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Experimental investigation on the hydrodynamics of falling liquid film flow by nonlinear description procedure

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Abstract

Extending a previous analytical investigation, the effect of wall heating on the hydrodynamics of falling liquid films was studied by calculating the fractal dimensions of reconstructed phase spaces from experimental measurements. The results illustrated that the wall heat flux has a significant influence on the hydrodynamics of falling liquid films, especially in the case of low flow rates. The causes for this effect may be attributable to density variations within the films and thermocapillarity effects acting on the free surface interface of the films, particularly for situations where wall heating is present. The combined effect of these two factors may be more apparent for thin films with a low flow rate than for thicker films with higher flow rates. The results indicated that the hydrodynamics and heat transfer of falling liquid films present a conjugate problem, especially in the case of low flow rates, and that this conjugation should be considered in any the study of heat transfer of falling liquid films. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Falling liquid film; Hydrodynamics; Fractal dimension

1. Introduction

The flow of falling liquid films is a complicated phenomenon and involves a number of parameters and characteristics not previously attributed to this physical process. Decades of previous studies have, however, confirmed that the flow of falling liquid films is intrinsically unstable [1,2]. Typically, one finds small or fine waves on the free surface interface of films at, or near the exit of orifices or flow distributors. Experimental results have confirmed that these small waves coalesce into larger, sometimes solitary waves as the film continues to flow downwards and move farther and farther from the exit [3–6]. Previous theoretical and experimental studies have indicated that falling liquid film flow is transient and nonlinearly unstable, and has a "chaotic" nature [7–11]. Statistical methods have previously been widely used to reveal the flow characteristics of these falling liquid films [12,13]. More recently, a number of researchers [14,15] have employed nonlinear methods to describe the wave characteristics of falling liquid films. In these studies, the phase space was reconstructed from the experimental time series of the film thickness within the framework of deterministic chaos. As a result, several indexes of deterministic chaos analyses were extracted

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Nomenclature

d	fractal dimension		
k	embedding dimension	*Greek symbols*	
m	dimension of compact manifold	Γ	liquid mass flow rate per width
q	heat flux	δ	distance to the nearest neighbor
Re	Reynolds numbers, $Re = 4\Gamma/\mu$	$\langle\delta\rangle$	average δ
x_i	time series	μ	dynamic viscosity
y_i	point of reconstructed phase space	τ	delay time

from these reconstructed spaces to describe the hydrodynamics of falling liquid film flow. Both of the previous investigations primarily concerned with the hydrodynamics of the film flow and as a result, were conducted under the conditions of no wall heating.

Several other previous investigations have demonstrated that the presence of wall heating may have an important effect on the wave nature of the falling liquid film [16,17]. In many cases, the experimental investigations were conducted in such a manner that this effect was visible to the naked eye. As stated in the literature [18–20], asymptotic motion in dissipative systems takes place on sets which usually have zero volume in state space. If such a set is chaotic, it usually has a non-integer dimension (fractal dimension), which is smaller than the dimension of the state space. The chaotic nature of the falling liquid provides some indication that if determined, the fractal dimension could be used to demonstrate the effect of wall heating on the film behavior.

In the current investigation, phase spaces were reconstructed from experimental time series, and the fractal dimensions were calculated. These calculated fractal dimensions indicated that, the hydrodynamic characteristics of falling liquid films with and without wall heating are different.

2. Experimental apparatus

The experimental apparatus shown in Fig. 1 was designed and constructed. This test apparatus is similar to one previously described by the authors [21], and some of the results utilized in the previous work were also utilized herein.

The entrance section of the test apparatus consisted of a 90 mm long plexiglass cylinder, 18 mm outer diameter. The test section was fabricated from a 300 mm long, 0.5 mm thick and 18 mm outer diameter stainless steel cylinder. The surface finish and measurement uncertainty in the outer diameter were 1.6 μm and 0.05 mm, respectively. The falling liquid film was formed from a 0.5 mm width circle orifice. A 100 mm inner diameter, 150 mm deep water container at the end of the test section and the upper water tank was used to keep the water level stable.

A optical–electronic method was used to measure the thickness of falling liquid film [18]. A sketch of the measuring system is shown in Fig. 2. The basic principle is as follows. A semiconductor laser beam from laser 1 is expanded by lens 2. The beam is then focused by a cylindrical lens 3 to form a light sheet at the measurement spot, with a sheet thickness of less than 0.5 mm. In experiments, the focus point of the cylindrical lens is positioned on the dashed line 8 in Fig. 2. The light sheet is stretched in the horizontal direction to the length scale of the cylindrical lens which is much wider than the liquid film thickness, but the beam is quite thin in the film flow direction. Hence, the entire liquid film is within the sheet to ensure a better spatial resolution. When a band of light reaches the surface of a transparent object, part of the light will be reflected and part will be refracted. The reflected and refracted light will stray from the original direction if the incident light is not perpendicular to the surface. Hence, as shown in Fig. 2, a photodiode or screen can be placed directly behind the test model to indicate the light that does not pass through the object. Then, in the ideal situation, the light encountering liquid film is completely deflected from the direction of the incident

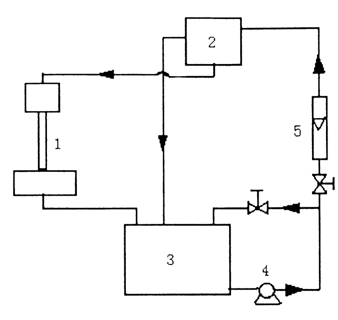

Fig. 1. Sketch of the experimental system. 1 — Entrance and test section, 2 — upper tank, 3 — lower tanker, 4 — pump, 5 — flowmeter.