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Review

Review of droplet entrainment in annular flow: Interfacial waves and onset of entrainment

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ABSTRACT

Annular two-phase flow has been vastly investigated because of its large and deep involvement in industrial processes, particularly in nuclear engineering. This paper reviews most of the recent literature on the matter, with emphasis in all those variables and processes occurring in the liquid–gas interface that cause droplet entrainment. Further than presenting correlations, the paper shows the existing scattering found when expressions are compared to each other and it highlights the gaps of knowledge still existing. Additionally, based on some of the open data, alternate equations are derived for key variables in the annular flow descriptions, like liquid film thickness and wave celerity and frequency.

1. Introduction

Two-phase gas–liquid flows are widely encountered in many different industrial applications: petroleum, chemical, civil and nuclear industries, and particularly in boiling and condensing heat transfer equipment. Nuclear power plants involve two-phase flow. In pressurized water reactors (PWRs) two-phase flow is especially encountered in the steam generators and in the upper-core components during normal operation and in the reactor itself during off-normal conditions, including accident sequences. In boiling water reactors (BWRs) the two-phase flow occurs in the core during normal operation. In all these processes two-phase flows play an important role in their operation, safety and cost that is why, a proper understanding of their behavior is particularly interesting. Consequently, a large number of publications have been performed focusing on the study of multiphase flow research, in particular its investigation began in the 40s and continues until present time.

Two-phase flows in pipes can be grouped into classes, commonly called flow regimes or flow patterns. The wide varieties of classifications that exist in the literature are mainly due to the subjective nature of the characterization method, and as a general reference maps for vertical and horizontal flow are presented in Fig. 1.

In particular, the annular flow pattern can be found in many important industrial applications. For instance, in the evaporators and condensers of conventional power generating plants; in pressurized water reactors of nuclear power plants during a LOCA (loss of coolant accident) and in boiling water reactors during normal operation; in geothermal and gas-oil wells, etcetera. As a result, the ability to understand and model annular two-phase flow is a subject of central importance to achieve a reliable design of this equipment.

Annular flow is normally characterized by: a gas core flowing through the center of the tube; a part of the liquid, as a thin film, flowing on the tube wall; while the other part flows as entrained liquid droplets in the gas core. For horizontal pipes, at the beginning of the transition from stratified wavy to annular flow, only the gas core (without entrained droplets) and the thin liquid film exist. As the difference in velocity between gas and liquid phases increases, a series of waves begin to appear on the gas–liquid interface. When this difference is high enough, a flow rate of droplets is entrained from the liquid film surface into the core of the gas stream. The point in which this entrainment phenomenon starts is called “onset of entrainment” and its associated velocity is the entrainment inception velocity. These entrained droplets

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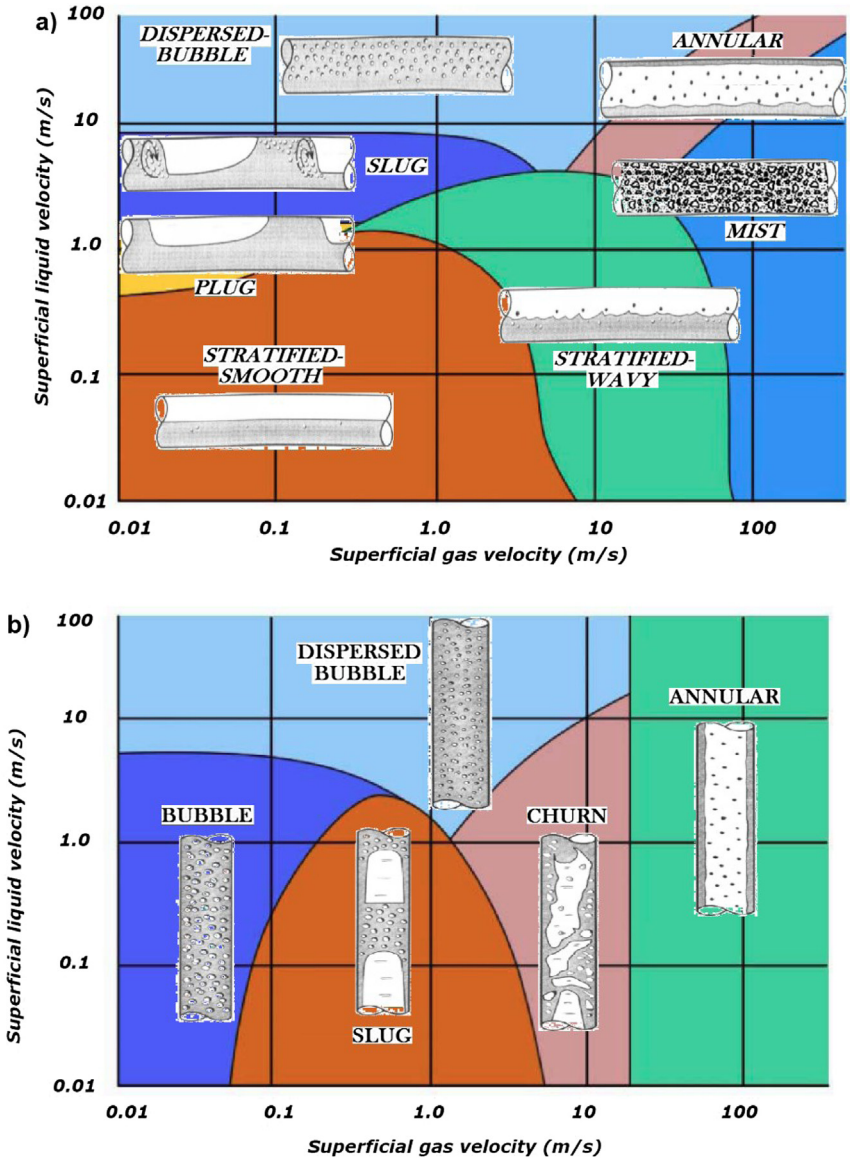

Fig. 1. Flow maps for two-phase gas–liquid flow: (a) vertical pipes; and (b) horizontal pipes.

contribute significantly to heat and mass transfer, and the modeling of the gas–liquid interface properties, droplets extraction mechanisms and droplets itself are of high practical interest. The contact area between the liquid film and the gas, gas–liquid interface, is covered with waves, and the water droplets are extracted from the crest of these waves and are then transported into the gas core by the high velocity gas stream.

This review presents and analyzes most of the extensive literature that exists on annular two-phase flow. In particular, the paper focuses on the study of the liquid film layer and the gas–liquid interface, presenting its main characteristics and analyzing the process of droplet extraction from this liquid phase to the gas phase (the entrainment process). The aim of this article is, firstly, to reveal the dispersion in the abundant information available, collecting them insofar as possible and, moreover, presenting the lacks of knowledge that still exist in annular flow. Secondly, its interest is to have on hand in the same document a summary of the various expressions found in the literature. And finally, several analyses of the different experimental values found in the open literature have been made, presenting a new set of correlations for its adjustment.

In this work, we will focus on the study of the liquid film properties, gas–liquid interface and the mechanisms governing these water droplets extraction processes. To do so, this paper is organized as follows.

- First, in Section 2, we present a summary of the main characteristics of the waves that are present on the gas–liquid interface.
- Section 3 is devoted to present the onset of entrainment process.
- Section 4 focuses on the entrainment inception velocity.
- Section 5, in which the comparison of the experimental measurements, the results obtained with the different expressions available in the literature and the developed in the present work are presented.
- Finally, Section 6 settles the main conclusions from this study.