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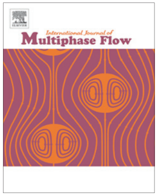

An indirect criterion for the laminar to turbulent flow transition in shear-driven annular liquid films

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ABSTRACT

An indirect method to identify the laminar to turbulent flow transition in shear-driven annular liquid films has been developed and used, together with literature measurements of the velocity profile, to approximately resolve the near wall structure in shear-driven annular liquid films. The limits between the laminar sublayer and the buffer layer and between the buffer layer and the turbulent layer have been found to correspond to about 9 and 40 wall units, respectively, which are higher than the corresponding limits of 5 and 30 wall units typical of single-phase boundary layers, thus indicating a weaker turbulence intensity in shear-driven annular liquid films with respect to single-phase wall-bounded flows. Additionally, a simple laminar to turbulent flow transition criterion and a prediction method for the average liquid film thickness have been developed for evaporation and condensation applications.

Introduction

Annular two-phase flow, characterized by the gas or vapor phase flowing in the center of the channel carrying entrained liquid droplets and shearing a thin liquid film that flows along the channel wall, is one of the most frequently encountered flow regimes in gas–liquid two-phase flow applications, such as steam generation, refrigeration and air conditioning, chemical processing, condensation and evaporation. Notwithstanding the extensive research carried out in the last decades, mostly driven by nuclear reactor cooling applications, annular flows are still actively investigated, particularly in connection with microscale high heat flux cooling applications and nuclear reactor fuel optimization, power uprate and license extension, where more accurate and reliable closure models are required for computer simulation codes.

The turbulence structure in the annular liquid film, in particular, is crucial in the analysis and modeling of annular flows, as it affects the transport of linear momentum and heat through the liquid film, thus determining the heat transfer effectiveness and hydraulic resistance of annular flows. As such, numerous experimental and theoretical studies have addressed turbulence in annular two-phase flow, focusing in particular on the prediction of the heat transfer rate through the liquid film (Anderson and Mantzouranis, 1960; Hewitt and Lacey, 1965; Levy, 1966; Kosky and Staub, 1971; Moeck and Stachiewicz, 1972; Butterworth, 1974; Ueda and Nose, 1974; Ueda and Tanaka, 1974; Levy and Healzer, 1981; Dobran, 1983; Tandon et al., 1985; Abolfald and Wallis, 1986; Oliemans et al., 1986; Jensen, 1987; Bellinghausen and Renz, 1992; Malamatenios et al., 1994; Fu and Klausner, 1997; Jayanti and Hewitt, 1997; Azzopardi, 1999; Kaji et al., 1999; Trabold and Kumar, 1999; Vassallo, 1999; Kumar and Trabold, 2000; Kishore and Jayanti, 2004; Pu et al., 2006; Peng, 2008; Cioncolini et al., 2009a, 2010; Cioncolini and Thome, 2011). It is normally accepted that in annular two-phase flow, depending on the local flow conditions, the flow in the annular liquid film can be either laminar or turbulent, similar to single-phase flows through pipes and channels. More precisely, in analogy with single-phase boundary layers, the liquid film is believed to contain a laminar sublayer close to the channel wall, where the flow is laminar, a turbulent layer extending all the way to the liquid–gas interface, where the flow is fully turbulent, and a buffer layer located between the laminar sublayer and the turbulent layer where turbulence is gradually emerging. Due to the significant technical difficulties in measuring the flow structure in liquid films that are highly dynamic and typically no more than a few hundred microns thick, the exact location and the turbulence intensity of

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the buffer layer and of the turbulent layer have not been experimentally resolved at present. In modeling the transport of linear momentum and heat through the annular liquid film, therefore, most of the solutions proposed to date have relied upon extrapolating single-phase boundary layer flow theory. This modeling approach has met with limited success, clearly indicating that in fluid-bounded, shear-driven annular liquid films the turbulent structure is similar but not the same as the turbulence structure of single-phase boundary layers.

Very recently, Ashwood et al. (2015) provided the first detailed velocity profile measurements in the liquid film of annular flow. In particular, they performed adiabatic tests with water–air in vertical upflow through a 33.0 mm × 20.3 mm rectangular channel, and used thin film particle image velocimetry to measure the time average velocity profile in the annular liquid film. Their measurements are reproduced in Fig. 1 (top) as dimensionless velocity V^+ vs. dimensionless distance from the channel wall y^+, where V^+ and y^+ are the standard wall coordinates for single-phase boundary layer flows defined as:

$$V^+ = \frac{V}{V^*}; \quad y^+ = \frac{y}{y^*}; \quad V^* = \sqrt{\frac{\tau_w}{\rho_l}}; \quad y^* = \frac{\mu_l}{\rho_l V^*} \tag{1}$$

where V is the local velocity in the annular liquid film at a distance y from the channel wall, y^* and V^* are the wall scales for length and velocity, ρ_l and μ_l are the liquid density and viscosity while τ_w is the wall shear stress. For comparison, the following von Karman (Kakaç et al., 1987) fitting expression for the universal velocity profile in single-phase boundary layers is included in Fig. 1 (top):

$$V^+ = y^+; \quad 0 \leqslant y^+ \leqslant 5 \tag{2}$$

$$V^+ = 5.0\ \ln(y^+) - 3.05; \quad 5 \leqslant y^+ \leqslant 30 \tag{3}$$

$$V^+ = 2.5\ \ln(y^+) + 5.5; \quad y^+ \geqslant 30 \tag{4}$$

In particular, Eq. (2) holds in the laminar sublayer, which in single-phase boundary layers is located from the wall up to 5 wall units, Eq. (3) holds in the buffer layer that extends from 5 to 30 wall units, while Eq. (4) holds for the turbulent layer that extends above 30 wall units from the channel wall. It is worth noting that Eq. (2) is analytical, while Eqs. (3) and (4) are semi empirical. As can be seen in Fig. 1 (top), the annular flow measurements conform to the laminar velocity profile, Eq. (2) up to a distance from the tube wall of about 10 wall units, based on visual inspection, twice the limit of $y^+ = 5$ characteristic of single-phase boundary layers. The consistency of the velocity measurements with the laminar flow velocity profile can be taken as indicative of laminar flow conditions in the annular liquid film, pretty much the same as consistency of friction factor measurements in single-phase tube flow with the Hagen–Poiseuille laminar flow resistance formula can be taken as indicative of laminar flow conditions in the tube. Plotting the measurements of Ashwood et al. (2015) as a ratio of dimensionless velocity to dimensionless distance from the channel wall (V^+/y^+) vs. dimensionless distance from the channel wall y^+ provides a more objective evaluation of the upper limit of the laminar sublayer, as shown in Fig. 1 (bottom) where error bars have been estimated based on the figures provided by Ashwood et al.

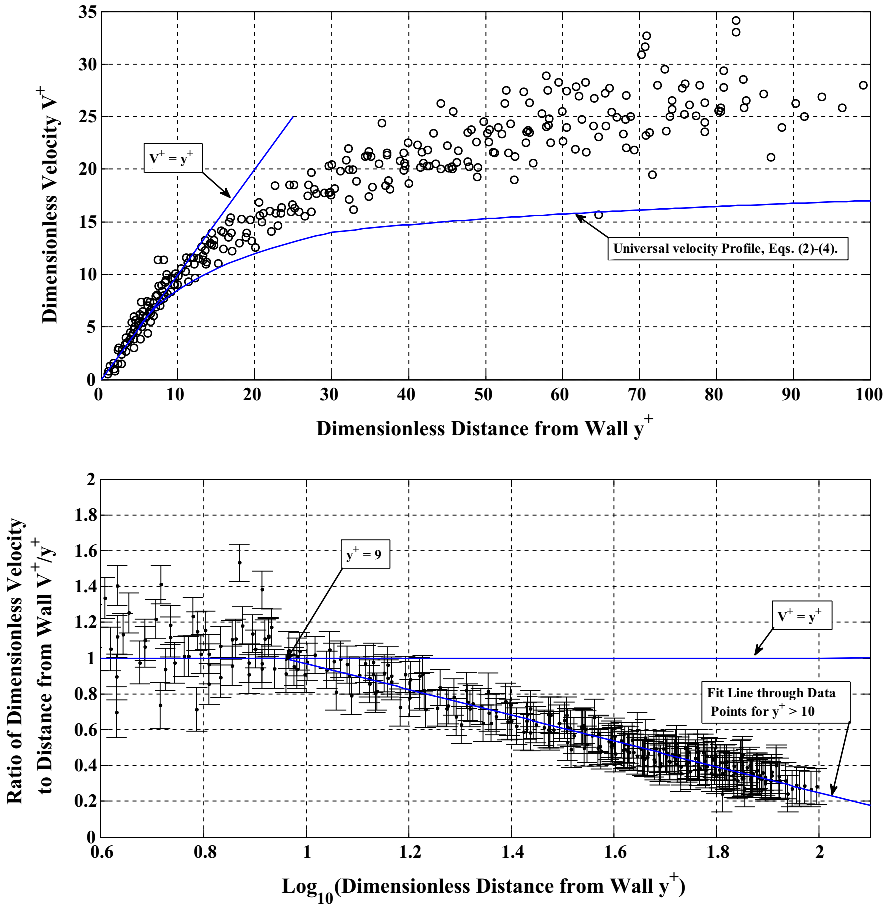

Fig. 1. Ashwood et al. (2015) velocity profile measurements in shear-driven annular liquid films (top) and the same data plotted as ratio of dimensionless velocity to dimensionless distance from wall V^+/y^+ vs. dimensionless distance from wall y^+ (bottom).