falling water film flow on a vertical and an inclined large flat plate. Statistical characteristics, such as film thickness, wave velocity, and so on, are analyzed to obtain better understanding of the mechanisms of film flow. Empirical correlations of these statistical characteristics including the thickness of film flow on large flat plate were proposed and compared with Nusselt model and other empirical correlations in open literature.

Focusing on efficient cleaning in the food industry, Fuchs et al. (2015) studied the influence of the surface inclination on the film flow on stainless steel within a film Reynolds number range of 1190–3110. The results show that the inclination angle has a major impact on the film thickness, wall shear stress, and then the mean cleaning rate, while a low surface roughness does not necessarily lead to a better cleaning result.

Since the countercurrent flow happens in film cooling of PCCS under hypothetical severe accident, the study of film-air countercurrent flow attracts more and more attentions. For example, Huang et al. (2014) studied experimentally water film behavior, such as film thickness and surface wave, in countercurrent flow at different inclination conditions in a large scale rectangular channel. The results show that the film thickness variation in the large scale channel under countercurrent flow condition is different from those from small scale tests. An empirical correlation derived from experiment of free falling film thickness without air flow was also reported.

Up to now, almost all of the researches focus upon fully developed falling films on straight flat plates or straight pipes with relatively large diameter compared with the film thickness. In these cases, film flow occurs at a fixed inclined angle with a constant width of the flow channel. The constant width also indicates that the extend angle of the flow channel is equal to zero. These results are often used directly for analyzing water film cooling characteristics of the PCCS (Pasek et al., 2011; Du et al., 2017). Water film flow, however, is a developing phenomenon in nature on the curved surface of PCCS, because the inclined angle, the width and the extend angle of the flow channel change continuously in the longitudinal direction. It is then questionable to use these theoretical models and/or empirical correlations directly for analyzing the film flow on the curved surface of PCCS without careful verification and validation. Thus, in the present research, the main objective is to measure the film thickness of free falling water flow on a large-scale ellipsoidal surface, to examine the influence of continuously varying inclined angle, width and extend angle of flow channel on the film flow, and to develop a new correlation for predicting accurately the film thickness on curved surface of PCCS.

2. Experimental apparatus

2.1. Test loop

In order to verify the performance of CAP1400 PCCS, an experimental facility WADE (WAter Distribution Experimental facility) was built in the State Nuclear Power Technology Research & Development Center (Lu and Li, 2011) to study the characteristics of falling water film on the dome of passive containment, including water coverage and its delay time (Zhang et al., 2013; Chang et al., 2017), film thickness, and so on.

The schematic diagram of the test loop is shown in Fig. 1. The working fluid is the processed municipal water which is cleaned for reducing the hardness to meet the containment cooling water index. It is pumped from the main vessel by the gear pump to the distribution bucket through a flow meter and the temperature sensor. The water falls down to the dome surface due to gravity, and passes through the first weir and the second weir which perform the function of redistribution water to ensure transverse uniformity of the falling water film. Then water is collected by collection buckets, and finally comes back to the main vessel. The inlet temperature of water, ranging from 16 °C to 18 °C, is the same as that in ambient environment. All the tests were carried out at atmospheric pressure and in stationary conditions.

The water flow rate is measured by using a LWGY-40 turbine flow meter with a range of 2–20 m^3/h and an uncertainty below 0.5% FS (Full Scale). Furthermore, the flow rate is adjusted to the predetermined value through coarse-control by frequency converter and fine-tuning by control valve, and the control accuracy is about ± 0.1 m^3/h (Chang