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Numerical Simulation of Unidirectional Stratified Flow by Moving Particle Semi Implicit Method

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Abstract. Numerical simulation of stratified flow of two fluids between two infinite parallel plates using the Moving Particle Semi-implicit (MPS) method is presented. The developing process from entrance to fully development flow is captured. In the simulation, the computational domain is represented by various types of particles. Governing equations are described based on particles and their interactions. Grids are not necessary in any calculation steps of the simulation. The particle number density is implicitly required to be constant to satisfy incompressibility. The weight function is used to describe the interaction between different particles. The particle is considered to constitute the free interface if the particle number density is below a set point. Results for various combinations of density, viscosity, mass flow rates, and distance between the two parallel plates are presented. The proposed procedure is validated using the derived exact solution and the earlier numerical results from the Level-Set method. Furthermore, the evolution of the interface in the developing region is captured and compares well with the derived exact solutions in the developed region.

AMS subject classifications: 76TXX

Key words: Moving particle semi-implicit, liquid-liquid stratified flow, flow developing.

1 Introduction

Stratified two-phase flow is commonly found in petroleum and chemical processing industries where crude oil and water are produced from wells and transported in a pipeline [1–3]. Therefore, it is necessary to understand the flow behavior phenomena of

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liquid-liquid systems. In particular, prediction of the flow characteristics, such as velocity distribution, pressure gradient, and holdup of liquid, are essential for proper design of two-phase flow systems, and have been predicted and measured since the 1930s.

Many empirical correlations based on different flow conditions were developed experimentally. Chenais and Hulin [4] measured water holdup in a 20cm-diameter pipe at mean velocities between 2.7 and 3.5cm/s. The pressure gradient of the liquid-liquid co-current flow in 2.54cm pipes was measured by Angeli and Hewitt [5]. Abduvyat et al. [6] measured pressure drop and liquid holdup of liquid-liquid flow in a horizontal pipe with 4 inch diameter. Some researchers also conducted experimental studies on liquid-liquid systems in various pipes [7–10]. However, the prediction capabilities are generally restricted to the flow conditions on which they are based.

Mathematical modeling provides another method to study the liquid-liquid flow system. Most of previous methods describing the liquid-liquid flow were based on empirical correction such as the correction proposed by Lockhart and Martinelli [11]. In a general case, analytical solution was limited to solving a laminar-laminar two-phase stratified flow based on different interface geometry. The other researchers [12–16] solved the fully developed Navier-Stokes equations and obtained exact solutions which were expressed in the terms of Fourier series or Fourier integrals with constant interface geometry. Brauner et al. [14] developed another model to improve the understanding of laminar-laminar two-phase flow. Hall and Hewitt [17] developed an analytical model to predict liquid-liquid laminar flow in a circular pipe. The exact solutions about holdup of liquid dependent on Martenelli parameter as well as viscosity ratio of the two phases were obtained. For complex problems, such as turbulent-turbulent liquid-liquid flow, accurate solutions can be obtained numerically. Torres-Monzon [3] introduced a two-dimensional model for fully developed, turbulent-turbulent liquid-liquid stratified flow. The velocity profiles of both phases showed an agreement with the experimental data.

Most of the analytical and semi-empirical models can predict and describe the fully developed conditions of two-phase flow. Computational fluid dynamic (CFD) plays an important role in understanding the physics in two-phase flows. Compared with experimental and analytical methods, CFD is simpler, faster and more economical. Khor et al. [18] numerically studied one-dimensional modeling to predict the phase holdups and developed a computer code. Elseth et al. [19] simulated the turbulent stratified liquid-liquid pipe flow using a Volume of Fluid (VOF) model. However, their numerical results cannot compare well with experimental data. Gao et al. [1] improved Elseth's VOF model to compute turbulent smooth-stratified liquid-liquid flow in a horizontal pipe. Surface tension is included in Gao's paper. Yap et al. [20] developed models for uniform stratified flow of two liquids using the Level-Set method. A significant advantage of the level set method is that it may be combined very effectively with anisotropic mesh adaptivity to get very efficient solutions [21, 22]. Razwan [2] numerically simulated stratified liquid-liquid two-phase flow using multiphase volume of fluid model. The velocity distribution and holdup of liquids were compared with experimental data.

The interfacial interaction is a critical factor to predict the flow behavior [23]. The