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Characteristics of solitary waves on a falling liquid film sheared by a turbulent counter-current gas flow

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ABSTRACT

We report an experimental investigation of a falling water film sheared by a turbulent counter-current air flow in an inclined rectangular channel. Film thickness and wave velocity measurements associated with visual observation are conducted to study the influence of the air flow on controlled traveling waves consisting of a large wave hump preceded by capillary ripples. First, we focus on the variation of the shape, amplitude and velocity of the waves as the gas velocity is gradually increased. We demonstrate that the amplitude of the main hump grows substantially even for moderate gas velocities, whereas modification of the wave celerity becomes significant above a specific gas velocity around 4 m/s, associated with an alteration of the capillary region. The influence of the gas flow on 3D secondary instabilities of the solitary waves detected in a previous study Kofman et al. (2014), namely rugged or scallop waves, is also investigated. We show that the capillary mode is damped while the inertial mode is enhanced by the interfacial shear. Next, the gas velocity is increased until the onset of upstream-moving patterns referred to as flooding in our experiments. At moderate inclination angles (typically $< 7^\circ$), flooding occurs for a gas velocity around 8 m/s and is initiated at the scallop wave crests by a backward wave-breaking phenomenon preceded by the onset of ripples on the flat residual film separating two waves. At high inclination angle, a rapid development of solitons is observed as the air velocity is increased preventing the waves to turn back. Finally, at high liquid Reynolds number, sudden and intermittent events are triggered consisting of very large amplitude waves that go back upwards very fast. These "slugs" either extend over the whole width of the channel or are very localized and can thus potentially evolve towards atomization.

1. Introduction

Falling liquid films flowing in the presence of a counter-current gas flow are commonly encountered in a number of industrial applications (cooling of microelectronic equipment, distillation columns in chemical industry, desalination plants). It is well known that the interfacial waviness of falling films enhances heat and mass transfer between the film and the surrounding gas (Miyara, 1999, 2000; Nosoko et al., 1996). On the other hand, surface waves at the liquid-gas interface of a film flowing through a confined channel can lead to the onset of undesired flooding phenomena when the entire cross section is obstructed by the liquid. As the optimal operating industrial conditions are generally close to the limit of flooding, it is essential to identify the relevant physical mechanisms responsible for this phenomenon with the aim to predict and control its occurrence.

Various aspects of flooding phenomena have been studied over the last decades and a significant number of experimental data have been produced as a result of numerous experiments. The scatter of the results obtained for the critical conditions of flooding is impressive (Govan et al., 1991; Jeong and No, 1994). Among the correlations most frequently used are the ones of the Wallis type (Wallis, 1961) that give good results in confined cases but do not include surface tension. The correlations that use the Kutateladze number (Tobilevitch et al., 1968) resolve this problem but are independent of the confinement. This variety of correlations is partly due to the inconsistency in the definition of the onset of flooding resulting from the complexity and the interplay of the underlying

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physical mechanisms. For instance, the formation and entrainment of liquid droplets, or the upstream propagation of surface waves, both phenomena emerging from the interfacial shear stress imposed by the gas flow, can be designated as “flooding”. Moreover, the great sensitivity of the flow to the liquid/gas entrance/exit geometries (Jeong and No, 1994; Vlachos et al., 2001; Zapke and Kröger, 1996) makes highly unlikely any agreement between experimental results. For instance, liquid bridges may develop at the liquid entrance in confined geometries (Mouza et al., 2002; Vlachos et al., 2001), or a large standing wave may be trapped at the liquid exit which ultimately blocks the passage of the gas flow (Mouza et al., 2005).

Despite the wide variety of flooding conditions, it is clear that this event is determined by the dynamics of surface waves at the liquid-gas interface, as the gas flow amplifies the liquid film instability. In the recent years, an ongoing effort has thus been devoted to the characterization of the dynamics of a wavy film sheared by a co- or counter-current turbulent gas flows. Theoretical works have focused on 2D waves, i.e. spanwise invariant waves, and weak interactions with a non-confined gas flow for which the Benjamin-Miles assumption of small deformations of the interface at the scale of the shear gaseous flow holds (Demakhin, 1981; Trifonov, 2010; Tseluiko and Kalliadasis, 2011). The onset of flooding in the core of the apparatus, i.e. when the geometrical edge effects are not dominant, was then identified with the occurrence of large-amplitude standing waves (Trifonov, 2010; Vellingri et al., 2013), which is favoured by the onset of an absolute instability of the base flow (Vellingri et al., 2015). Dietze and Ruyer-Quil (2013) have thus proposed to promote ordered wave patterns at the interface as a way to delay the onset of flooding while maximizing heat/mass transfer. Indeed, natural surface waves in falling liquid films generally interact and coalesce forming larger amplitude waves (Dietze and Ruyer-Quil, 2013). The challenge is then to control the film dynamics in the presence of a gas flow. However, if comparisons of theoretical works with experimental data show similar trends (Vellingri et al., 2015), it is clear that confinement effects as well at the 3D nature of the waves shall play a role in the actual onset of flooding, which calls for more investigations.

On the experimental side, a significant progress in the understanding of a free falling film dynamics has been achieved by applying a spatial or temporal forcing at the liquid inlet (Kofman et al., 2014; Liu and Gollub, 1994; Park and Nosoko, 2003). The sequence of transitions, primary and secondary instabilities, leading from the Nusselt flat film solution to a disordered sate characterized by 3D horseshoe waves in interaction is now quite well known and has helped to improve the different modeling attempts. Concerning flooding experiments, numerous studies have been conducted in pipes during the past decade attempting to go beyond the previous works based on time-averaged description of the flow. The effects of the physical properties of the liquid (Deendarlianto et al., 2010; Mouza et al., 2005), the tube length (Carvalho and Costa, 2006), its diameter (Mouza et al., 2002; Pantzali et al., 2008; Vijayan et al., 2001), and inclination (Mouza et al., 2003; Ousaka et al., 2006), on the shape of the waves and the onset of flooding have been characterized mainly by visual observation. By contrast, very few flooding experiments have been performed in planar geometries. In this configuration, measurements of the film thickness can be more easily performed (Drosos et al., 2006; Njifenju, 2010; Roy and Jain, 1989), providing local information on the film dynamics, but none of these experiments attempted to control the film dynamics before being impacted by the counter-current flow.

In the current study, experiments are conducted on water films falling down the bottom plate of an inclined rectangular channel in the presence of a turbulent counter-current air flow. A particular attention has been paid to the boundary conditions, specifically designed to avoid flooding at the liquid inlet or outlet, thus allowing to focus on the wave dynamics in the core of the channel. Temporal forcing is applied at the liquid inlet to excite surface waves before they come into contact with the air flow. First, the influence of the air flow on the shape and amplitude of the 2D waves as well as on 3D secondary instabilities identified in a previous study in the case of an unsheared film (Kofman et al., 2014) is investigated. The gas velocity is then increased until the onset of upstream-moving patterns classified into two different wave families, subsequently referred to as “ripples” and “slugs”. The emergence of these two types of waves in our experiment is identified with the onset of flooding.

Table 1
Experimental parameters and their domain of variation.

Physical parameter	Notation	Domain of variation
Angle of inclination	β	$0-20^\circ$
Liquid flow rate	Q_L	$0-3.5$ l/min
Liquid Reynolds number	R_L	$0-150$
Frequency	f	$2-15$ Hz
Mean gas velocity	U_G	$0-12$ m/s
Gas Reynolds number	R_G	$0-14600$

The experimental set-up and the measuring techniques are discussed in Section 2. The results are presented in Section 3 and summarized in Section 4.

2. Experimental set-up

We present here the experimental set-up and the measurement techniques that are used in this study (see Fig. 1). The experimental parameters and their domain of variation are presented in Table 1. For clarity, we separate the discussion depending if it is related to the liquid phase or gas phase.

2.1. Set-up and measurement methods: liquid phase

The liquid-related part of the experimental set-up is identical to the one used in our previous study (Kofman et al., 2014). We recall it here briefly as a matter of consistency. It consists of an inclined glass plate (150 cm × 37 cm) placed on a massive framework mounted on rubber feet to reduce the influence of environmental vibrations. The inclination angle β can be changed in the range $0-20^\circ$. A gear pump brings the liquid from a collection tank located at the lower end of the plane to an upstream tank, from which it emerges and flows down the plane. This upstream tank is filled with several glass sphere layers in order to homogenize the entering flow. Water is used as a working fluid. The volumetric flow rate Q_L is measured by a magnetic-inductive flow meter and the temperature is controlled during the experiments. A temporal forcing of the film is introduced at the inlet to trigger two-dimensional reproducible traveling waves. An aluminum plate is fixed to the membranes of two loudspeakers and generates controlled vibrations above the liquid surface over the whole width of the upstream tank. The forcing frequency f is varied typically from 2 to 15 Hz. The wave patterns are visualized by illuminating the liquid film with an oblique white light and by observing from above with a 2D camera to provide shadow images. A one-point temporal measurement of the liquid film thickness based on CCI (Confocal Chromatic Imaging) technique is performed through the glass plate. The Schlieren method, developed by Moisy et al. (2009) and adapted to our configuration, is also used to obtain non-local measurements of the film thickness (see Kofman et al., 2014 for details). By visualizing the film in the central axis of the test section, a linear CCD camera enables to draw spatiotemporal diagrams. This representation allows us to determine conveniently