Experimental and numerical investigation on transient liquid velocity in hilly-terrain wet natural gas pipelines

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Abstract. In the present work, the transient liquid velocity in hilly-terrain pipelines is experimentally and numerically investigated through ultrasonic Doppler technique and CLSVOF method. An ultrasonic transducer mounted on upward inclined pipeline is employed for transient liquid velocity measurement, and the results agree well with simulations. It is found that the slug flow is only presented in the inclined pipeline. The superficial gas and liquid velocity has a significant influence on the slug frequency while it has a slight influence on the slug translational velocity.

1. Introduction

The gas gathering pipelines between well sites, gas gathering stations and natural gas processing facilities can be divided into wet and gas pipelines. In most wet-gas pipelines, small amount of free water and condensate, resulting from pressure and temperature decrease, leads to the formation of a two-phase flow [1, 2, and 3]. Natural gas resources in China are mostly located in basins surround by mountains. Due to the terrain effect, the two phase flow is prone to liquid accumulation and slug flow with a low flow rate, which cause severe liquid holdup and pressure fluctuation and flow-dependent corrosion [4]. Therefore, it is important to understand and predict the slug flow behavior in a hilly-terrain pipeline [5].

Ultrasonic Doppler velocimetry (UDV), a non-invasion flow field measurement method with the advantage of high precision and flexibility, has been used to measure flow velocity in some studies. Takeda [6] extended the application range of UDV method to general fluids for the first time, which was originally applied in the medical diagnosis. Treenuson [7] used the ultrasonic velocity profile method for flow rate measurement in the downstream of double bent pipe. Fachun Liang [8] measured the velocity profile of the liquid film using the UDV in a gas-liquid swirling flow.

A coupled Level Set and volume of fluid method (CLSVOF) [9] has been employed for two phase flow simulation in recent years. Kharangate [10] simulated the annular flow behavior of a condensation system in a vertical pipeline using the CLSVOF method. Shang [11] used the CLSVOF method in the transition of two-phase flows in a vertical pipeline through validation of single bubble cases.

In this work, ultrasound Doppler measurement and CLSVOF simulation are conducted for the research of transient liquid flow velocity in a hilly-terrain wet gas pipeline. A multiphase flow experimental loop with an inside diameter of 40 mm is employed, and a three-dimensional numerical
model is simultaneously carried out, which is verified through comparison with the experimental results. The researches on the transient velocity characteristic of liquid slug and liquid film contribute to the improvement of theoretical model and numerical simulation.

2. Experimental apparatus

2.1. Multiphase flow loop

A schematic of the multiphase flow loop is presented in Fig. 1. The inner diameter of the pipe is 40mm. Air and water are employed as the experimental medium. The energy of fluids is supplied from a screw compressor and a centrifugal pump. The gas and liquid phase are separately measured in the measuring section, and are mixed through a three-way mixture tee. At the end of the pipeline, the fluid enters a cyclone separator where air and water are separated. The air is vented to the atmosphere, while the water flows back to storage tank. The superficial gas velocity range is 1.985m/s-10.076m/s, and the superficial liquid velocity range is 0.0204m/s-0.1003m/s.

The test section consists of three parts: three sections of horizontal pipe, one ascending pipe and one descending pipe, which are made of polymethyl methacrylate (PMMA). Since slug flow is only presented in the upward inclined pipeline, an ultrasonic transducer is installed on the position of 1.5 m from the elbow, as shown in Fig.2. The trace particles made of copolyamide have a diameter of 75 μm and a concentration from 100 to 1000 ppm.
2.2. Ultrasonic Doppler velocimetry

The working principle of Ultrasound Doppler Velocimetry is to detect and process many ultrasonic echoes issued from pulses reflected by micro particles contained in a flowing liquid. The measurement time lapse between the emission of ultrasonic bursts and the reception of the pulse gives the position of particles. By measuring the Doppler frequency in the echo as a function of time shifts of these particles, a velocity profile after few ultrasonic emissions is obtained.

The velocity of the particles is given as follows:

\[ u_{\text{real}} = \frac{c f_d}{2 f_e \cos \beta} \]  

(1)

Where, \( u_{\text{real}} \) is the velocity of the particles. \( c \) is the sound velocity of the ultrasonic wave in fluid medium. \( f_d \) is the phase shift of the received echo. \( f_e \) is the emitting frequency. \( \beta \) is the installation angle of ultrasonic transducer.

![Figure 2. Photograph of testing pipeline.](image)

**Figure 2.** Photograph of testing pipeline.

![Figure 3. Velocity measurement principle of UDV.](image)

**Figure 3.** Velocity measurement principle of UDV.
3. CFD simulation

3.1. Geometry model
The geometry model of the simulation is shown in Fig. 4. The slope of the inclined pipeline is $10^\circ$, and the inner diameter is 40 mm. The pipeline lengths are noticed in the figure. The radian in the junction of the horizontal and inclined sections is $5D$.

![Figure 4. Geometry of simulation domain.](image)

3.2. Multiphase flow model
A coupled Level Set and volume of fluid method (CLSVOF) approach is applied for multiphase flow simulation in this work. The governing equations are as follows:

**Continuity:**

$$\nabla \cdot \vec{u} = 0$$

(2)

Where, $\vec{u}$ is the underlying velocity field.

The evolution of the level-set function:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\vec{u} \phi) = 0$$

(3)

Where, $\phi$ is the level-set function, defined as a signed distance to the interface. $t$ is the dimensionless time.

**Momentum:**

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\frac{\nabla p}{\rho} + \frac{1}{\rho} \nabla \cdot (2\mu \nabla D) + \frac{1}{\rho} \sigma \kappa \delta(\phi) \nabla \phi$$

(4)

Where, Continuity:

$$\delta(\phi) = \begin{cases} 1 + \cos\left(\frac{\pi \phi}{a}\right) & |\phi| < a, \ a = 1.5 \ h \\ \frac{2a}{a} & |\phi| \geq a \end{cases}$$

(5)

Where, $p$ is the total pressure. $g$ is the gravitational acceleration. $\sigma$ is the surface tension coefficient. $\kappa$ is local mean curvature, $\kappa = \nabla \cdot \left(\frac{\nabla \phi}{|\nabla \phi|}\right)$. $D$ is the rate of deformation tensor, $D = \nabla \vec{v} + \left(\nabla \vec{v}\right)^T$. $h$ is the grid spacing. $\rho$ and $\mu$ are the density and viscosity, which are written as:
\[ \rho = \delta (\varphi) \rho_l + (1 - \delta (\varphi)) \rho_g \quad \text{And} \quad \mu = \delta (\varphi) \mu_l + (1 - \delta (\varphi)) \mu_g \quad (6) \]

Where, the subscript \( l \) and \( g \) represent the liquid phase and the gas phase respectively.

### 3.3. Realized k-ε model

The realized k-ε model has been used to deal with the turbulent effect. The transport equations of turbulent kinetic energy \( k \) and dissipation rate \( \varepsilon \) are as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k v_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M \quad (7)
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon v_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_f E \varepsilon - \frac{\rho C_{\varepsilon} \varepsilon^2}{k + \sqrt{\varepsilon}} + C_{\varepsilon} E \frac{\varepsilon}{k} C_{\varepsilon} G_b \quad (8)
\]

\[
C_f = \max \left( 0.43, \frac{\eta}{\eta + 5} \right), \quad \eta = \left( 2 E_{ij} \cdot E_{ij} \right)^{1/2} \frac{k}{\varepsilon}, \quad E_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \quad (9)
\]

Where, \( v_i \) is the velocity in the \( i \) direction. \( \mu_t \) is the turbulent viscosity. \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl numbers of \( k \) and \( \varepsilon \). \( G_k \) is the generation of turbulence kinetic energy due to the mean velocity gradients. \( G_b \) is the generation of turbulence kinetic energy due to buoyancy. \( Y_M \) is the contribution of the fluctuating dilatation in compressible turbulence. \( C_2, C_{\varepsilon}, C_{\varepsilon} \) are constants.

### 3.4. Mesh generation

A computational grid with 560,000 hexahedral cells is built through the pre-processor ICEM-CFD, and the meshing quality of the cross and elbow sections is shown in Fig. 5. The cross section includes 1045 elements, and boundary layer and elbow meshes are added to guarantee the capture of complex flow behavior around the boundary.

![Figure 5. Mesh quality.](image)

### 4. Results and discussion

The transient liquid velocity can present the character of velocity change for liquid film, liquid slug and their correlation in the ascending pipe. Considering the requirement of liquid phase continuity, the dynamic characteristics of liquid flow velocity at measuring point which is 5 mm from the bottom of
the pipe inner wall on the pipe centerline that is perpendicular to the pipe flow is studied. The velocity simulation values at the experimental measuring point were processed with the FLUENT post-processing software. The comparison of the experiment and simulation is shown in Fig. 6. The simulation results agree well with the experiments.

The variation of transient liquid velocity is similar regardless of the different gas and liquid velocity in this study. Due to the entrainment effect of gas and liquid, the liquid velocity suddenly increases to its peak when the fronts of the liquid slugs reach the measuring point, and then decrease gradually owing to the slug body and liquid film throughout.

At the superficial gas velocity of 1.985 m/s, as the superficial liquid velocity raises, the liquid volume in the elbow and upward pipeline increases, which lead to a higher slug frequency. Owing to the inertia effect of the liquid phase, the peak velocity has a little change. The liquid slugs with a low peak velocity increase, and it is prone to dissipate and cause serious backflow in the inclined pipeline. At the superficial liquid velocity of 0.0204m/s, as the superficial gas velocity raises, the enhancement of liquid-carrying cause the decrease of slug frequency. The peak value of liquid velocity has small variations since a pseudo slug is formed in the pipeline.
5. Conclusion
The simulation model shows a reliable prediction of transient liquid velocity behavior in hilly-terrain wet gas pipelines.

The slug frequency increases with the increase of superficial liquid velocity, and decreases with the increase of superficial gas velocity. The peak value of liquid velocity, namely the translational velocity of slug flow, changes little in the research range.

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