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Numerical simulation of vapor condensation in gas-water stratified wavy pipe flow with varying interface location

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ABSTRACT

When the natural gas with vapor is flowing in production pipeline, condensation occurs and leads to serious problems such as condensed liquid accumulation, pressure and flow rate fluctuations, and pipeline blockage or corrosion. The motivation is to study phase change of vapor and liquid level change during the condensing process of water-bearing natural gas characterized by coupled hydro-thermal transition and phase change process. A hydro-thermal-mass transfer coupling model is established to investigate the mechanisms and effects of the condensation on the gas-liquid two-phase wavy flow in production pipelines. The bipolar coordinate system is utilized to obtain a rectangular calculation domain. An adaptive meshing method is developed to automatically refine the grid near the wavy gas-liquid interface which is moving continuously. Large eddy simulation model is used to calculate turbulent viscosity. The pressure gradient, liquid holdup, velocity distribution, shear stress and temperature value are predicted and validated. A good agreement is achieved when compared with experimental data. During phase change process, the numerical model is well exploited to investigate mass transfer in pipeline flow. The temperature drop along the pipe leads to the reduction of gas mass flow rate and the rise of liquid level, which results in further pressure drop. Latent heat is released during the vapor condensing process which slows down the temperature drop. Larger temperature drop results in bigger liquid holdup while larger pressure drop causes smaller liquid holdup. The value of velocity with phase change is smaller than that without phase change while the temperature with phase change is higher. The highest temperature locates in gas phase. But near pipe wall the temperature of liquid region is higher than gas region. Thus, the numerical model can be widely applied to predict the pipeline operating parameters and global fluid properties which are essential to the design of downstream equipment and the guarantee of flow assurance.

1. Introduction

At present, the exploration and development of natural gas is oriented towards uninhabited areas like deserts and challenging offshore locations. The combination of dry gas and vapor gathered and transported in pipeline network has its advantage in efficiency and is widely applied in those puzzling gas fields [1,2]. However, there still exist several problems in the pipeline network system that the saturated vapor in gas would condense due to pressure and temperature drop [3,4]. The condensate would attach to the pipe wall as a form of film or droplet [5,6]. The condensation will decrease the effective cross-sectional area and cause the increase of pressure drop which may lead to system shutdown [7,8]. Generally, the condensed water accumulates at the lower parts of the pipeline due to the hilly pipeline route topography, which results in a continuous change of liquid holdup along the pipeline [2,9,10]. The changing liquid holdup and flow area, are bounded to affect the flow patterns which inevitably influence the operating pressure and temperature inversely. Thus, the flow of condensed water and water-bearing gas in production pipelines is a complex process with coupling of hydraulic, thermal, and phase change phenomena [1,7,8,11,12]. Thus, the study of heat and mass transfer mechanisms in pipeline together with the accurate prediction of pressure gradient, velocity, temperature field and water holdup is

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essential to determine the pipe size, design the downstream equipment and guarantee the flow assurance.

Researchers have investigated the gas-liquid two-phase pipe flow system by experiments or hydrodynamic and thermodynamic models. The one-dimensional (1D) two-dimensional (2D) or three-dimensional (3D) stratified gas-liquid two-phase model including mass conversation equation, momentum conversation equation, turbulence model equation, boundary conditions and related auxiliary equations for model closure were applied to describe the flow in pipelines [13]. Differences among them mainly existed in two aspects. On one hand, different turbulence models were built including SAM (Spalart-Allmaras Model) [13,14], $k-\varepsilon$ series model [15,16,17,18,19], $k-\omega$ series model [20], DNS(Direct Numerical Simulation) [21], LES (Large Eddy Simulation) [22], etc. On the other hand, different gas-liquid interface configuration models were built including smooth interface model [16,19,20], wavy interface model [17,18,23,24], curve interface model [25], and double-circle model [26]. The relationship between pressure drop, liquid holdup, velocity distribution, turbulent viscosity, and shear stress has been determined through these formula or methods. The flow pattern and flow regime and even secondary flow have also been discussed under different boundary conditions [27]. However, the energy conservation equation and phase change of fluid components were not taken into consideration in those studies.

Recently, attempts have been made to introduce energy equation into the improved model and the detailed solutions about temperature distribution have also been worked out by considering potential energy, kinetic energy, heat transfer and Joule-Thomson effect [11,28,29,30,31]. Even the phase change models were employed in these models [1,5–12,32,33,34]. Although Equation of State (EOS) was utilized in some previous studies to calculate condensation or evaporation of gas-condensate flow in pipelines [1,5,7,8,9,10,12,32], the flow rate, temperature, pressure were not coupled with varying liquid level. They did not consider the effect of the varying wavy gas-liquid interface on the turbulent flow model, which would lead to different numerical results in their models. Moreover, some 1D models could not present the detailed distribution of hydraulic and thermal parameters at pipe cross section [7,25,35].

To sum up, the early related studies were made on the basis of experiments or establishment of isothermal hydraulic model to calculate the pressure drop and turbulent flow. The recent researches mainly considered the hydraulic and thermal coupling process by virtue of CFD theory to set up 2D or 3D coupling models, where the velocity and temperature distributions were obtained. However, majority of those numerical simulations failed to consider the influence of phase change and mass transfer, especially the varying gas-liquid interfacial location. In practice, the gas-liquid flow in water-bearing natural gas production pipelines is a 3D complex flow process involving hydraulic, thermal factors and phase change behavior which need to be taken into consideration in the further investigation. Meanwhile, the turbulence model and the varying wavy interface should be taken into account.

This paper is aimed at studying gas-liquid two-phase pipe flow through establishing a steady-state 3D non-isothermal gas-liquid two phase stratified flow model including phase change model in bipolar coordinate system, where LES model is utilized to simulate the turbulence flow and the wall attenuation function is used to describe the inadequacy performance of wavy gas-liquid interface. Then the finite difference method is used to solve the model and an adaptive grid meshing method is utilized to discrete the gas and liquid flow regions. After the convergence of velocity, turbulence and temperature field, the total mass flow conservation is used to adjust the pressure drop and the liquid mass flow conservation is applied to restrict the liquid level. In the condition of isothermal flow process without phase change, pressure gradient, liquid holdup, velocity field and shear stress are compared with experimental data to validate the presented hydraulic model. Finally, several examples of non-isothermal flow coupled with phase change in horizontal pipelines are carried out and compared respectively with the ones without phase change.

2. Numerical modeling of stratified gas-liquid wavy pipe flow

2.1. Problem description and model assumptions

Since pressure and temperature drop along the pipeline, the water existed in saturated natural gas in the form of vapor condenses gradually resulting in continuous change of liquid level and accumulation of condensed water at the lower part of pipeline. The flow pattern is likely to change from single saturated gas phase flow to gas-liquid two phase flow. The stratified flow pattern is the most likely to form, in view of the gas-liquid two-phase pipe flow containing the condensate. Normally, for the gas-condensate two-phase flow, slug flow is not likely to form due to the low liquid holdup; annular flow is also not likely to form because the gas flow rate is not particularly high. Thus, a hydraulic and thermal model of stratified gas-liquid two-phase flow coupled with phase change is proposed in this paper. It is significant to calculate the liquid level, the exact position of liquid film and the migration patterns of condensed liquid (as shown in Fig. 1).

Assumptions are made as follows: (1) Precipitation of condensed water is a flash evaporation equilibrium process which occurs in a short moment; (2) Regardless of the attachment to inner wall of the pipe, all the condensed water accumulates at the bottom of the pipe as the water would fall downward in a short time due to the greater gravity than buoyancy; (3)Two phase flow in gas-liquid pipeline has a stratified flow pattern as well as a fully developed flow area in every calculated pipeline segment Δz; (4) Because the gas-liquid interface is notflat but rough, the wavy gas-liquid interface model is adopted to describe the interface shape; (5) The phase change of heavy component of hydrocarbon and gas dissolved in the water are both neglected due to their slight content.

2.2. Coordinate system and governing equations

The non-circular liquid and gas domains in stratified pipe flow, as shown schematically in Fig. 1, are conveniently described with the bipolar coordinate system, which is helpful in solving the problem caused by inhomogeneity of boundaries. "Inhomogeneity of boundaries" means that the boundaries are not body-fitted. Namely, the pipe wall location and the change of interface location are not easy to describe in rectangular coordinate system, because the pipe wall is not a straight line and the shape of the area between the two interfaciallines (before and after the change of interface location) is not rectangular. However, both of the pipe wall location and the interface location are straight lines in bipolar coordinate system. Bipolar cylindrical coordinate is composed of two orthogonal circles in rectangular coordinate, as shown in Fig. 2(a). As the flow field in both phases is bounded by a circular pipe wall and a plane interface, the calculation domain has been converted to rectangle form from the anomalous physical domain by adopting the bipolar coordinate system, seen in Fig. 2(b).

The conversion from Cartesian system to bipolar system can be denoted as follows:

$$\begin{cases} x = a\frac{\sinh\eta}{\cosh\eta-\cos\xi} \\ y = a\frac{\sin\xi}{\cosh\eta-\cos\xi} \\ z = z \end{cases} \quad (1)$$