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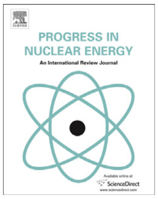

Experimental study of water film flow on large vertical and inclined flat plate

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ABSTRACT

Free falling water film flow is widely applied in many industrial fields, including the PCCS (Passive Containment Cooling System) of the Generation III nuclear power plant. This paper describes an experimental study of free falling water film flow on a vertical and an inclined flat plate (2 × 5 m and 0.4 × 5 m). A capacitance probe and high-speed camera were used to capture the characteristics of film flow with different Reynolds (50 ~ 3600). Many statistical variables of the film flow are presented, such as film thickness, wave length, wave frequency, and wave velocity etc. The test data are also compared with Nusselt theory and some empirical correlations from other researches. The effect of Reynolds number and inclination of the plate on film flow are studied.

Three transition points which indicate different flow mechanism changes are found by analyzing different statistical film flow variables. With the increase of Reynolds number, the solitary waves of film flow develop from low speed waves of high frequency and short wave length to high speed waves of low frequency and long wave length. Empirical correlations of $\bar{\delta}$, $\delta_{\min}$, $\delta_{\max}$, δ_{sub}, δ_p, U_{wave} of film flow on large flat plate are obtained. It could be applied to the safety analysis program for PCCS.

1. Introduction

Free film flow has been widely applied in industrial fields and investigated for decades due to the high thermal efficiency. Nusselt (1916) proposed a laminar model for film flow. The model assumes that the film flow is laminar with smooth surface and the shear stress on liquid–gas interface is neglected. A parabolic velocity distribution inside film flow can be obtained by solving Navier–Stokes equations for film flow.

$$U_z\left(y\right) = \frac{\rho g \delta^2}{2\mu}\left[\frac{2y}{\delta} - \left(\frac{y}{\delta}\right)^2\right] \tag{1}$$

Based on the principle of mass conservation, velocity distribution and definition of Reynolds number of film flow (Equation (2)), the relationship between film thickness and Reynolds number can be obtained in Equation (3).

$$\text{Re} = \frac{4\Gamma}{\mu} \tag{2}$$

$$\delta = \left(\frac{3}{4}\right)^{1/3} \text{Re}^{1/3} \left(\frac{\nu^2}{g}\right)^{1/3} \tag{3}$$

where Γ is the linear mass velocity (kg/m s), Re is Reynolds number and υ is dynamic viscosity of film flow (m^2/s). The disadvantage of Nusselt theory is its smooth surface assumption. The instability is one of the most significant characteristic of film flow, which leads to the production of surface wave. When film is falling down, it is influenced by small disturbances which will gradually develop to big solitary waves. The fluid in substrate is laminar while the fluid in solitary wave can be turbulent. Most theoretical studies are based on smooth surface assumption, the fidelity of which is poor.

In the PCCS (Passive Containment Cooling System) of the Generation III nuclear power plant AP1000, the water from a storage tank is driven by gravity and forms a film over the containment during accidents. Film flow on the containment plays the role of final heat sink. Due to large diameter of the containment, film flow on a slice of the containment can be considered as film flow on a large flat plate. Table 1 presents some parameters of film flow

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Nomenclature

Re	Reynolds number
Γ	linear mass velocity (kg/m s)
ρ	is fluid density (kg/m3)
g	gravitational acceleration (m/s2)
ν	dynamic viscosity (m2/s)
n	number of data
μ	molecular viscosity (Pa·s)
δ	film thickness (m)
s	standard deviation of film thickness (m)
δ_p	Height of solitary wave (m)
δ'	growth rate of film thickness (m/s)
δ''	acceleration of film thickness growth (m/s2)
w	shear stress velocity (m/s)
τ_c	characteristic shear stress (Pa)
τ_w	wall shear stress (Pa)
τ_i	interfacial wall shear stress (Pa)
PDF	Probability Density Function
U	velocity (m/s)
f	wave frequency (Hz)
λ	wave length (m)
t	time (s)
ϕ	angle between plate and horizontal direction
σ	surface tension (N/m)
γ	Kapitza number

Subscripts

min	minimum value
max	maximum value
sub	substrate value
wave	solitary wave
film	film flow

Superscripts

$-$	average
$+$	dimensionless

experiments on flat plates. Telles and Dukler (1970) tried to portray the wave characteristic of film flow with a statistical approach. Nosoko et al. (1996) and Yoshimura et al. (1996) observed temporal and spatial flow patterns of a falling film on a flat plate under artificial disturbances. The relationship between the film velocity, wave amplitude, wave length, fluid property and Reynolds number of film flow were obtained. These researches also proposed a double boundary layer model to explain the enhancement of mass transfer due to surface waves in laminar film flow. Takamasa and Hazuku (2000) applied LFD (Laser Focus Displacement meter) to study the effect of Reynolds number and the plate length on film flow behavior. They believed that film flow remains laminar when the Reynolds number is less than 500. Philipp and Ulrich (2000) observed the wave morphology of film flow. They found remarkable changes of flow behavior and wave structure when the Reynolds number of film flow is close to some transition point. Moran et al. (2002) measured the thickness, velocity distribution and wall shear stress of film flow on an inclined plate. Their results showed that the Nusselt theory underestimates the film thickness and overstates the film velocity. The study also suggested that film fluid is not in a steady state of uniform motion but in a semi steady state of continuous acceleration and deceleration. Ambrosini et al. (2002) studied the statistical characteristics of film flow with different temperature, plate inclination, and Reynolds number. Tihon et al. (2006) found that wave length and height of a solitary wave are proportional to Reynolds number and inversely proportional to enforced disturbance frequency. A linear relationship between wave velocity and maximum film thickness was found. Non-Newtonian liquid spreading on an inclined plate was studied experimentally and numerically by Sutalo et al. (2006). The film shape, width and time dependent velocity profiles were reported. Xu (2010) observed the characteristics of surface waves and film breakup on flat plates.

Brissinger et al. (2014) use optical method to study films with average thicknesses between 100 and 380 μm on a vertical 2 m high and 1 m wide wall. The observations showed that the water flow velocity decreases until the film is broken into streams, no longer covering the plate as a continuous film. For both thickest thicknesses, a near-Gaussian shaped distribution is obtained. Gondaa et al. (2014) presented experimental results of both hydrodynamic and thermal tests on the study of falling water film evaporation on a single vertical corrugated stainless steel plate. Study of the falling film hydrodynamics has shown that the decreasing film flow-rate mode could ensure a good wetting of the plate surface area, even at low flow-rates. However, this is not the case for increasing film flow-rate. Wang et al. (2013) conducted film flow experiments in a 1.2 m × 1.2 m × 1.7 m high chamber with Perspex walls. Flow patterns created by liquid jets impinging at angles off horizontal were studied. The falling film exhibited three forms of behavior: a wide film, termed gravity flow; a narrowing film, termed rivulet flow, and a wide film which split into two with the formation of a dry patch. The transition to form a dry patch was found to obey the minimum wetting rate criterion.

Table 1
Film flow experiment on flat plate.

Researcher	Experimental area width × length (cm)	Plate material	Inclination angle	Range of Reynolds number	Measured parameters
Takamasa and Hazuku (2000)	22 × 46	Plastic	90^{O}	128–2824	Film thickness, film velocity, volume flow rate
Nosoko et al. (1996)	20.5 × 24.5	Glass	90^{O}	40–400	Film temperature, volume flow rate, wave morphology, wave frequency, wave length
Yoshimura et al. (1996)	20.5 × 49				
Philipp and Ulrich (2000)	3 × 20	Glass	90^{O}	108–800	Film thickness, film velocity, volume flow rate
Sutalo et al. (2006)	5 × 38.1	Plastic	45^{O}	12–52	Film thickness, film morphology, volume flow rate
Moran et al. (2002)	8 × 192	Copper	45^{O}	11–220	Film thickness, film velocity, volume flow rate
Xu (2010)	5 × 8	Stainless steel	60^{O}	50–300	Film thickness, film velocity, volume flow rate
Tihon et al. (2006)	22 × 200	Stainless steel	5^{O}	40–400	Film thickness, wall shear stress, volume flow rate
Ambrosini et al. (2002)	60 × 200	Stainless steel	45^{O} 90^{O}	140–3200	Film temperature, volume flow rate, air velocity, wall temperature, wave velocity