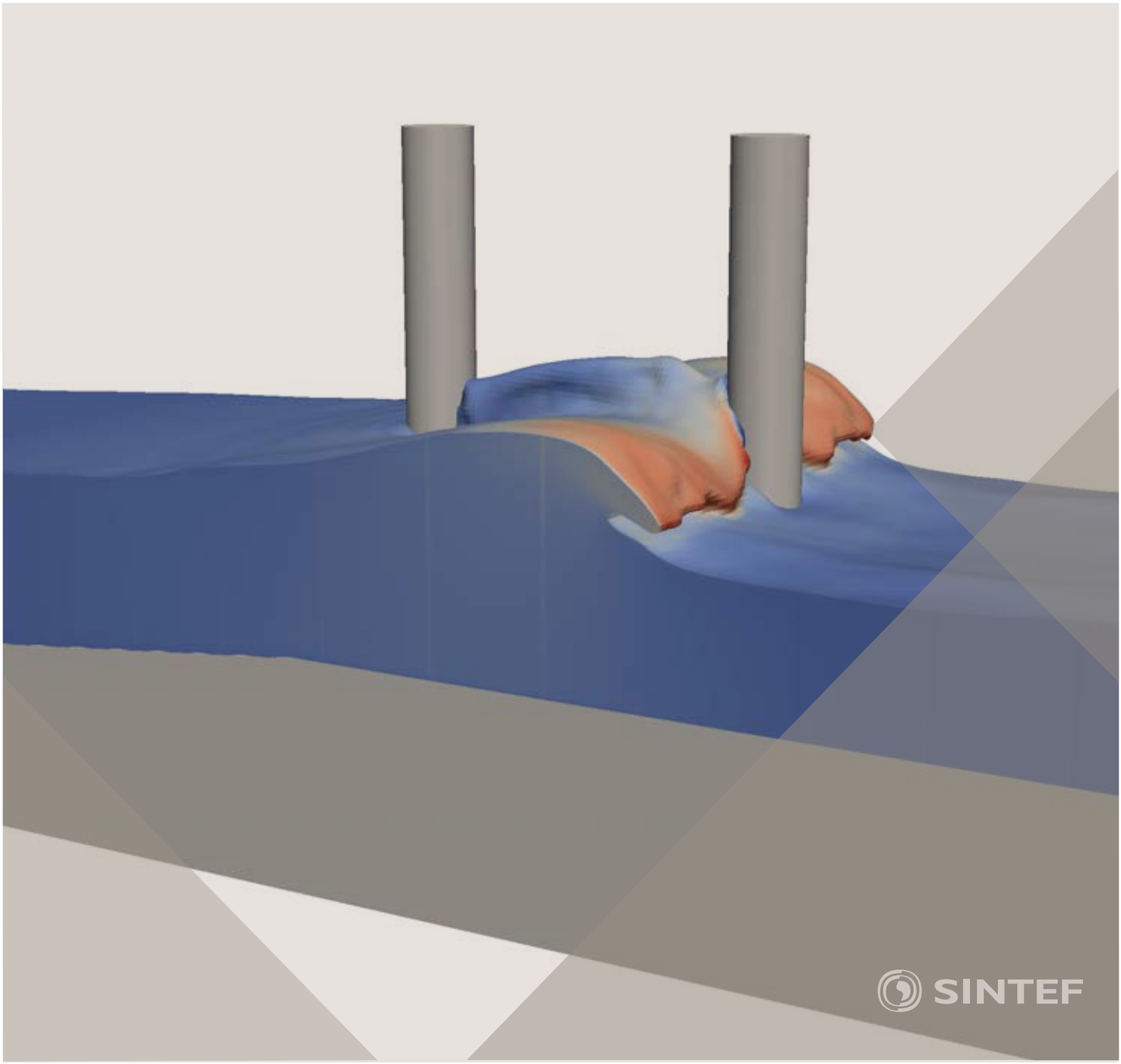
SINTEF
PROCEEDINGS
2

Proceedings of the 12th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries

Progress in Applied CFD – CFD2017



SINTEF Proceedings

Editors:
Jan Erik Olsen and Stein Tore Johansen

Progress in Applied CFD – CFD2017

Proceedings of the 12th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries

SINTEF Academic Press

SINTEF Proceedings no 2
Editors: Jan Erik Olsen and Stein Tore Johansen
Progress in Applied CFD – CFD2017
Selected papers from 10th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries

Key words:
CFD, Flow, Modelling

Cover, illustration: Arun Kamath

ISSN 2387-4295 (online)
ISBN 978-82-536-1544-8 (pdf)

SINTEF Academic Press
Address: Forskningsveien 3 B
PO Box 124 Blindern
N-0314 OSLO
Tel: +47 73 59 30 00
Fax: +47 22 96 55 08

www.sintef.no/byggforsk
www.sintefbok.no

SINTEF Proceedings
SINTEF Proceedings is a serial publication for peer-reviewed conference proceedings on a variety of scientific topics.
The processes of peer-reviewing of papers published in SINTEF Proceedings are administered by the conference organizers and proceedings editors. Detailed procedures will vary according to custom and practice in each scientific community.

PREFACE

This book contains all manuscripts approved by the reviewers and the organizing committee of the 12th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries. The conference was hosted by SINTEF in Trondheim in May/June 2017 and is also known as CFD2017 for short. The conference series was initiated by CSIRO and Phil Schwarz in 1997. So far the conference has been alternating between CSIRO in Melbourne and SINTEF in Trondheim. The conferences focuses on the application of CFD in the oil and gas industries, metal production, mineral processing, power generation, chemicals and other process industries. In addition pragmatic modelling concepts and bio-mechanical applications have become an important part of the conference. The papers in this book demonstrate the current progress in applied CFD.

The conference papers undergo a review process involving two experts. Only papers accepted by the reviewers are included in the proceedings. 108 contributions were presented at the conference together with six keynote presentations. A majority of these contributions are presented by their manuscript in this collection (a few were granted to present without an accompanying manuscript).

The organizing committee would like to thank everyone who has helped with review of manuscripts, all those who helped to promote the conference and all authors who have submitted scientific contributions. We are also grateful for the support from the conference sponsors: ANSYS, SFI Metal Production and NanoSim.

Stein Tore Johansen & Jan Erik Olsen

Organizing committee:

Conference chairman: Prof. Stein Tore Johansen
Conference coordinator: Dr. Jan Erik Olsen
Dr. Bernhard Müller
Dr.Sigrid Karstad Dahl
Dr.Shahriar Amini
Dr.Ernst Meese
Dr.Josip Zoric
Dr.Jannike Solsvik
Dr.Peter Witt

Scientific committee:

Stein Tore Johansen, SINTEF/NTNU
Bernhard Müller, NTNU
Phil Schwarz, CSIRO
Akio Tomiyama, Kobe University
Hans Kuipers, Eindhoven University of Technology
Jinghai Li, Chinese Academy of Science
Markus Braun, Ansys
Simon Lo, CD-adapco
Patrick Segers, Universiteit Gent
Jiyuan Tu, RMIT
Jos Derksen, University of Aberdeen
Dmitry Eskin, Schlumberger-Doll Research
Pär Jönsson, KTH
Stefan Pirker, Johannes Kepler University
Josip Zoric, SINTEF

CONTENTS

GAS-LIQUID TWO-PHASE FLOW BEHAVIOR IN TERRAIN-INCLINED PIPELINES FOR WET NATURAL GAS TRANSPORTATION

Yan Yang[1], Jingbo Li[1], Shuli Wang[1], Chuang Wen[2]*

[1] School of Petroleum Engineering, Changzhou University 213016 Changzhou, CHINA

[2] Department of Mechanical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, DENMARK

* E-mail: cwen@mek.dtu.dk

ABSTRACT

The liquid slug formation in a hilly-terrain pipeline is simulated using the Volume of Fluid model and RNG k-ε turbulence model. The numerical model is validated by the experimental data of the horizontal slug flow. The influence of pipe diameter on liquid slug formation is discussed in detail. The results show that the pipe is blocked by the liquid slug at the moment of slug formed. The pipe pressure suddenly increases, and then decreases gradually in the process of liquid slug formation and motion. The pipe diameter has little effect on liquid slug formation, while the pipe pressure drop and liquid holdup change small.

Keywords: gas-liquid two-phase flow, CFD, natural gas, pipe flow.

NOMENCLATURE

A complete list of symbols used, with dimensions, is required.

Greek Symbols

α Volume fraction, [-].
α_k Constant, [-].
α_ε Constant, [-].
β Constant, [-].
ε Turbulent dissipation rate, [-].
δ_{ij} Kronecker delta, [-].
μ Dynamic viscosity, [m^2s^{-1}].
μ_t Turbulent viscosity, [m^2s^{-1}].
η_0 Constant, [-].
ρ Density, [kgm^{-3}].
θ Inclination angle of pipe, [°].
θ_1 Inclination angle of descending pipe, [°].
θ_2 Inclination angle of ascending pipe, [°].

Latin Symbols

$C_{1\varepsilon}$ Constant, [-].
$C^*_{1\varepsilon}$ Constant, [-].
$C_{2\varepsilon}$ Constant, [-].
C_μ Constant, [-].
D Pipe diameter, [mm].
E_{ij} Mean strain rate, [-].
$\vec{F}$ External body force, [N].
F_{vol} Surface force, [N].
G_k Generation of turbulence kinetic energy, [-].
g Acceleration of gravity, [m/s^2].
h Level of stagnant liquid, [mm].
k Turbulent kinetic energy, [m^2s^{-2}].
L Pipeline length [m].
$\dot{m}_{pq}$ Mass transfer from phase p to phase q, [kgs^{-1}].
$\dot{m}_{qp}$ Mass transfer from phase q to phase p, [kgs^{-1}].
p Pressure, [Pa].
Q Volume of pipe, [m^3s^{-1}].
Q_L Volume of stagnant liquid, [m^3s^{-1}].
S_{aq} Source term, [-].
t Time, [s].
$\boldsymbol{u}$ Velocity, [ms^{-1}].
$\boldsymbol{V_G}$ Inlet gas velocity [ms^{-1}].
$\boldsymbol{V_{SL}}$ Superficial liquid velocity [ms^{-1}].
$\boldsymbol{V_{SG}}$ Superficial gas velocity [ms^{-1}].

Sub/superscripts

G Gas.
L Liquid.
i Index *i*.
j Index *j*.

INTRODUCTION

Natural gas field usually locates in hilly or basin region, and then the hilly-terrain pipelines are used inevitably. The water in wet gas can assemble in the low-lying pipes, and becomes stagnant liquid in the process of transporting wet gas. It leads to the formation of the liquid slug or the slug flow which can cause the shapely pressure and liquid holdup fluctuation in the pipeline. Therefore, it is important to study and predict the slug flow in the hilly-terrain pipelines.

For the slug flow, the study mainly focuses on the horizontal pipe, vertical pipe and hilly-terrain pipes. For the horizontal pipelines, a prediction method based on one-dimensional two-fluid model was presented for

predicting hydrodynamic slug initiation and growth by Issa and Kempf (2003). Al-Safran et al. (2015) proposed a new empirical relationship for predicting slug liquid holdup in high viscosity liquids. For the studies of a slug in the vertical pipelines, Taha and Cui (2006) used the Volume of Fluid (VOF) model to simulate the motion of a single Taylor bubble in the vertical tubes and obtained the shape and flow parameters of the slug. Abdulkadir et al. (2015) conducted the experimental and numerical studies in the vertical pipes with 6 m long and 0.067 m internal diameter. Henau and Raithby (1995) investigated the slug behavior in two-phase pipes which contained several uphill and downhill sections. Ersoy et al. (2011) investigated gas-oil-water three-phase slug flow in hilly-terrain pipelines.

The gas-liquid slug flow attracts attention all the time. However, the formation and motion of a single liquid slug still needs to be further studied in hilly-terrain pipelines, in particular the existence of the stagnant liquids. In this paper, the numerical study is carried out to understand the formation process of a single liquid slug in hilly-terrain pipelines. The influence of pipe diameter on liquid slug formation is analysed in detail.

MODEL DESCRIPTION

The slug flow is a sort of complex gas-liquid flow which has a distinct phase interface. The interface catching is a key step for the simulation of the liquid slug. The Volume of Fluid (VOF) model is a kind of surface-tracking technology based on fixed Eulerian mesh and it can be used for modelling two or more immiscible fluids. Therefore, the VOF model is employed here to track the gas-liquid phase interface in hilly-terrain pipelines. In addition, the turbulence model is necessary due to the flow is turbulent in our simulation.

Governing Equation

Continuity equation

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

Momentum equation

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

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

Volume fraction equation

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(a_q\rho_q)+\nabla\cdot(a_q\rho_q\bar{v}_q)=S_{a_q}+\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})\right] \tag{3}$$

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, S_{α_q} is the source term.

Continuum Surface Force Model

The effect of surface force along the interface is included in the VOF model. The continuum surface force (CSF) model proposed by Brackbill et al (1992) is used in this paper. It is implemented as a source term in the momentum equation. The surface force F_{vol} is expressed as follows:

$$F_{vol}=\sigma_{ij}\frac{\rho\kappa_i\nabla\alpha_i}{\frac{1}{2}\left(\rho_i+\rho_j\right)} \tag{4}$$

where

$$\rho=\alpha_2\rho_2+(1-\alpha_2)\rho_1 \tag{5}$$

$$\kappa=\nabla\cdot\hat{n} \tag{6}$$

$$\hat{n}=\frac{n}{|n|} \tag{7}$$

$$n=\nabla\alpha_q \tag{8}$$

Turbulence Model

The RNG k-ε turbulence model has an additional term in its ε equation that significantly improves the accuracy for rapidly strained flows. It also provides an option to account for the effects of swirl or rotation by modifying the turbulent viscosity appropriately. Therefore, the RNG k-ε turbulence model is employed here because the flow turns at the elbow of the pipe which connects the uphill section and downhill section in hilly-terrain pipelines. The turbulence kinetic energy, k, and its rate of dissipation, ε, are as follows:

$$\begin{aligned}&\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}\\&=\frac{\partial}{\partial x_j}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right]+G_k+\rho\varepsilon\end{aligned} \tag{9}$$

$$\begin{aligned}&\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}\\&=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right]+\frac{C_{1\varepsilon}^{*}\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}\end{aligned} \tag{10}$$

where

$$\mu_{eff}=\mu+\mu_t \tag{11}$$

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{12}$$

$$C_{1\varepsilon}^{*}=C_{1\varepsilon}-\frac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3} \tag{13}$$

$$\eta=(2E_{ij}\cdot E_{ij})^{1/2}\frac{k}{\varepsilon} \tag{14}$$

$$E_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{15}$$

where C_μ=0.0845, α_k=α_ε=1.39, $C_{1\varepsilon}$=1.42, $C_{2\varepsilon}$=1.68, η_0=4.377, β=0.012.

GEOMETRY AND MESH

The sketch of hilly-terrain pipeline is shown in Figure 1. This pipeline contains a descending pipe and an ascending pipe, respectively. The inclination angles of two pipes are θ_1 and θ_2. The stagnant liquid is water and the gas phase is methane. Two pressure monitoring points (P1 and P2) are set at the center of the pipe cross section which locates in x = -15 D and x = 15 D. The pipe pressure drop is the value of $|P1-P2|$ in this paper.

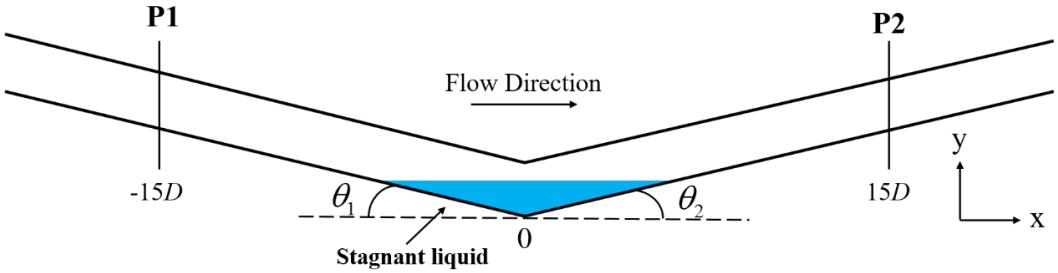


Figure 1 Sketch of the hilly-terrain pipeline

The computational domain should be meshed after the geometric model is established. The commercial software ANSYS ICEM CFD is selected as the meshing tool. The hexahedral mesh and O-block technology are selected as the grid partition strategy for improving the quality of grid. The grid system is shown in Figure 2. Around 300 000 cells are performed for our simulations after the grid independence test.

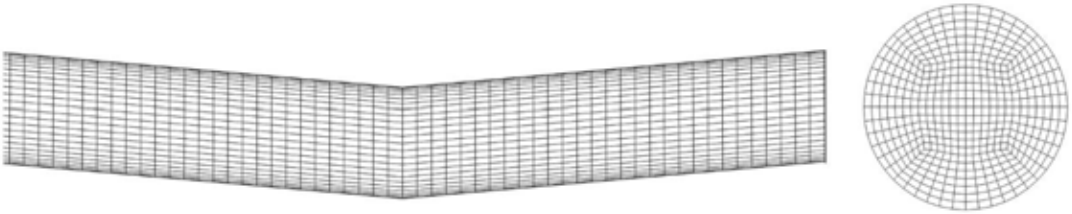


Figure 2 Mesh generation

RESULTS AND DISCUSSION

Model Validation

In this paper the experimental data obtained by Heywood and Richardson (1979) are employed to validate our numerical method. The experiments were carried out in an air-water flow loop system, which included a horizontal pipeline of 42 mm inner diameter. The γ-ray absorption method was used to measure the slug liquid holdup (liquid volume fraction). Six experimental data in the same superficial liquid velocity (0.978 m/s) were selected for the model validation in different superficial gas velocities. The results of the comparison between the experimental and numerical data are shown in Figure 3. It presents that the maximum relative error is 5.9% in superficial gas velocity of 4.145 m/s. Therefore, the numerical results are in good agreement with the experimental data.

Liquid Slug Formation Process

Figure 4 shows the formation process of a liquid slug in the 150 mm diameter pipe with the inclination angle of $\theta_2 = \theta_2 = 5°$. The inlet gas velocity is 6.5 m/s, and the ratio of the stagnant liquid height, h, to the pipe diameter is 0.75 (h/D=0.75). The phase fraction distribution with different moment (t) is described in the contours. The blue region represents the gas phase, while the red one represents the liquid phase. The axis, x is the position coordinates of pipe along the flow direction.

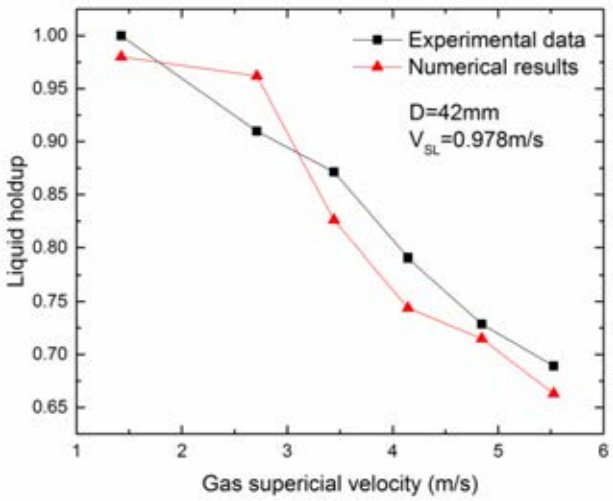


Figure 3 Comparison between exprimental and numerical results in a horizontal pipe

The flow area decreases due to the stagnant liquid accumulated at the bottom of hilly-terrain pipes, which cause the increase of the gas velocity. This flow structure further induces the decline of the pressure above the liquid level. Then suction force generates in the vertical upward, which destroys the stability of gas-liquid interface. For this reason, a wave crest forms. When the liquid level uplifts to the top of the pipe and

blocks the entire pipe cross section, the liquid slug flow finally appears (t=0.005 s -0.100 s in Figure 4). The liquid slug then goes into the next process of moving forward under the pressure difference between the upstream and downstream of the slug flow (t=0.105-0.120 s in Figure 4).

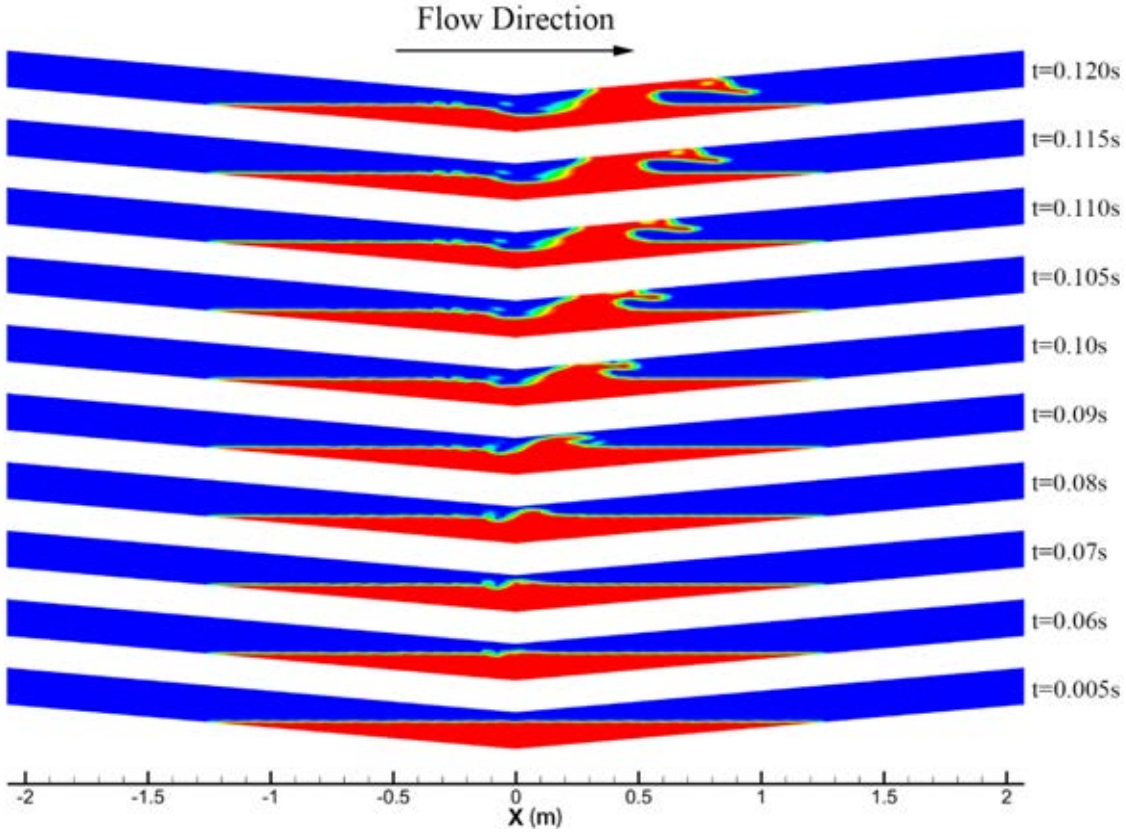


Figure 4 Formation process of a liquid slug

Pipe Diameter Effect

In this section, the influence of the pipe diameter on the formation of a liquid slug is discussed in detail. The pipe diameters are 90 mm, 120 mm, 150 mm, 180 mm and 210 mm, respectively. The length of the ascending and descending pipes is 50 D, while the inclination angle is set to be 5°. The numerical simulation is implemented in the identical condition which the inlet gas velocity is 6.5 m/s with h/D=0.75.

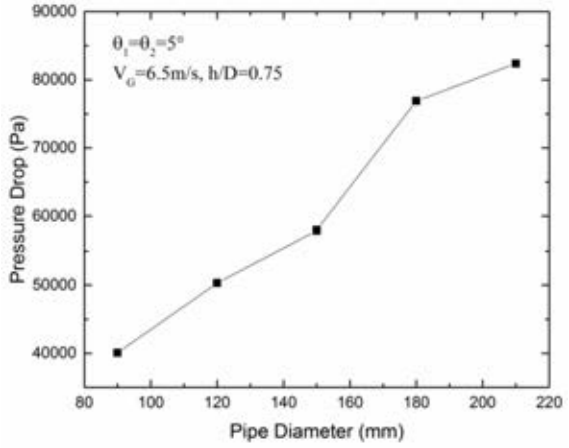


Figure 5 Influence of pipe diameter on pressure drop at the moment of slug formed

The pressure drops in different pipe diameter at the moment of slug formed are shown in Figure 5. The pressure drop increases along with the pipe diameter. The pressure drop ranges from 40,000 Pa to 82,000 Pa. The rate of increasing pressure drop is about 30% with the pipe diameter from 90 mm to 210 mm. Figure 6 describes the slug liquid holdup in different pipe diameters. We can see that the liquid holdup increases slowly in the pipe diameters from 90 mm to 180 mm, while it declines slightly in the 210 mm diameter pipe. However, the value of slug liquid holdup distributes approximately 0.5 in the entire pipe diameters.

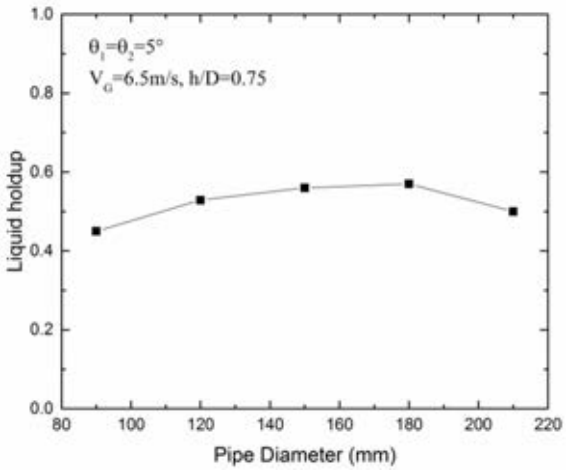


Figure 6 Influence of pipe diameter on liquid holdup at the moment of slug formed

CONCLUSIONS

The VOF and RNG k-ε turbulence models show the reasonable results in simulating the formation process

of a liquid slug. The distinct gas-liquid two-phase distribution and the formation process of a liquid slug are obtained by numerical simulation. The pipe cross-section is blocked by the liquid phase at the moment of a liquid slug formed. The pressure suddenly increases, and then declines gradually in process of liquid slug formation and motion. The pipe diameter has tiny effect on the slug formation, since the pressure drop and the liquid holdup change little.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (51444005, 51574045).

REFERENCES

ABDULKADIR, M., HERNANDEZ-PEREZ, V., LO, S., LOWNDES, I.S. and AZZOPARDI, B.J., (2015), "Comparison of experimental and Computational Fluid Dynamics (CFD) studies of slug flow in a vertical riser", *Exp. Therm Fluid Sci.,* **68**, 468-483.

AL-SAFRAN, E., KORA, C. and SARICA, C., (2015), "Prediction of slug liquid holdup in high viscosity liquid and gas two-phase flow in horizontal pipes", *J. Pet. Sci. Technol.*, ***133***, 566-575.

BRACKBILL, J.U., KOTHE, D.B. and ZEMACH, C., (1992), "A continuum method for modeling surface tension", *J. Comput. Phys.*, ***100***, pp.335-354.

CLARKE, A. and ISSA, R.I., (1997), "A numerical model of slug flow in vertical tubes", Comput. Fluids, **26**, 395-415.

ERSOY, G., SARICA, C., AL-SAFRAN, E. and ZHANG, H.Q., (2011), "Experimental Investigation of Three-Phase Gas-Oil-Water Slug Flow Evolution in Hilly-Terrain Pipelines", *SPE Annual Technical Conference and Exhibition*, Denver, Colorado, USA, 30 October - 2 November.

DE HENAU, V. and RAITHBY, G.D., (1995), "A study of terrain-induced slugging in two-phase flow pipelines", *Int. J. Multiphase Flow*, ***21***, 365-379.

HEYWOOD, N.I. and RICHARDSON, J.F., (1979), "Slug flow of air—water mixtures in a horizontal pipe: Determination of liquid holdup by γ-ray absorption", *Chem. Eng. Sci.*, ***34***,17-30.

ISSA, R.I. and KEMPF, M.H.W., (2003), "Simulation of slug flow in horizontal and nearly horizontal pipes with the two-fluid model", *Int. J.Multiphase Flow*, ***29***, 69-95.

TAHA, T. and CUI, Z.F., (2006), "CFD modelling of slug flow in vertical tubes", *Chem. Eng. Sci.*, ***61***, 676-687