International Journal of Heat and Mass Transfer 54 (2011) 3761–3776

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A quasi one-dimensional method and results for steady annular/stratified shear and gravity driven condensing flows

S. Mitra, A. Narain *, R. Naik, S.D. Kulkarni

Department of Mechanical Engineering – Engineering Mechanics, Michigan Technological University, Houghton, MI 49931, USA

ARTICLE INFO

Article history:
Available online 8 April 2011

Keywords:
In-channel and in-tube condensing flows
Annular condensing flows
Micro-meter scale condensing flows
Shear and gravity driven condensing flows

ABSTRACT

This paper presents an effective quasi one-dimensional (1-D) computational simulation methodology for steady annular/stratified internal condensing flows of pure vapor. In-channel and in-tube flows are considered for a range of gravity component values in the direction of the flow. For these flows, three sets of results are presented and they are obtained from: (i) a full 2-D CFD based approach, (ii) the quasi-1D approach introduced here, and (iii) relevant experimental results for gravity driven condensing flows of FC-72. Besides demonstrating differences between shear and gravity driven annular flows, the paper also presents a map that distinguishes shear driven, gravity driven, and "mixed" driven flows within the non-dimensional parameter space that govern these duct flows. The paper also demonstrates that μm-scale hydraulic diameter ducts typically experience shear/pressure driven flows.

1. Introduction

Reliable design and effective integration of condensers in traditional macro-scale as well as modern micro-scale thermal systems require good flow prediction capabilities and proper flow control strategies. For this, one needs to investigate issues pertaining to attainability of steady/quasi-steady flows in different flow regimes. Among these regimes, particular interest is in attainability and controllability of annular/stratified (or film wise condensation) flows under gravity or shear driven conditions. This is because annular/stratified flows have high thermal efficiencies and should be rigorously studied (i.e. by a synthesis of computations and experiments) to: (i) develop predictive abilities, and (ii) develop the boundaries between annular stratified and adjacent flow regimes (such as plug/slug, bubbly, etc. discussed in [1]) in the context of the general non-dimensional parameter space considered here. However, this paper addresses only the first of these two objectives.

For shear or gravity driven annular/stratified internal partially condensing flows (as in the channel of Fig. 1a or vertical tube of Fig. 1b) with a given inlet vapor mass flow rate and a known vapor to wall temperature difference, our earlier established computational and experimental results [2–7] have been corrected (also see [8–10]) to state that there exists a *unique* annular/stratified steady solution and a unique steady exit condition of the strictly steady equations. The multiple steady solutions that were reported to exist in [2–7] were not *all* strictly steady solutions (see [10]). In fact all but one of them were quasi-steady (steady-in-the-mean) solutions [10] mistaken for strictly steady solutions. Here and henceforth, the unique steady solutions for the steady "parabolic" boundary conditions, namely, the *inlet* conditions (vapor mass flow rate, pressure, and temperature) and thermal boundary condition for the condensing-surface (i.e. known uniform or non-uniform spatial variations for the condensing surface's temperature or heat-flux values) are termed "natural" solutions. The value of an appropriate exit parameter (exit pressure, or exit liquid mass flow rate, or exit vapor mass flow rate) obtained from the "natural" solution is termed "natural" exit condition for the flow.

The new "quasi" 1-D technique presented and implemented here is different from the other 1-D tools ([11–13], etc.) that are available in the literature. This 1-D tool avoids the use of average flow variables and/or empirical models (such as friction factor models for the interface, pressure gradient models, etc.) used in [11–13] by keeping the method close to the exact solution technique for laminar vapor and laminar liquid flows (with smooth or nearly smooth wavy interface). Because of the absence of empirical/semi-empirical models in the formulation, the results from this computationally efficient 1-D technique are shown to be in agreement with the results obtained from a full 2-D CFD technique as well as numerous relevant experimental runs [9,14,15] for which the modeling assumptions of this paper hold.

The paper presents key differences between purely shear driven and gravity dominated (and driven) annular flows inside tubes and channels. A map that partitions the parameter space (for annular/stratified flows) into strongly gravity driven, shear driven, and "mixed" driven regions is presented here. The solutions of the unsteady governing equations in the vicinity of the steady

* Corresponding author.
E-mail address: narain@mtu.edu (A. Narain).

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doi:10.1016/j.ijheatmasstransfer.2011.03.008