Experimental Thermal and Fluid Science 94 (2018) 134–147

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental investigation of shear-driven water film flows on horizontal metal plate

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ARTICLE INFO

Keywords:
Aerodynamics
Shear-driven flow
Interfacial shear factor
Film thickness
Wave statistics

ABSTRACT

In this article, an experimental investigation has been conducted to characterize the instantaneous thickness of the surface water film driven by high-speed airflow pertinent to aerodynamic icing and anti-icing modeling. Non-intrusive results of the film flowing on a metal plate were obtained using the high-speed camera and confocal chromatic technique. The wind speed (U_a) ranges from 17.8 m/s to 52.2 m/s, and the film Reynolds number (Re_f) ranges from 26 to 128. The effect of the high-speed airflow on the structure of the wave film was observed and analyzed qualitatively. A new correlation of the interfacial shear factor was proposed for the prediction of the average film thickness. The predictions were compared with the previous annular flow models by applying the dimensionless analysis method and a good agreement is achieved. The superficial roughness, characterized by root-mean-square of the thickness, was well-correlated using a piecewise linear function of the average film thickness. Furthermore, a comprehensive description of the superficial waves including spectrum analysis and division of film thickness data between underlying film and large waves was presented. Transformations of the wave frequency and amplitude with the wind speed and the film Reynolds number were also addressed.

1. Introduction

Structural and aircraft icing usually occurs when supercooled droplets from clouds impact on the cold surface, causing performance degradation and even serious threat to safety [1,2]. Droplets may freeze directly after impingement at lower temperature, building up fluffy rime ice. However, droplets may not completely freeze when the latent heat cannot be rapidly released into the ambient under glaze icing condition, or when the anti-icing system is working. The unfrozen part will redistribute the surface water, resulting in the accumulation of the ice outside the impingement area or protection area, severely changing the aerodynamic shape [3,4]. At the same time, the disturbance on the interface between the air and water would introduce additional surface roughness [5], resulting in disturbed boundary layer flow and instability factor during ice accretion process. For the above reasons, the presence of the liquid water on the aerodynamic surface does not only raise the danger caused by the ice accretion, but also make the icing/anti-icing modeling more complex.

Messinger [6] model was the first successful trial to consider the flow of the liquid water in predicting the ice accretion, and it was widely applied in numerical simulations. The developed model assumed that the unfrozen part completely went downstream due to the mass conservation, regardless of the shape state of the surface water. Through high speed videos taken in wind tunnel experiments [7,8], it was observed that the water mass could be in a bead, film or rivulet state as a consequence of the presence of the water remaining stationary on the surface. The impinging droplets form beads on the surface, and then their water content is removed by wind or gravity. If much more water is present on the surface, the beads would coalesce into water film. The rivulets appear by the runback of the deformed beads, or the breakoff of the film beyond the collection area of the impinging droplets. Based on the experimental observations, several improvements have been proposed and examined from both a computational and analytical viewpoint [9,10,11]. But still some assumptions and approximations such as undisturbed boundary layer and uniform shear stress were made in their models, which introduced various limitations on the applicability of the predictions. To reveal the microphysical mechanism and inherent laws behind the water transport behavior, some experimental investigations were carried out aiming at different water states respectively. For the bead, force analysis, shedding correlation and coalescence were obtained corresponding to the surface wettability, wind speed and bead volume [12,13]. For the

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https://doi.org/10.1016/j.expthermflusci.2018.02.004
Received 28 November 2016; Received in revised form 17 November 2017; Accepted 3 February 2018

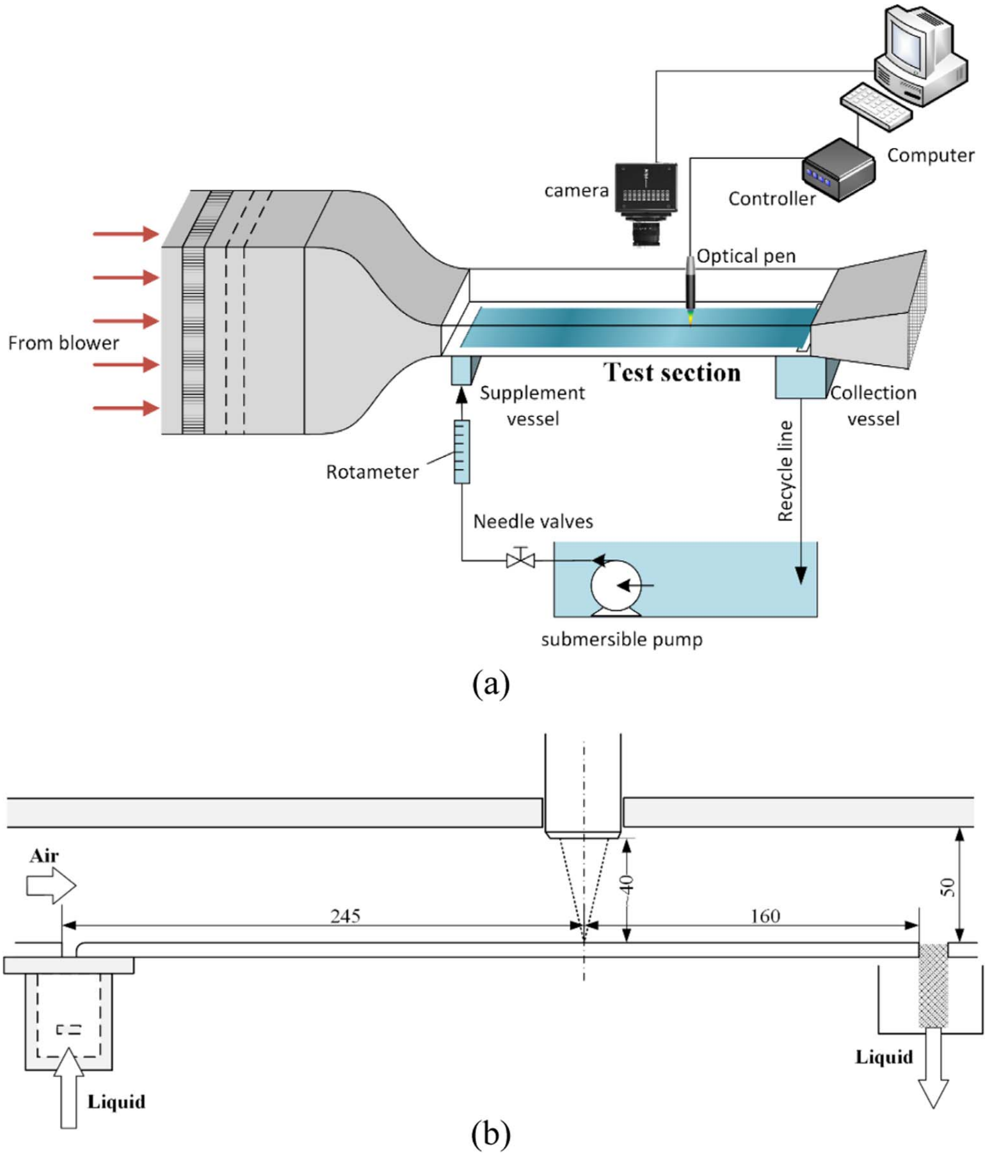

Fig. 1. Schematic diagram of experimental setup. (a) Flow loop; (b) test section.

rivulet, the formation and breakoff criteria were studied, as well as the thickness, width and interval under different flow rate and wind speed were investigated [14,15]. With respect to the film, which is frequently accounted for the main part on the airfoil surface, Feo and Tsao [16] obtained the film thickness at stagnation point using conductance sensor for the sake of scaling calculation. Muzik et al. [17] and Alzaili and Hammond [18] recorded the superficial images of the continuous film. Zhang et al. [19,20] developed a technique based on the digital image projection (DIP) to observe the film thickness on an airfoil. It was concluded from their experimental results that the thickness of the film was at micro scale and accompanied with high-frequency fluctuations, but the correlation between the film flowing and effect factors was still absent.

There are several characteristics of the water film, such as micro-scale thickness, complex interfacial waves, high-reflective surface, fast variation in time and space and easiness to be disturbed, which make the measurement of the thickness complicated. Although it was full of challenges, extensive investigations have been done regarding the liquid film issues using various techniques. Examples include the capacitance probe [21], laser focus displacement meter [22,23], planar laser-induced fluorescence imaging [24,25], conductance method [26], and optical measurement method [27,28]. Majority of the previous experiments considered the gravity driven films or the two-phase flow in a vertical or horizontal tube, while few attentions were paid on the shear-driven film on the outer surface of the components. For shear-driven film flow in a large-scale space, which means the influence of the side and top walls could be neglected, there are few experimental results reported in the open literatures [25,29]. Besides, a low dependency on the geometry of the flow duct is ideal for the validation of a computational fluid dynamic (CFD) code.

A flow model of the water film under aircraft icing condition has been derived by Myers [30,31], in which multiple effect factors are obtained, including ambient pressure, surface tension, gravity and shear stress. Myers' model was then applied in glaze icing, runback ice ridge and anti-icing simulations [32,33,34,35]. Among the several effect factors, interfacial shear stress was found to be a key factor to calculate the local film thickness, but it is difficult to be evaluated due to lack of the measured data. The most common substitute in CFD computations was the wall friction stress in boundary layer of the airflow, which was evaluated from the control volumes of the first layer near the body. Considering that the superficial fluctuations between the gas and liquid phases would strengthen the interfacial shear. Karev et al. [36] and Du et al. [33] applied the correlations from experiments of the stratified flow. In regarding to the surface roughness, the interval