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Annular flow stability within small-sized channels

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ABSTRACT

An analytical study based on a variational thermodynamic principle is presented to evaluate the influence of surface tension on the stability of annular flow within small-sized channels. The model introduces phenomenological assumptions in the interfacial structure of the flow regime and theoretically draws the equilibrium transition line from an annular regime to the initiation of the partial wetting condition on the inner surface. By including surface tension, this model expands previous theories and identifies the stable flow configuration in terms of void fraction and interfacial extension. The significant influence of a higher surface tension and smaller diameter (i.e. lower Weber number) are responsible for a lower stable void fraction and higher slip ratio. A complete screening of the main influential parameters is conducted to explore the descriptive ability of the model. This analysis aims at contributing to the understanding of the stability of two-phase flow regimes and can be extended to the transition between other neighbouring regimes, including wall friction as well as liquid entrainment phenomena.

1. Introduction

Multiphase flows are used as transport media in a variety of technical systems, such as nuclear reactors, power plant boilers, internal combustion engines, heat transfer and storage devices, cooling equipment for electronic hardware, and food processing systems. Given the obvious differences in these examples with regard to their scale, transport phenomena, and operating conditions, these systems have been generally researched individually via the development of models and heuristic correlations having restricted applicability [1]. The co-presence of multiple phases substantially affects the operability of a system in terms of heat transfer performance, pressure drops, and flow stability, which, respectively, alter the capacity of the system, the power required to steadily circulate the fluid, and its reliability [2]. Even though phase change processes have been observed and technically used for centuries, owing to a flawed understanding of the concepts of heat, energy, and temperature, the theoretical background needed to model these phenomena was not consistently established until the 17th century. The presence of dynamic and deformable phase-interfaces and the related discontinuities of fluid properties are the main reasons for the high degree of complexity in writing the governing transport laws and physical principles. However, in spite of this difficulty, the theory of multiphase systems relies on the classical laws of thermodynamics, fluid mechanics, and principles of heat and mass transfer. Liquid–vapour flow is the most recurrent as well as complex flow regime class. Owing to the presence of deformable interfaces, different neighbouring flow patterns can be encountered in the same system [3,4]. Numerous theoretical, numerical, and empirical approaches have been developed to predict the characteristics of liquid–vapour flows [5,6]. The most widely accepted map describing the adiabatic transition between different flow patterns was semi-theoretically obtained by Taitel and Dukler [7].

The demand for high performance and reliable electronic devices and miniaturized heat exchangers for refrigeration plants requires heat transfer devices to be able to extract the given heat load within a limited temperature range and certain overall dimensions. The structural characteristics of the interface in two-phase flows constitute the criteria by which they are classified into flow regimes. However, the concept of classifying flow regimes, which assumes a certain degree of similarity between corresponding flow structures, is based on the definition of a given volume or length-scale. Therefore, regime dependent models may yield results contingent to the selected length-scale. Furthermore, multi-phase transport phenomena occurring at different scales may vary significantly [2]. Most of the studies related to liquid–vapour flow regime transitions have been carried out for conventionally sized passages, in which surface tension effects can typically be neglected. However, inside mini- or micro-channels, surface tension effects can significantly affect the way in which heat, mass, and momentum are transferred [8]. Therefore, it has not yet been possible to theoretically predict the characteristics of two-phase flows within small-sized channels with the accuracy needed for reliable system design and control.

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Nomenclature

e_{tot}	energy rate per unit cross-sectional area (W m^{-2})
E	energy rate (W)
m	mass flowrate (kg s^{-1})
S	phase interface (m^2)
σ	surface tension (J m^{-2})
u	fluid velocity (m s^{-1})
A′	total cross-sectional area of the channel (m^2)
ρ	density (kg m^{-3})
β	interfacial area concentration (m^{-1})
x	vapour quality (–)
α	steam void-fraction (–)
δ	thickness of the liquid flow (m)
r	inner radius of the channel (m)
θ_d	dry angular-portion of the channel (rad)
G	total mass flowrate per unit cross-sectional area (kg m^{-2} s^{-1})

Subscripts

g	vapour/gas-phase
gl	vapour–liquid interface
i	internal energy
k	kinetic energy
s	Solid-phase
sg	vapour–solid interface
sl	solid–liquid interface
tot	total
σ	surface tension energy

Superscripts

*	dimensionless form
′	reference value

In a previous work [9], evident differences were reported between various empirically proposed regime maps for microchannels, starting with the pioneering work of Suo and Griffith [10] on the transition boundaries in heptane and water flow, through the graphical map of Triplett at al. [11] for an air–water mixture in a 1.1 mm channel, to the experimental work of Revellin et al. [12] on the flow transition of the refrigerant R134a. The significant differences in the thermo-physical properties of the refrigerants were considered responsible for the large deviations between the results obtained by the different authors. This suggested a need for designing generalized maps, based on first principles instead of utilizing one-of-a-kind flow pattern maps, which would take into account the wide range of operating conditions and be applicable to fluids commonly used in the refrigeration field. Akbar et al. [13] used the Weber number to summarize the data for an air–water flow on a common flow regime map. For a comprehensive literature review, please refer to Ref. [14]. The present research effort applies a variational thermodynamic approach to idealized two-phase flow structures to investigate the effect of surface tension on their stability and suggests a phenomenological transition boundary. Particularly, the focus of the study is directed towards an annular flow regime and breaking of the liquid film leading to partial or complete dryout of a channel.

2. Fundamental equations

Regarding initiation of the dryout of a channel, previous theoretical analyses mostly assume that it occurs when the thickness of the liquid film in an annular flow becomes zero. However, earlier experimental works [15,16] and modelling efforts [17,18] have shown that the dryout, i.e., the transition to partial wetting conditions, occurs when the liquid film is relatively thin, but not zero, and the corresponding thickness is referred to as critical film thickness. To develop mechanistic criteria to predict the characteristics and stability of multiphase flow structures, Zivi [5] applied the principle of minimum entropy production and, recently, in Ref. [19], the thermodynamic equilibrium conditions of their Helmholtz potentials have been explored. A corresponding approach has been implemented in Refs. [20,21] to establish the minimum stable thickness and characteristics of a falling liquid film. The principle of minimum entropy production is an approximate restatement of the second law of thermodynamics for characterising the steady state of open systems kept away from the thermodynamic equilibrium, when all the fluxes that cross the system are constant, and under the assumption that the rate of entropy production is governed by linear phenomenological laws [22–24]. Following the approach of Zivi [5], the present paper formulates the energy flux of two different flow structures in terms of void fraction and liquid-vapour interface extension to search for the values of these parameters which minimise the entropy production rate of the process under analysis. Particularly, the thickness of the liquid film and extension of the liquid–vapour interface is critical information for predicting the heat and mass transfer rates; please refer, for instance, to the model developed by Younes et al. [25]. By doing so, it is tacitly assumed that the energy of the flow is gained within the channel, and that the work required for accelerating and extending the interface between the two phases is the largest part of the total flow work. Under this point of view, the principle of minimum entropy production indicates that the stable flow configuration is achieved through a process that requires the minimum work.

Then, comparing the energy rate of the two flow structures at corresponding conditions, the theoretical transition line between them is drawn and analysed with respect to the main parameters at play. This procedure further implies that the transition between the two flow patterns is triggered by disturbance that qualifies as a zero-energy interaction. Previous results applied to hypothetical two-phase structures [5] have shown a remarkable agreement with time averaged values of the main significant parameters of steady two-phase flows.

2.1. Evaluation of the flow energy contents

The open thermodynamic system under consideration is a channel with finite length, defined radius and a smooth inner surface, and emerging into a receiver, where liquid and vapour are removed separately, at a constant rate corresponding to the rate of inlet supply, but with very low effluent velocities. In this manner, the kinetic and surface tension energy fluxes are almost entirely dissipated at the outlet. As pointed out by Zivi [5] this circumstance is commonly matching technical applications.

The energy rate per unit cross-sectional area of the channel can be quantified by Eq. (1), where E_k, E_G, E_i and E_σ represent the kinetic, potential, internal, and surface tension contributions, respectively; A and S are the cross-sectional area of the channel and the contour between neighbouring phases, respectively; and σ is the surface tension.