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Heat transfer for fully developed stratified wavy gas–liquid two-phase flow in a circular cross-section receiver

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Abstract

Stratified gas–liquid two-phase flow occurs during the direct steam generation in the receivers. In order to understand how such a receiver can work under stratified two-phase flow regime forms, the numerical modeling of fully developed stratified wavy gas–liquid flow in a circular cross-section receiver is presented. The steady-state axial momentum and energy equation are coupled and solved together with a low Reynolds number $k \sim \varepsilon$ turbulence model for the eddy viscosity. The interface boundary conditions are more complex in the wavy flow than the smooth due to the unsteadiness of the wave motion itself. It is found that the interface configuration and wavy character must be taken into accounted for hydro and heat transfer simulation to be valid. Unfortunately, this has not been accounted for in all previous studies. The boundary conditions for the wave gas–liquid interface are devised from empirical consideration. In hydro dynamic simulation, the numerical calculations of global properties, such as pressure gradient and liquid holdup, shear stress distribution and the velocity field have been compared with the experimental data. In addition, for heat transfer simulation, the predictions of bulk and inside receiver wall temperature have been compared with the experimental result. It is concluded that a perfect agreement between this numerical calculation and experimental results could be achieved.

Keywords: Numerical simulation; Heat transfer; Stratified flow; Receiver

1. Introduction

It has been observed experimentally that when stratified two-phase flow occurs during the direct steam generation. Thermal gradients are created in the wall of the receivers that lead to severe mechanical stress (Almanza et al., 1997). In order to understand how such a receiver work under stratified two-phase flow regime forms (Flores and Almanza, 2004), the calculation of hydro and heat transfer must be presented.

Gas–liquid two-phase stratified flow is often observed in horizontal or slightly inclined systems in a gravity filed (Zhao et al., 2013). This flow pattern is commonly encountered in the petroleum and chemical processing industry, heat exchangers, nuclear reactors, cooling systems, solar energy system and in various heat and mass transfer processes (Adachi, 2013). The fundamental engineering design parameters are the pressure drop, liquid holdup and temperatures.

The numerical calculation of these parameters in stratified wavy gas–liquid receiver flow is often difficult, because

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there is not enough information to describe the wave characteristic of the interface and the interaction between two phases through the wavy and unsteady interface (Akansu, 2006). The main problem of their prediction is related to the modeling of momentum and energy transfer for each phase at the wall and the interface, which are significantly different from the single phase flow (Hassam and Ben, 2014). Over the past few decades, for an isothermal flow, some hydro dynamic numerical studies are available for fully developed stratified flow in pipe (Akansu, 2006; Hassam and Ben, 2014; Akai et al., 1981; Issa, 1998; Line et al., 1996; Lorencez et al., 1997; Shoham and Taitel, 1984; Berthelsen and Ytrehus, 2004; Meknassi et al., 2000; Newton and Behnia, 2001). For non-isothermal flow in a pipe or plane channel, some numerical studies are found (Newton and Behnia, 2000; Berthelsen and Ytrehus, 2005; Gada et al., 2013; Mansoori et al., 2009).

The stratified flow is divided into two main regimes: the stratified smooth (SS) and the stratified wavy (SW) regimes. For the isothermal stratified smooth flow, the two-dimensional numerical simulation in horizontal rectangular ducts has been presented, including Akai et al. (1981), Issa (1998), Line et al. (1996), Lorencez et al. (1997). For two-dimensional stratified smooth flow in pipes, Shoham and Taitel (1984) developed a two-dimensional steady-state momentum equation in the liquid region using bipolar coordinate system, and the turbulent viscosity calculated by a zero equation model. However, the axial momentum equation applied in the study did not include first order viscosity gradient, generating some doubt over the validity of the results. Berthelsen and Ytrehus (2004) studied the fully developed stratified smooth two-phase flow in pipes using the immersed interface method. The level set function was used to describe the interface shape. The grid near the interface and the pipe wall is refined using overlapping grid technology. However, the calculating speed is low, due to the overlapping grid technology.

For the two-dimensional isothermal stratified wavy flow in pipe, Meknassi et al. (2000) extended the work of Line et al. (1996) to a circular pipe, introduced an interfacial roughness to calculate the stratified wavy two-phase flow. The secondary flow was characterized by an anisotropic turbulence model. Newton and Behnia (2001) extended their previous model (Newton and Behnia, 2000) of stratified smooth pipe flow to calculate the interfacial wavy flow, and the gas–liquid interface contains roughness. An empirical shear stress distribution was imposed on the wave interface condition. Berthelsen and Ytrehus (2005) developed a technique including the effect of interfacial waves in gas–liquid stratified flow. The wavy interface is represented by a rough surface and a two-layer turbulence model is introduced to resolve the flow in the vicinity of the wall and the interface, and the distribution of the shear stress is predicted directly.

Furthermore, for two phase non-isothermal stratified flow, Gada et al. (2013) developed analytical and numerical heat transfer solution for two-phase stratified fully-developed flow in a plane channel for without and with phase change under different thermal boundary conditions. However, the simulation is limited for both two-phase laminar flow. It will not apply to gas–liquid stratified flow, because the gas phase is turbulent. To our knowledge, the recently reported working for non-isothermal stratified flow in a circular pipe is limited. Mansoori et al. (2009) solves the two dimensional momentum and energy equations for both phases and accounts, for the effects of turbulence through the use of high Reynolds $k \sim \varepsilon$ two-equation model of turbulence, for fully developed, turbulent, smooth stratified two-phase flow. Very good results were obtained for the pressure drop, liquid height, temperature field compared with experimental data. The interface between gas and liquid is assumed flat and smooth for all time. However, the smooth and planar interface can be obtained only in a limited range of low flow rates. With increasing the relative velocity between the two layers the interface becomes unstable (Ullmann and Brauner, 2006).

From the literature review on numerical simulation of hydro and heat transfer in stratified flow, it is concluded that most of the work is restricted to SS flow regime. Although some studies on hydrodynamic are done for fully-developed SW flow, no work is found for the heat transfer. Furthermore, no numerical study on heat transfer dealing with the effect of interface wavy and configuration in SW flow is found.

The present work is continuation of our previous work on stratified smooth (Duan et al., 2014) to wavy flow with hydro and heat transfer, where the gas–liquid interface contains roughness caused by the presence of waves. Stratified smooth interface condition is difficult to achieve in practice, especially with gas having a high flow rate and liquid having a relatively low viscosity. A model considering the wavy interface stratified flow will be far more practical than the stratified smooth flow under the design conditions. The primary intention of the present study is to develop and coupling solve the two-dimensional steady axial momentum equation and three-dimensional steady heat transfer equation in order to derive temperature variations in pipe flow. For turbulent flow, the eddy viscosity is calculated by a low Reynolds number $k \sim \varepsilon$ model with using special boundary conditions at the waves interface, solves the govern equation by using finite difference method. The wave interface is treated as a rough surface, and the shear friction factor is obtained from the experimental data by calculating a one dimensional momentum balance, for hydro dynamic simulation and it is treated as a heat conducting wall for heat transfer simulation. Furthermore, the interface shape is used to take into account the model. A good prediction of interface shape is important when performing stratified gas–liquid two-phase flow calculations (Gorelik and Brauner, 1999). In conclusion, this model could have important application for optimization of transportation rates and estimation of corrosion in pipeline.