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Dominant flow mechanisms in falling-film and droplet-mode evaporation over horizontal rectangular tube banks

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ABSTRACT

Visualization of evaporating water films falling over flat horizontal tubes, representative of the external surfaces of rectangular microchannel tubes, is presented using high-speed video. Experiments were conducted with a bank of three tubes at a saturation temperature of 17 °C. In addition to a qualitative description of the flow mechanisms, this work quantifies key droplet and wave characteristics using a semi-autonomous image analysis technique that develops a mathematical description of the droplets and waves. This allows the surface area, volume, velocity, and impact frequency of the droplets, as well as the width, surface area, and velocity of the waves to be measured. It was observed that droplet diameters, surface areas, and volumes are smaller than those measured in flow over round tubes, but were not influenced significantly by Reynolds number. The observed roll waves demonstrated similar surface area growth rates throughout their development, with stretched profiles relative to those described in flow over round tubes.

Mécanismes dominants d'écoulement dans l'évaporation à film tombant et l'évaporation en mode gouttelettes au-dessus de rangées de tubes horizontaux

Mots clés : Film tombant ; Transfert de chaleur ; Visualisation de l'écoulement ; Tube horizontal ; Onde ; Gouttelette

1. Introduction

Falling-film evaporators have applications in refrigeration, desalination, and other areas. They have several advantages over flooded evaporators: a lower refrigerant charge, minimal pressure drop, and operation over small temperature differences. Several possible configurations for falling-film evaporators, based primarily on films falling over horizontal or

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Nomenclature

C	empirical constant
d	droplet diameter, [m]
n	constant
Re	film Reynolds number, $4\Gamma/\mu$
Greek symbols	
Γ	liquid flow rate per unit length on one side of tube, [kg m^{-1} s^{-1}]
λ	wavelength, [m]
μ	dynamic viscosity, [kg m^{-1} s^{-1}]
ρ	density, [kg m^{-3}]
σ	surface tension, [N m^{-1}]

vertical round tubes, have been investigated. However, one promising geometry that has received little attention is flat microchannel tubes. Microchannel tubes have a thin, rectangular profile with a series of small internal ports, each with a hydraulic diameter on the order of 1 mm, allowing fluid flow in the lengthwise direction. In an evaporator utilizing microchannel tubes, the tubes could be orientated horizontally in a vertical array with in-tube cooling and an external evaporating thin film. These microchannel tubes possess several characteristics that make them ideal for such a configuration: high surface area-to-volume ratios for the internal and external flows, the ability to withstand high internal pressures, and a low refrigerant charge. The use of external falling-film evaporation over the microchannel tubes is expected to provide high heat transfer coefficients by enhancing thin film heat transfer on a vertical surface with droplet-induced waves. Combining this flow mode with internal cooling is expected to provide very high overall heat transfer conductances. Evaluating the potential of this configuration requires an understanding of the fluid flow and heat transfer of falling films on this geometry. This study begins to address this need by conducting a flow visualization study of falling films over a horizontal rectangular tube bank with quantification of key parameters.

1.1. *Falling-films on horizontal tubes*

There is very little information available in the literature on falling films over rectangular horizontal tubes. However, falling-film evaporation over horizontal round tubes has received considerable attention. In an early study, Chun and Seban (1971, 1972) measured heat transfer coefficients for evaporating water films on vertical tubes and developed correlations for the laminar, wavy-laminar, and turbulent regimes. Then, Fletcher et al. (1974, 1975) examined the heat transfer coefficients for evaporation of water and sea water films from horizontal tubes with plain and knurled surfaces. Chyu and Bergles (1987) conducted additional experiments on water evaporating from plain tubes and introduced a segmented model for the prediction of heat transfer coefficients that divided the flow into the jet impingement, thermally developing, and fully developed regions. Chen and Kocamustafaogullari (1989) experimentally and numerically demonstrated the potential of coupling external falling-film evaporation with internal steam condensation, achieving overall heat transfer coefficients on the order of 3 kW m^{-2} K^{-1}. Parken et al. (1990) investigated evaporating and boiling falling films on horizontal smooth tubes and developed empirical correlations for heat transfer coefficients under both conditions, and Fujita and Tsutsui (1998) conducted tests with R11, studying the impact of dryout on heat transfer. These investigations have continued, with several recent studies providing heat transfer coefficients over wider operating ranges and examining key issues such as dryout. These include a study by Roques and Thome (2007a,b) on boiling of R134a falling films over four types of tubes, and experiments by Li et al. (2011a,b) on falling-film evaporation of water at 1000 Pa with smooth and enhanced tubes, using the low pressure to eliminate nucleate boiling and only allow convective evaporation. A more detailed discussion of the experimental and modeling efforts in these areas can be found in the reviews by Thome (1999), Ribatski and Jacobi (2005), and Mitrovic (2005). These experiments have provided data on heat transfer coefficients for a wide range of fluids, flow rates, geometries, and tube surfaces. In addition, insight has been gained into flow mode transitions, wave characteristics, dryout, and other key flow mechanisms. However, to the authors' knowledge, only Wang et al. (2010, 2011) have studied falling-films over similar rectangular tube geometries. Their initial work (Wang et al., 2010) focused on the flow modes and transitions of water and ethylene glycol in adiabatic conditions with no vapor flow over tubes with a height of 25.4 mm and width of 3.18 mm, and recognized the potential for a microchannel evaporator with in-tube condensation and external evaporation. They observed flow modes similar to those observed between horizontal tubes: sheet, sheet-jet, jet, jet-droplet, and droplet. In addition, they noted several potential differences between round and flat tubes, including the possibility that the Taylor instabilities known to determine the spacing between droplet departure sites will not be as significant on flat tubes, and that different gravitational and shear force distributions could result in new velocity profiles, leading to new flow patterns. A second study (Wang et al., 2011) explored the local and average sensible heat transfer coefficients for falling films on horizontal flat tubes for a range of heat fluxes, tube spacings, and flow rates. They found that the average Nusselt numbers for flat tubes are similar to those for round tubes in the droplet mode, but are approximately double those of round tubes in the jet- and sheet- flow modes.

1.2. *Droplet characteristics on horizontal tubes*

In addition to studies on the heat transfer of flows over horizontal tubes, investigations focusing on droplet formation, break-up, and impact, which have been studied extensively, are relevant to the present work. A review by Eggers (1997) discusses many of the experimental, analytical, and computational approaches used to understand droplet behavior. Reviews by Rein (1993) and Yarin (2006) provide further information on droplet impacts on dry walls, liquid pools, and thin films. In addition to these general studies, several investigations have focused specifically on aspects of droplet