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A thermodynamic basis for predicting falling-film mode transitions

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ABSTRACT

Horizontal-tube, falling-film heat exchangers are used in many air-conditioning and refrigeration systems. Depending on the tube diameter and spacing, the flow rate, and fluid properties, when a liquid film falls over a series of horizontal tubes three distinct flow patterns can be manifested. These flow patterns are the droplet mode, the jet mode, and the sheet mode. A thermodynamic analysis is undertaken to predict the transitions between these modes. By seeking the condition corresponding to thermodynamic equilibrium between two neighboring modes, a scaling relation is developed for the transitional Reynolds number. This theoretical framework is used to provide the first explanation for the relationship between the transitional Reynolds number and modified Galileo number which has been previously based solely on experimental observations. This approach offers insight into the prevailing physics, and it suggests a tube-spacing effect on the mode transitions which has not previously been anticipated. Using limited data and prior results from the literature it is found that this effect is likely to exist. The implications of this thermodynamic approach to predicting two-phase flow patterns are discussed in terms of entropy generation minimization and transition hysteresis, as is its incompleteness.

Une base thermodynamique pour la prévision de transitions de mode de films tombants

Mots clés : Film tombant ; Régime d'écoulement ; Transitions de mode ; Thermodynamique

1. Introduction

A falling liquid film is used for heat and or mass transfer in a number of important technical applications, such as sea water desalination (Fletcher et al., 1975), condensers and spray evaporators (Honda et al., 1987a,b; Moeykens et al., 1996), and absorption systems (Jeong and Garimella, 2002; Perez-Blanco, 1988). Often, the arrangement is such that a liquid film falls from one horizontal tube to another below it, as a heating or cooling fluid flows inside the horizontal tubes (see Hu and Jacobi, 1996a). Fairly recent thorough reviews of falling-film

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Nomenclature

A	area (m^2)
E	extensive total energy (J)
D	tube diameter (m)
e	intensive total energy ($J\ kg^{-1}$)
Ga	Galileo number $\rho\sigma^3/\mu^4 g$ (–)
g	gravitational acceleration ($m\ s^{-2}$)
L	tube length (m)
M	mass (kg)
Re	Reynolds number $2\Gamma/\mu$ (–)
S	entropy ($J\ K^{-1}$)
u	intensive internal energy ($J\ kg^{-1}$)
Z	vertical location (m)
V	velocity ($m\ s^{-1}$)
δ	film thickness (m)
Γ	mass flow rate per unit length ($kg\ m^{-1}\ s^{-1}$)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($N\ m^{-1}$)
ξ	capillary length $(\sigma/\rho g)^{1/2}$ (m)

Subscripts

lv	liquid/vapor
o	dead state (ambient/laboratory conditions)
J	jet
S	sheet

heat exchangers have been provided in the literature (Ribatski and Jacobi, 2005; Thome, 1999). Since those reviews, significant progress has been made in using tubes with surface enhancements (Habert and Thome, 2010a,b; Christians and Thome, 2012a,b), enhanced fluids (Ruan and Jacobi, 2012a,b), and with non-circular tubes (Wang et al. 2012, 2013a). It is well known that when the liquid film falls from tube to tube, the flow can manifest several different flow patterns; these so-called falling-film modes are depicted in Fig. 1.

Three distinct falling-film modes have been observed: the droplet mode, jet (or column) mode, and sheet mode, as well as mixed modes (Mitrovic, 1986). Early observations of the falling-film mode transitions on smooth tubes in quiescent surroundings disclosed that the liquid flow rate per unit length of tube, Γ, was important to determining which mode would prevail (Dhir and Taghavi-Tafreshi, 1981). Further experimental work disclosed that the thermophysical properties of the fluid were important, usually represented by a modified Galileo number[2] (Honda et al., 1987a,b). A number of strictly empirical relationships have been presented in the literature to relate the Reynolds number at a mode transition to fluid properties (*Ga* or an equivalent) (see Mitrovic, 1986; Honda et al., 1987a,b; Armbruster and Mitrovic, 1994; Hu and Jacobi, 1996a,b; Roques et al., 2002). Hu and Jacobi (1996a,b) provided a study of falling-film mode transitions, which included transitional modes, hysteresis in the transitions, and limited findings for non-quiescent surroundings for a wide range of $Ga^{1/4}$ (see also Ruan et al., 2009). Recently, Mitrovic (2005) reviewed the transition criteria and found they were all essentially in agreement.

Further experimental work has been conducted to characterize the falling-film modes and the transitional Reynolds numbers for cases other than smooth tubes in a quiescent gas. The departure site spacing for the droplet and jet modes, λ, was studied experimentally, and found to be closely related to wavelength associated with the Taylor instability (Hu and Jacobi, 1998). Experimental studies of local film thickness have shown that the film thickness generally follows Nusselt theory on the upper part of the tube, with departures from Nusselt theory near the bottom of the tube (Gstoehl et al., 2004). The falling-film mode transitions for low-finned tubes have been studied in detail, and the experimental results show that a functional dependence of *Re* on *Ga* can fit the data well (Honda et al., 1987a,b; Roques et al., 2002; Roques and Thome, 2003). A rather awkward classification of falling-film modes and transitions in the presence of a flowing gas was presented by Wei and Jacobi (2002), and later refined and clarified by Ruan et al. (2009). Very recently there has been some work on the falling-film modes of nanofluids (Ruan et al., 2011), and experimental methods (Wang et al., 2013b). All of this research also shows that a functional dependence of *Re* on *Ga* can fit the data well, and it is very common to use $Re = A\cdot Ga^{1/4}$, where the constant A is experimentally determined for a particular mode transition (alternatively, $Re = A\cdot Ga^B$, where $B \approx 1/4$).

The work described above was experimental, and almost all of the research on this topic has relied heavily on experiments. There have been two theoretical or semi-theoretical approaches to predicting mode transitions. In one semi-theoretical approach, a single droplet departure site was studied, and using empiricism to estimate the droplet size, the Reynolds number at which the rate of droplet production would necessarily exceed the frequency associated with capillary oscillations was asserted to represent a droplet-to-jet transition (Yung et al., 1980). While this approach provides a basis for predicting that transition, it cannot be adopted for any of the other transitions. It is a highly restricted theoretical framework confined to address one and only one of the transitions in one direction. However, with rearrangement is of the same form as used by others. The transition criteria discussed are summarized in Table 1.

The second approach to theoretical prediction of mode transitions has been linear stability analysis (*e.g.*, Joo et al., 1991; Grant and Middleman, 1966). This approach assumes a base state (sheet or jet) and makes a determination as to when that state will become unstable. However, such a stability analysis only allows for transitions in the direction of decreasing Reynolds number; such an analysis cannot start with a droplet-mode base state and consider a transition to the jet mode, nor can it start in a jet-mode base state and consider transitions to the sheet mode. In this theoretical framework, transitions from jet to droplet are fundamentally different from droplet to jet; likewise for sheet-to-jet and jet-to-sheet transitions. However, the experimental evidence shows that hysteresis in the transitions is often very small; hysteresis is often neglected. A theoretical framework that is

[2] The naming of this parameter has been debated, with some suggesting Kapitsa number is more appropriate; however, the use of modified Galileo number is widely adopted in the germane literature.