Applied Thermal Engineering 98 (2016) 862–871

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Modeling the scooping phenomenon for the heat transfer in liquid–gas horizontal slug flows

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HIGHLIGHTS

- A low computational tool for heat transfer prediction on slug flows is presented.
- The scooping phenomenon is modeled on a stationary approach.
- The scooping phenomenon improved in 8% the heat transfer results.

ARTICLE INFO

Article history:
Received 22 September 2015
Accepted 19 December 2015
Available online 4 January 2016

Keywords:
Slug flow
Heat transfer
Scooping phenomenon
Mathematical modeling

ABSTRACT

The heat transfer between the deep sea waters and the oil and gas mixtures flowing through production lines is a common situation in the petroleum industry. The optimum prediction of the liquid–gas flow parameters along those lines, when the intermittent flow pattern known as slug flow is dominant, has extreme importance in facilities' design. The mixture temperature drop caused by the colder sea waters, which can be regarded as an infinite medium with constant temperature, directly affects physical properties of the fluids such as the viscosity and specific mass. Gas expansion may also occur due to pressure and temperature gradients, thus changing the flow hydrodynamics. Finally, the temperature gradient affects the thermodynamic equilibrium between the phases, favoring wax deposition and thus increasing pressure drops or even blocking the production line. With those issues in mind, the present work proposes a stationary model to predict the mixture temperature distribution and the two-phase flow heat transfer coefficient based on the mass, momentum and energy conservation equations applied to different unit cell regions. The main contribution of the present work is the modeling of the thermal scooping phenomenon, i.e., the heat transfer between two adjacent unit cells due to the mass flux known as scooping. The model was implemented as a structured Fortran95 code with an upwind difference scheme. The results were compared to experimental data and presented good agreement. The analysis showed that the inclusion of the scooping phenomenon into the model resulted in an averaged 8% improvement in the temperature gradient calculation and heat transfer coefficient prediction for the flowing mixture.

1. Introduction

Slug flow is a gas–liquid two-phase flow pattern that occurs over a wide range of gas and liquid flow rates. It is characterized by the intermittent succession of two bodies: a liquid slug, which may or may not contain dispersed gas bubbles in it, and an elongated bubble sliding over a thin liquid film. Together, those two structures constitute that what is known as a *unit cell* [1]. The slug and the elongated bubble possess characteristic velocities and geometric features such as lengths and phase fractions. Those characteristics depend on time and space and their prediction is central in the design of facilities for industrial applications such as nuclear power plants and oil and gas transportation systems.

The mathematical modeling of the phenomena involved in slug flow has been an important research topic over the last decades. Earlier works modeled slug flows as periodic and stationary, achieving good mean values for the main parameters (regions lengths, phase fractions, pressure drops). Those are the so-called mechanistic or stationary models [2–4]. Since 1990s, with the evolution of informatics, some transient models that capture the intermittent nature of slug flow have been developed [5–9] – at a higher computational cost nevertheless.

The aforementioned mathematical models applied mass and momentum conservation equations in a unit cell in isothermal conditions. Yet, the heat transfer in slug flows is relevant to oil and gas transportation in long production lines exposed to external conditions, as the effects caused by heat transfer in the flow must often not be neglected. The temperature variation along the pipe is related to the variation of the phases' properties, to the gas expansion/contraction and to the thermodynamic equilibrium of the phases.

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http://dx.doi.org/10.1016/j.applthermaleng.2015.12.104
1359-4311/

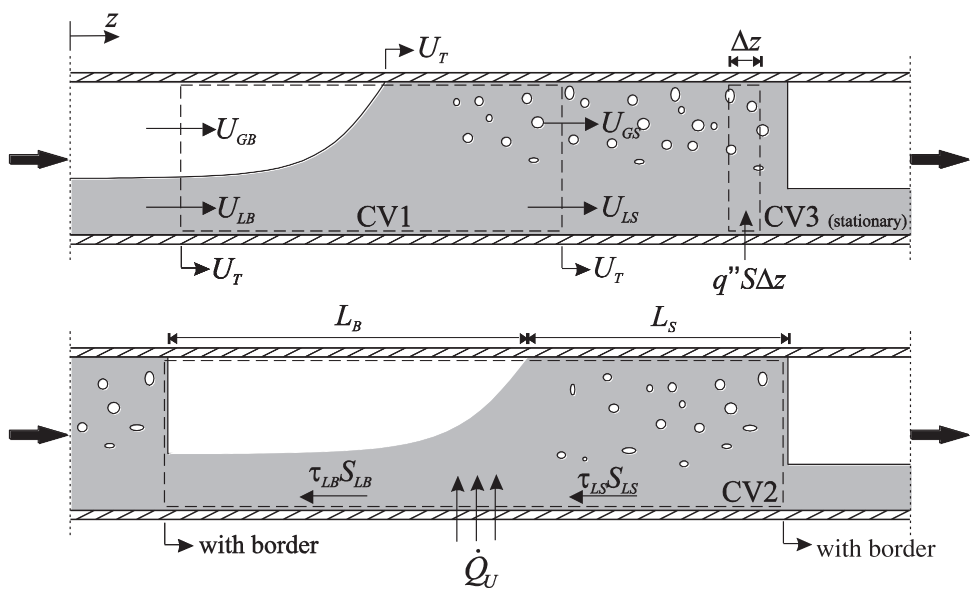

Fig. 1. Control volumes for conservation equations.

The latter is a main concern in flow assurance, since paraffin and wax deposition on the pipe wall increases the head losses and might block the production line under extreme conditions.

Most literature studies on two-phase flow heat transfer focus on micro channels [10–12] for micro components cooling. However, the present work focus on oil and gas pipelines, where capillary forces are not as influential as they are in micro channels. In this case, the main parameters affecting heat transfer are the superficial liquid velocity, the bubble length and translational velocity and the frequency [13]. Heat transfer experimental studies for medium-scale slug flows are focused on developing experimental correlations for the two-phase heat transfer coefficient [1,14–16], whilst some other works focus on mathematical modeling and simulation with stationary approaches [17,18], transient approaches [19–21] and the ones relying upon commercial software as ANSYS-Fluent [22] and ANSYS-CFX [23]. The mentioned models differ not only with regard to their approaches but also on their applications (e.g. micro channels [22], engine cooling [23], medium to large scale slug flow in ducts [17–21]).

Since the objective of the present work is to present a simple algebraic model for predicting the main parameters of slug flow in circular ducts, a stationary approach was chosen, following the efforts of Medina et al. [18]. Those approaches usually generate explicit equations, thus turning the relationship between hydrodynamic and heat transfer easier to address. The present work introduces a mathematical modeling coupling the heat transfer to the slug flow hydrodynamics, mainly discussing the thermal scooping phenomena [1], i.e., the heat exchanged between two consecutive unit cells. This phenomenon was not taken into account in the previous stationary model [18]. The characterization of gas–liquid slug flows in oil and gas production operations is this model's main objective. However, only air–water simulations will be herein presented so that their results can be compared with laboratory data [24] and the model can be validated.

2. Mathematical model

The mathematical model is based on a dimensional stationary approach. The mass and momentum conservation equations are applied in the form of an integral analysis, as already done in literature [18]. Otherwise, the thermal scooping phenomenon is modeled by applying the energy conservation equation in its differential form to predict the temperatures at the boundaries of the slug and the liquid film. In addition, an energy balance in its integral form to model the mixture temperature is used.

The following hypotheses were assumed during the modeling: (i) stationary, periodic and one-dimensional slug flow, (ii) Newtonian fluids, (iii) the mixture is far from the saturation region, (iv) incompressible liquid and ideal gas, (v) uniform velocity profile in each unit cell structure, (vi) constant liquid slug holdup, R_{LS}, and constant void fraction in the elongated bubble region, R_{GB}, (vii) no dispersed bubble entrainment in the liquid film, (viii) no axial pressure variation inside each elongated bubble, (ix) constant pressure throughout the cross section, (x) negligible shear stresses in the elongated gas bubble and in the liquid–gas interfaces, (xi) negligible gas momentum and internal energy when compared to the liquid phase due to the lower density and specific heat of the gaseous phase, (xii) negligible viscous energy dissipation, (xiii) negligible kinetic energy compared to the internal energy, (xiv) negligible heat transfer between the dispersed bubbles and the liquid slug, (xv) constant external temperature as boundary condition and (xvi) no mass exchange between the liquid and gas phases.

2.1. Hydrodynamic model

The hydrodynamic model follows the Medina et al. [18] approach. The mass and momentum conservation equations in their integral forms are applied to find, respectively, the specific velocities of each unit cell region and the pressure drop.

2.1.1. Mass conservation

The liquid and gas mass conservation are applied to the control volume CV1 shown in Fig. 1, which encloses half of the bubble and the slug region and is moving forward with the bubble translational velocity, U_T. The mass balance led to the following expressions for the liquid film U_{LB} and the elongated bubble U_{GB} velocities:

$$U_{LB} = U_T - (U_T - U_{LS})\frac{R_{LS}}{R_{LB}} \quad (1)$$