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Gas-liquid two-phase flow behavior in terrain-inclined pipelines for gathering transport system of wet natural gas

Yan Yang[a], Jingbo Li[a], Shuli Wang[a], Chuang Wen[b,*]

[a] School of Petroleum Engineering, Changzhou University, Zhonglou District, Changzhou, 213016, China
[b] Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, 2800, Kgs. Lyngby, Denmark

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ABSTRACT

The Volume of Fluid method and Re-Normalisation Group (RNG) k-ε turbulence model were employed to predict the gas-liquid two-phase flow in a terrain-inclined pipeline with deposited liquids. The simulation was carried out in a 22.5 m terrain-inclined pipeline with a 150 mm internal diameter. The flow parameters were numerically analyzed in detail including the phase distribution in pipes, the velocity and pressure around the elbow, the liquid flow rate and liquid holdup in different cross-section and the volume of liquid outflow. The numerical results presented that a wave crest formed on the liquid level under the suction force which caused by the negative pressure around the elbow, and then it touched to the top of the pipe. When the liquid blocked the pipe, the pressure drop between the upstream and downstream of the elbow increased with the increase of the gas velocity. At larger gas velocity, more liquid was carried out of the pipeline. The liquid periodically flowed and returned along the uphill section when the liquid was no longer flowing out of the pipeline.

1. Introduction

During the development of condensate natural gas fields, such as the Puguang Gas Field in China's Sichuan Basin, there are many uphill and downhill pipes due to the large rolling terrain. The liquid often accumulates in the low section of the pipeline during the wet natural gas transportation. The deposited liquid may block the pipeline under the action of the gaseous phase and cause the sharp fluctuation of pressure [1]. It affects the normal operation of the pipeline, even damages the conveying equipment. In addition, the pipeline is more easily subjected to the corrosion issues [2,3], because the deposited liquid is difficult to be removed. Therefore, it is significant to study the flow behavior of the deposited liquid in the wet natural gas pipelines.

The gas-liquid two-phase flows in the horizontal and inclined pipes have been studied for decades. Taitel et al. [4] proposed a model to calculate the flow behavior under the transient flow conditions in a hilly-terrain pipeline system. The model was applied to the low liquid and gas flow rates, where the frictional pressure losses could be neglected. Grolman and Fortuin [5] modified the apparent rough surface model to predict the pressure gradient and liquid holdup in slightly inclined pipes. Salhi et al. [6] improved the one-dimensional two-fluid model to study the stability of stratified gas–liquid two-phase flows in an inclined pipe. Goldstein et al. [7] proposed the exact solutions for the laminar stratified flows in the inclined pipes. The solution could be used for investigating the influence of the pipe inclination and flow geometry on the liquid holdup and pressure gradient. Gawas et al. [8] proposed a new wave celerity correlation for the gas-liquid two-phase stratified flow using the low viscosity fluids and compared with a mechanistic model proposed by Watson. The Poisson probability theory was employed to predict the slug frequency in the gas-liquid horizontal pipelines [9]. The results indicated that the theoretical model resulted in a great improvement with the average error of 15% for 1.2 m/s and 0.4 m/s superficial liquid velocities. Ferrari et al. [10] developed a novel two-fluid model to capture the slug flow in pipes using a one-dimensional transient hyperbolic five-equation. This theoretical model successfully captured the slug onset, growing, and development from a stratified flow in horizontal pipes.

Barnea and Shoham [11] carried out an experimental study in an air-water system with 2.55 cm and 1.95 cm pipes and compared with the theoretical prediction of Taitel and Dukler. The results showed that the experiment data agreed with the theoretical prediction. Tzotzi and Andritsos [12] gave a modified form of Andritsos-Hanratty model to study stratified gas–liquid two-phase flow and estimate pressure drop and interfacial friction factor in a horizontal pipe. Jia et al. [13] used two absolute pressure sensors to measure differential pressure and obtained the void fraction from differential pressure model in a horizontal gas-liquid two-phase pipe. Arunkumar et al. [14] used the dielectric sensors to identify the gas-liquid two-phase flow regime. The bubbly,

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[*] Corresponding author.
E-mail address: cwen@mek.dtu.dk (C. Wen).

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slug and stratified flow regimes could be identified in their experiments. Abdulkadir et al. [15] investigated the unsteady hydrodynamic behavior of slug flow in a horizontal pipe using the an air–silicone oil mixture as the working fluid. Their results showed that the drift velocity component of the bubbles in horizontal pipes far exceeds the value found for vertical riser pipes. Dinaryanto et al. [16] experimentally studied the initiation and flow development mechanisms of the gas-liquid two-phase slug flow in a horizontal pipe. The initiation frequency of slug flow and the evolution of passing slug frequency along the pipeline were also observed by using two high-speed video cameras in their experiments. Bouyahiaoui et al. [17] employed intermediary of the conductance probe technique to study the slug flow behavior in the vertical downward air-water two-phase pipelines. The experimental results showed that the mean averaged void fraction increased with the gas superficial velocity.

The numerical approach was employed to predict the flow regime and flow characteristics of gas-liquid two-phase flows. Mouza et al. [18] used the computational fluid dynamics (CFD) modeling to simulate the wave stratified two-phase flow in a horizontal pipe. The distribution of the shear stresses and the velocity profiles of both phases were calculated by using the CFD modeling. Loilier [19] applied the two-fluid model to simulate the gas-liquid two-phase flow in vertical and terrain-inclined pipelines consisting of the uphill, downhill and horizontal sections. The vertical bubble flow, stratified and terrain-inclined slug flows were simulated and the avoid fraction, slug frequency, slug length and other parameters were obtained in this work. Ekambara et al. [20] performed a numerical study of the bubbly two-phase flow in a horizontal pipeline. The numerical results agreed well with the experimental data. Vallée et al. [21] investigated the stratified and slug flow by using the CFD modeling, particle image velocimetry and high-speed video observation experiments. The main flow characteristics obtained by the CFD modeling were successfully validated against the experiments. Verdin et al. [22] used the CFD modeling for simulating the transport behavior of water droplets in 38 in. diameter pipes and compared the oil flow behavior and droplets with that of water. Santim et al. [23] compared different methodologies in transient isothermal gas-liquid two-phase slug flows in a horizontal pipeline. The comparison studies indicated that the Drift-Flux Model presented the better agreement with the pressure wave velocity by the experiments. Wang et al. [24] developed a fluid-structure interaction dynamic model for the conveying severe slugging flow in a pipeline-riser system. Their results showed that the dynamic response of the riser is closely related to the characteristics of severe slugging, which can be used to eliminate severe slugging phenomenon to improve the stability of the riser system.

The gas-liquid two-phase flows in horizontal and vertical pipelines attract a great many of experimental and numerical studies, while the flow mechanism of the gathering liquids in the elbow of hilly-terrain pipes is still not understood very well. The purpose of this work is to study the gas-liquid two-phase flow in the terrain-inclined pipelines to obtain local and global flow characteristics using the CFD modeling, which can provide the detailed information for removing the deposited liquid effectively and correspondingly can protect natural gas pipeline and equipment. The Volume of Fluid (VOF) method and Re-Normalisation Group (RNG) k-ε turbulence model are used to predict the deposited liquid motion under the action of the gaseous phase in the terrain-inclined pipeline system including an uphill section and a downhill section. The flow parameters are analyzed in detail, including the velocity and pressure distribution, phase fraction and cross-section liquid holdup.

2. Terrain-inclined pipelines

The terrain-inclined pipeline is employed for our current studies, which contains a downhill section and an uphill part. The inclination angles of downhill and uphill segments are both assigned to be 5°. It is assumed that a certain amount of liquids is gathering at the bottom of the inclined pipeline system, as shown in Fig. 1. The three-dimensional geometry of terrain-inclined pipeline is established for the computational domain, including the pipe diameter of $D = 150$ mm and the length of every section is 75 D, which ensures a fully developed flow for this terrain-inclined pipeline system.

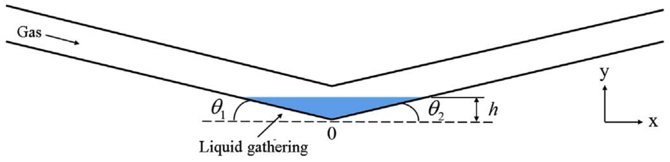

Fig. 1. Terrain-inclined pipelines.

The flow data for the gas-liquid two-phase is presented in Table 1, obtained from Puguang gas field in Sichuan Basin of China. The working fluids are methane and water, respectively. In this case, the solubility of methane in water can be neglected, and we, therefore, assume that the water and methane are the immiscible fluids in the numerical studies.

3. Computational methods

3.1. Governing equations

The gas-liquid two-phase flow in the terrain-inclined pipeline represents a distinct phase interface. The interface catching is a key issue for our simulation of this kind of flow behavior. The VOF model [25] uses the surface-tracking technology based on the fixed Eulerian mesh, which can be employed to model two or more immiscible fluids. Therefore, we utilize the VOF model here to track the gas-liquid phase interface in the terrain-inclined pipelines.

The continuity equation is as follows [26]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

The momentum equation [27] is solved throughout the computational domain, and the velocity field is shared among all the phases.

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla\cdot(\rho \vec{u}\vec{u}) = -\nabla p + \nabla\cdot[\mu(\nabla\vec{u} + \nabla\vec{u}^{T})] + \rho\vec{g} + \vec{F} \tag{2}$$

where ρ is the density, u is the velocity, p is the static pressure, μ is the dynamic viscosity, $\rho\vec{g}$ is the gravitational body force and $\vec{F}$ is external body force.

For the gas-liquid two-phase flow, the ρ and μ in each computational cell are given by the following equations:

$$\rho = \alpha_2\rho_2 + (1-\alpha_2)\rho_1 \tag{3}$$

$$\mu = \alpha_2\mu_2 + (1-\alpha_2)\mu_1 \tag{4}$$

The volume fraction of each phase in each grid cell is calculated throughout the domain. The interface between two phases is tracked by solving the continuity equation for the volume fraction of one (or more) phases. The volume fraction equation is as follows [28]:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q\rho_q) + \nabla\cdot(\alpha_q\rho_q u_q) = \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})\right] \tag{5}$$

where $\dot{m}_{pq}$ is the mass transfer from phase q to phase p and $\dot{m}_{qp}$ is the mass transfer from phase p to phase q, α_q is the volume fraction of phase q.

The primary phase volume fraction is solved based on the following constraint:

$$\sum_{q=1}^{n}\alpha_q = 1 \tag{6}$$