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Hydrodynamics of vertical falling films in a large-scale pilot unit – a combined experimental and numerical study

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ABSTRACT

The hydrodynamics of vertical falling films in a large-scale pilot unit are investigated experimentally and numerically. We study a broad range of operating conditions with Kapitza and Reynolds numbers ranging from $Ka = 191–3394$ and Re 24–251, respectively. We compare film thickness measurements, conducted by a laser triangulation scanner, with those obtained by directly solving the full Navier–Stokes equations in two dimensions and using the volume of fluid (VOF) numerical framework. We examine the evolution of the liquid film at multiple locations over a vertical distance of 4.5 m. In both our experiments and simulations we identify a natural wave frequency of the system of approximately 10 Hz. We investigate the formulation of the inlet boundary condition and its effects on wave formation. We show how potentially erroneous conclusions can be made if the simulated domain is shorter than 1000 film thicknesses, by mistaking the forced inlet frequency for the natural wave frequency. We recommend an inlet disturbance consisting of a multitude of frequencies to achieve the natural wave frequency over relatively short streamwise distances.

1. Introduction

Falling liquid film is a technique where a thin liquid film is flowing down an inclined or vertical wall in the presence of a gas layer. Instabilities in the liquid film grow as they travel downwards and evolve into various flow regimes depending on the operating conditions. Advantages, such as a large contact area and high heat transfer at low flow rates give this technique excellent heat and mass transport characteristics (Kalliadasis et al., 2012). As a consequence, falling films are utilized in a wide range of engineering and technological applications, such as chemical reactor columns or heat exchangers. Regardless of the field of application, it can be assumed that hydrodynamics governs other physical phenomena (e.g. heat and mass transfer), as well as the overall performance of a reactor (Dukler, 1976). For that reason, there is great interest to study hydrodynamics of falling films.

The hydrodynamics of falling films have been extensively studied in the literature (Alekseenko et al., 1994; Kalliadasis et al., 2012) and a number of papers exist using analytical, experimental or numerical methods. Kapitza and Kapitza (1965) were one of the pioneers in this field and used shadow photography of the liquid in order to study the wave development. Since then, several authors have carried out similar studies e.g. Alekseenko et al. (1985); Ishigai et al. (1972); Oyakawa (1994); Patnaik and Perez-Blanco (1996); Plerson and Whitaker (1977); Wasden and Dukler (1989). Density, viscosity, gravity, surface tension and the flow rate were identified as the important factors for the hydrodynamics. These factors are typically expressed as functions of non-dimensional numbers, such as Reynolds (Re) and Kapitza (Ka) numbers, in order to distinguish between influences from flowrates and material properties and to classify different flow regimes. The average film thickness has been extensively measured and mapped for different running conditions (Brötz, 1954); (Lukach et al., 1972). In addition, as measurement techniques have become increasingly sophisticated, it has become possible to study the flow structure beneath the liquid interface and measure the velocity components with techniques such as Laser Doppler Velocimetry (LDV) (Dietze et al., 2009), Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) (Zadrazil et al., 2014).

When it comes to modelling of dynamics of falling films, analytical modelling has been a subject of research for a long time e.g. Brauner (1989). Such studies have often predicted a

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certain phenomenon that has later been proven experimentally (Kalliadasis et al., 2012). In recent years, it has been possible to directly numerically solve the Navier–Stokes equations for falling films (Gao et al., 2003). Numerical simulations in a two-dimensional (2D) framework have made it possible to study in great detail the hydrodynamics inside a liquid film which otherwise would be either very difficult or impossible to measure experimentally (Malamataris and Balakotaiah, 2008). Recently, there have appeared also three-dimensional (3D) simulations of falling films (Dietze et al., 2014; Doro, 2012) resolving the spanwise fluid movement.

In spite of the fact that extensive work has been carried out in studying the hydrodynamics of falling films, more research is needed before the gained knowledge can be used for the design of new industrial units. For instance, although it is known that the liquid flow is non-symmetrical in the spanwise direction in large-scale units (Al-Sibai, 2005), only a limited number of experimental and even less numerical studies address this issue. Recently, Kharlamov et al. (2015) made a thorough investigation of the spanwise liquid redistribution, but were unable to obtain direct experimental evidence for the underlying mechanism causing the 2D to 3D shift. In addition, it is yet to be seen up to what extent this transition affects large-scale falling film units. Typical industrial units are large and the surface consists of long plates or tubes, and they are at the moment excessively expensive to numerically simulate (unless the physics of the problem are extensively simplified). More research is thus required concerning what can be achieved with the presently available computational resources, and, additional information is needed on the flow regimes and especially the flow development in such systems.

Several authors, (Al-Sibai, 2005; Ishigai et al., 1972; Morioka et al., 1993), have studied different flow patterns that emerge for vertical falling films. At the top of a unit, i.e. when the liquid starts to flow downwards, the film is considered smooth (Al-Sibai, 2005). As the film travels downwards, the present instabilities, if sufficiently large, will grow into waves. Afterwards, there is a possible transition from two- to three-dimensional waves (Al-Sibai, 2005). Many studies argue that, after sufficient length, denoted an entrance region, the flow is considered *fully developed* (alternatively, the term “statistically steady” can be used here). The manifestation of the *fully developed* regime and the length where the latter regime takes place depend heavily on the operating conditions (Ishigai et al., 1972). Al-Sibai (2005) developed models for *fully developed* regimes under non-evaporative conditions. In that study, the models depend on the Reynolds (*Re*) and Kapitza (*Ka*) numbers and the flow was mapped into five different regimes: Laminar (L), Sinusoidal (S), Wavy-Laminar (WL), Transition (TR) and Turbulent (T).

The laminar regime exists for small *Re* numbers and it is characterised by a calm liquid film without the presence of waves. In this region, the Nusselt analytical solution (Nusselt, 1916) is considered valid. The sinusoidal regime, also known as the first transition, is characterized by the presence of capillary waves, which may be understood as small ripples at the liquid surface appearing with high frequency and small wavelengths. These waves have almost no influence on the near-wall hydrodynamics (Karimi and Kawaji, 1999).

At higher flowrates the wavy-laminar regions come into place, also referred to as the stable wavy laminar or inertial wavy-laminar regime. Here, the film is partly laminar in the substrate and partly turbulent in the waves (Miller and Keyhani, 2001). Turbulence is generated from the wave motions (Ishigai et al., 1972). In this zone the waves grow larger and so does the wavelength. The waves are sometimes referred to as roll waves or inertial waves driven by gravity.

In the transition regime, also known as the turbulent-laminar or inertial wavy-turbulent, the turbulence gradually changes from being wave-governed to a shear-governed one (Ishigai et al., 1972). Individual waves can still be seen in this regime, but it is likely that they start to interfere with each other (Miller and Keyhani, 2001). In the turbulent regime the flow becomes fully turbulent. The flow is entirely shear-driven and individual waves cannot be detected (Ishigai et al., 1972).

Turbulence production in the liquid film is important for the heat and mass transfer as it enhances mixing of the bulk and, therefore, it is of great importance to study the wavy laminar and the transition regimes. Since the turbulence in the liquid phase is connected to the wave shape, it is interesting to study the topology of the waves. Dietze (2016) made a detailed numerical study on the shape of the waves for a large range of Kapitza numbers at small Reynolds numbers. The results of that work showed that a wave in this WL region consists of a large liquid hump, with small capillary waves in the front. The same study also specified that the topology is very dependent on the *Ka* and *Re* numbers and the wave frequency.

In the present paper we look in detail at the spatiotemporal evolution of the liquid film as it advances downwards a large-scale pilot unit. In particular, our interest is to look beyond the entrance effects. We combine measurements of film thickness conducted by a laser triangulation scanner with two-dimensional simulations directly solving the full Navier–Stokes equations using the volume of fluid (VOF) numerical framework. We work here with a number of subcooled liquids under operating conditions belonging to different flow regimes and over vertical lengths relevant for industrial applications. The scanner is mounted at multiple vertical positions and yields information about the spatiotemporal evolution of the film at each location. For our operating conditions we identify a natural wave frequency of approximately 10 Hz far downstream in our system. In addition, focus is put on the effect of different inlet boundary conditions and the minimum simulation length required to facilitate a transition from the forced inlet frequency to the natural wave frequency.

2. Methodology and investigated operating conditions

Before we go into the methodology used in our study we will first motivate the choice of conditions under which our unit is operated. Our goal here is to work with cases that are *i)* industrially relevant and *ii)* spread as much as possible over the interesting flow regimes discussed above. For that purpose, we have chosen to work with three different types of Newtonian fluids at different wetting rates, resulting in four different cases. The chosen conditions place our cases in either the WL or the TR regime. The investigated cases, together with the flow regimes developed by Al-Sibai (2005), can be seen in Fig. 1. The *Re* and *Ka* numbers are used to characterize the cases and we use the following definitions here:

$$Re = \frac{\Gamma}{\mu}, \tag{1}$$

$$Ka = \frac{\sigma}{\rho \cdot \nu^{4/3} \cdot g^{1/3}}, \tag{2}$$

where μ is the dynamic viscosity, σ is the surface tension, ρ is the density, ν is the kinematic viscosity and g is the gravitational acceleration. The specific wetting rate Γ is given by

$$\Gamma = \frac{\dot{m}}{\pi \cdot d_{tube}}, \tag{3}$$

with $\dot{m}$being the mass flow rate and d_{tube} the tube diameter.

The working fluids were produced by mixing water with different fractions of dairy powder. Adding dairy powder increases the