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Numerical simulation of the heat transfer in fully developed horizontal two-phase slug flows using a slug tracking method

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ABSTRACT

The gas–liquid slug flow pattern is characterized by the alternate succession of two structures: an aerated liquid slug and an elongated gas bubble, which together constitute that what is known as a *unit cell*. Computationally, the unit cell concept is used in modern slug tracking models in order to develop transient, lagrangian models capable of accurately predicting the flow behaviour with low computational costs, although early commercial packages using the unit cell concept did not offer slug tracking capabilities [3]. However, slug tracking models generally predict the hydrodynamic parameters only, whereas heat transfer is usually neglected. The present work couples heat transfer governing equations to a slug tracking model through energy balances in deformable, moving control volumes using the Reynolds transport theorem in its integral form, so as to achieve numerical simulations of heat transfer in developed, non-boiling, horizontal two-phase slug flows. In addition, a new expression for the calculation of the two-phase heat transfer coefficient is proposed. The numerical results were compared with data from the literature, and a good agreement was found.

1. Introduction

Gas–liquid slug flows occur over a wide range of gas and liquid flow rates. It is characterized by the alternate succession of two bodies: a liquid slug with tiny gas bubbles in its interior and a bullet-shaped elongated bubble sliding over a thin liquid film of variable thickness. Together, those two bodies constitute that what is called a *unit cell*. The characteristics of each of the bodies composing a unit cell change with time and space, that is, they possess an intermittent behaviour. The accurate prediction of the characteristics of the intermittent flow is essential in the design of the facilities where this type of flow occurs. Therefore, it comes as no surprise that the development of reliable mathematical models for the simulation of slug flows has been an important research topic over the last decades.

Different approaches can be used to model the transient nature of the slug flows. The *slug tracking model* is one of those approaches, and it has proved to be capable of accurately predicting the intermittency of slug flows [14,17]. A slug tracking model performs the mass and momentum balance equations in deformable control volumes from a reference frame that moves along with the unit cell. This type of model uses the integral form of the conservation equations which considers an average value for each control volume, therefore resulting in lower computational times.

Early works using slug tracking models simulated the movement of the bubbles by simply displacing the whole unit cell with the bubble translational velocity [1]. Recently Rodrigues (2009) [17], presented a slug tracking model that considers the expansion of the gas bubble due to the gas compressibility and to aerated slugs. This model performs the balance equations for separated liquid slug, liquid film and elongated bubble. This balance yields two differential equations: one for the mass and the other for the momentum balance. Yet, the slug tracking model developed by Ref. [17] is limited to the hydrodynamics of the flow, thus neglecting the heat transfer effects.

The study of the heat transfer in slug flows has important industrial applications such as the oil transfer in long production lines exposed to external conditions, thus causing heat exchanges between the two-phase mixture and the surrounding environment. As a result, the temperature of the fluids will vary along the pipeline producing changes in the *in-situ* properties of the fluids such as the density and the liquid viscosity, which influence pressure drop. Wax deposition or hydrate formation might also occur, as these processes depend on the thermodynamic equilibrium.

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Nomenclature

A	flow area of pipe, m^2
C	specific heat, J/(kg K)
D	diameter, m
e	total specific energy, J/kg
f	friction factor, –
Fr	Froude number, –
g	acceleration of gravity, m/s^2
$\hbar$	wake effect coefficient, –
h^G	global heat transfer coeff., W/(m^2 K)
i	specific enthalpy, J/kg
J	mixture velocity, m/s
L	length, m
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa or kPa
P^*	modified pressure, m^2/s^2
Pr	Prandtl number, –
q''	heat flux provided to the unit cell, W/m^2
$\dot{Q}$	heat provided by the control volume, W
R	volumetric fraction of a phase, –
Re	Reynolds number, –
S	perimeter, m
T	temperature, K
t	time, s
U	velocity, m/s
V	velocity, m/s
$\not{V}$	volume, m^3
$\hat{u}$	specific internal energy, J/kg
$\dot{W}$	energy loss, W
x	position of the liquid slug front, m
y	position of the bubble front (nose), m

Greek symbols

β	angle with horizontal, radians
Δ	differential (discrete)
ρ	density, kg/m^3
τ	shear stress, Pa

Subscripts

0	external
GB	gas in the elongated bubble region
GS	gas in the slug region
$j-1$	previous unit cell
j	current unit cell
$j+1$	next unit cell
k	kinetic
L	liquid
LB	liquid in the bubble region
LS	liquid in the slug region
m	mixture
p	potential
p_g	of the gas at constant pressure
r	relative
S	slug
T	translational
TP	Two-phase
v_g	of the gas at constant pressure
visc	due to viscous dissipation
w	wall
ϕ	relative to each component of the unit cell

Superscripts

O	old time step
OO	last but one ("old–old") time step
N	new time step

The main concern in studies on heat transfer in two-phase flows is the evaluation of the two-phase convective coefficient. Some authors developed correlations disregarding the flow pattern. Shah (1981) [18] for instance, considered the liquid as the main contributor and a minor influence due to the gas superficial velocity. Researchers such as Hetsroni et al. (1998) [8] and França et al. (2008) [6] developed models exclusively for intermittent flow. Hetsroni et al. (1998) [8] determined that the main parameters affecting heat transfer are the superficial liquid velocity, the bubble length, the bubble translational velocity and the frequency. França et al. (2008) [6] modelled the forced convection through a time averaging process in the unit cell. Kim and Ghajar (2006) [10] emphasized the importance of the wetted perimeter for the estimation of this coefficient and proposed a correlation based on a flow pattern factor. De Leebeeck et al. (2010), Kjeldby et al. (2013a, 2013b) [4,11,12] gave an important contribution on the similarities and differences pertaining to slug tracking modelling approaches, as well as about their functionality.

Despite the interest that authors have shown on this matter, only a handful of studies aimed at evaluating the heat transfer in non-boiling slug flows through energy balances were published. Moreover, two-phase flow heat transfer approaches are limited to calculating the heat transfer coefficient, thus disregarding temperature simulation. In such a context, the objective of the present work is to develop a heat transfer model using the slug tracking approach. Heat transfer governing equations are coupled to the [17] slug tracking model so as to calculate the hydrodynamic and thermal characteristics of the two-phase slug flow along a pipe. The deformation of the gas bubble due to pressure and temperature changes is also considered. Numerical simulations with literature data were carried out, and a good agreement between theory and data has been found.

2. Hydrodynamic model

In this section, the heat transfer effects are added to the slug tracking model presented by Ref. [17]. The slug tracking model considers the bubble and liquid slug regions as separated bodies that propagate along the pipe. The model produces two differential equations where the variables to be determined are the liquid slug velocity and the gas bubble pressure. Some simplifying hypotheses are assumed: the equilibrium state of both phases is far from the saturation region and hence the liquid can be considered as

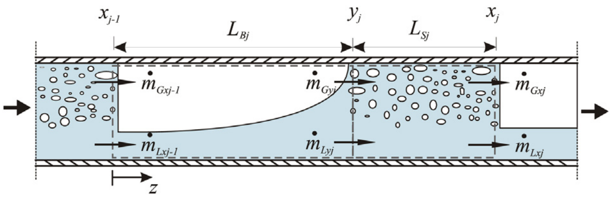

Fig. 1. Slug tracking control volumes.