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NUMERICAL SIMULATION ON GAS-LIQUID TWO PHASE SPIRAL FLOW ROTATED BY VANE

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ABSTRACT

With the development and utilization of natural gas, the natural gas storage and transportation using gas hydrate has been paid more and more attention, which is safe, clean and low cost. The core of natural gas hydrate storage and transportation technology is the rapid formation of hydrate. The gas hydrate formation rate can be improved significantly using spiral flow, because spiral flow can promote the mixture between gas and liquid. In addition, the technology that gas-liquid two phase spiral flow is combined with hydrate slurry transportation also has a broad development prospect. The gas-liquid two phase spiral flow rotated by vane in a horizontal pipe has been simulated by Fluent, the law of gas and pressure distribution in the pipe has been investigated, and characteristic of the axial and tangential velocity has been studied. The Solid wall boundary condition of no slip was used. The range of the entrance gas volume fraction is 0.167-0.728. The calculation results show that gas volume fraction in the pipe centre line is the highest, gas volume fraction becomes higher when the distance between measure point and wall is shorter. In the flow, the centre of vortex is the centre of low pressure, there are obvious different pressures inside and outside the vortex. The highest axial velocity happens in the tube wall because of centrifugal force created by vortex. The tangential velocity became small in the downstream. The law that the high or low entrance gas volume fraction went against the mixture between gas and liquid has been found, and gas volume fraction within the range of 0.35-0.5 is the best.

NOMENCLATURE

p pressure
Q_l liquid flow
Q_g gas flow
W_{sl} liquid superficial velocity
W_{sg} gas superficial velocity
ρ density
β gas volume fraction

INTRODUCTION

With the development and utilization of natural gas, natural gas hydrate storage and transportation technology has been increasingly attached importance to oil and gas transportation which is safe, reliable, clean and low cost. The key to bring about the economic and efficient gas hydrate storage and transportation is rapid formation of natural gas hydrate. The new methods of natural gas hydrate rapidly formation and the systematic study of them can provide guidance for the optimization of existing hydrate reactor operating conditions and developments to design more efficient new reactor. This is of great importance to solve the oil and gas pipeline transportation and energy environmental issues. A new method based on spiral flow for enhancing gas hydrate formation in pipeline is presented. The spiral flow carries discrete particles easier than the general flow, and can greatly improve the heat and mass transfer between gas and liquid, theoretically, the formation rate of gas hydrate can be improved greatly. For intensive investigation of the relationship between the spiral flow and the hydrate formation, it is necessary to study the flow characteristics of the two phase spiral flow.

Currently, several investigations on spiral flow with different spiral generator devices were performed. Wang mainly reviewed the CFD research progress of gas-liquid two-phase flow in stirred reactors. Nowadays, the cyclone separator coupled with the vane spiral flow generator has been applied to improve the gas-liquid separation efficiency. Wang experimentally investigated the influence of vane cross-sectional areas and outlet angles on tangent velocity and separation efficiency of vane-guided liquid-liquid hydrocyclone, and the optimum outlet angle and vane cross-sectional area was obtained. Jin studied the influence of guide vane angles on pressure distribution within the axial flow type gas-liquid cyclone, and the highest separation efficiency at a constant guide vane angle was achieved. Wu experimentally analyzed the influence of structural parameters on inside resistance and heat transfer. Therefore, a correlation of inside resistance and heat transfer was correspondingly obtained. And the application of axial vane cyclone would impart some favours to the heat transfer enhancement of in-tube fluid within the range of experimental condition. Sarac practically examined the characteristics of heat transfer and pressure drop in spiral attenuation flow field generated by propeller-driver vortex generator in a horizontal tube, the influence of several manipulation factors including the in-tube position of propeller-drive vortex generator and the vane quantity as well as angle of the vane on heat transfer and pressure drop was also studied at the range of Re values from 5.0×10^3 to 3.0×10^4. Additionally, an increasing range of Nusselt number value from 18.1 to 163% was also achieved based on the variation of the factor combination mentioned-above. Raj and Ganesan studied the flow field in the combustion chamber at the outlet of the vane cyclone equipped in horizontal-circular tube by means of experimental investigation and numerical simulation, in order to obtain the optimal vane angle of spiral flow in flame combustion application. And the water was applied as the medium. The influence of vane quantity and angle as well as turbine hub on flow field characteristic (such as the dimension of recirculation zone, the mass and pressure drop of fluid trapped in the recirculation zone) was also taken into discussion. The optimal spiral angle of the vane at 45° was achieved.

At present, the research group has done some exploration in the relevant aspects. The first experimental study of Wang Shuli, the flow pattern of gas-liquid two-phase spiral pipe with the twist tape and the vane, and the flow pattern and pressure drop of different conditions were obtained. The results showed that the pressure drop gradient of the spiral dispersed flow was the smallest. In order to study the characteristics of the spiral flow in the hydrate formation environment, the influence of SDS on the flow characteristics of the gas-liquid two-phase flow was investigated. The study showed that the spiral bubble flow and the spiral slug flow were not apparent. Moreover, the concentration of SDS solution had a great influence on the flow pattern of the two-phase spiral flow. Then the LDV experiment on flow field distribution of the liquid phase spiral flow was studied, and the influence of the attenuation of the spiral flow, the average Reynolds number, the angle of rotation and the impeller area on the velocity distribution were studied. The spiral strength was attenuated exponentially and the mathematical model of attenuation was deduced. At the same time, the characteristics of hydrate flow in the pipe based on the spiral flow were studied. The gas hydrate formation and slurry flow experiments in the apparatus whose total length of the pipeline is 97 meters were investigated. The design pressure of the experimental device is 10 MPa, the temperature regulation range is from -10 to 50℃ and the diameter is 25 mm. The hydrate formation and flow rule under the water/natural gas system with 10-30% of void fraction and 6.2-8.8 of torsion rate were studied. And it was found that there is no gas-liquid stratification and the particle deposition while the gas flow from the dispersed bubble flow directly to the homogeneous hydrate particles.

Now, most research studies based on experiments, and the experiment range had some limitations because of the limitation of experimental conditions is apparent, so, it is necessary for further exploration using numerical simulation.

GEOMETRIC MODEL AND NUMERICAL METHOD

Geometric Model

◆**mass conservation equation**

The continuity equation of q phase is

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla\cdot\left(\alpha_q\rho_q v_q\right)=\sum_{q=1}^{n}\dot{m}_{pq} \quad (1)$$

In the equation, v_q is the velocity of q phase, $\dot{m}_{pq}$ is mass transfer from p phase to q phase. From the mass conservation equation,

$$\dot{m}_{pq}=-\dot{m}_{qp} \quad (2)$$

and

$$\dot{m}_{pp}=0 \quad (3)$$

◆**momentum conservation equation**

Momentum balance of q phase creates

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\vec{v}_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\vec{v}_q\right)=-\alpha_q\nabla p+\nabla\cdot\overline{\overline{\tau}}_q+\sum_{p=1}^{n}\left(\vec{R}_{pq}+\dot{m}_{pq}\vec{v}_{pq}\right)+\alpha_q\rho_q(\vec{F}_q+\vec{F}_{lift,q}+F_{vm,q}) \quad (4)$$

In the equation, $\overline{\overline{\tau}}_q$ is the strain tensor of q phase:

$$\overline{\overline{\tau}}_q=\alpha_q\mu_q\left(\nabla\vec{v}_q+\nabla\vec{v}_q^T\right)+\alpha_q\left(\lambda_q-\frac{2}{3}\mu_q\right)\nabla\cdot\vec{v}_q\overline{\overline{I}} \quad (5)$$

In the equation, μ_q and λ_q are shear viscosity and bulk viscosity of q phase, $\vec{F}_q$ is the external volume force, $\vec{F}_{lift,q}$ is lift force, $\vec{F}_{vm,q}$ is virtual mass force, $\vec{R}_{pq}$ is virtual mass force between phases, p is pressure, $\vec{v}_{pq}$ is relative velocity. Defines as follows, if $\dot{m}_{pq}>0$, $\vec{v}_{pq}=\vec{v}_p$; if $\dot{m}_{pq}<0$, $\vec{v}_{pq}=\vec{v}_q$ and $\vec{v}_{pq}=\vec{v}_{qp}$.

To make the equation (4) closed, the following form of interaction force has been used:

$$\sum_{p=1}^{n}\vec{R}_{pq}=\sum_{p=1}^{n}K_{pq}\left(\vec{v}_p-\vec{v}_q\right) \quad (6)$$

In the equation, K_{pq} (= K_{qp}) is the momentum exchange coefficient.

For momentum exchange coefficient of gas-liquid can be written as the following general form:

$$K_{pq}=\frac{\alpha_p\rho_p f}{\tau_p} \quad (7)$$

In the equation, Drag force function f is different for exchange coefficient model definition, particle relaxation time τ_p is defined as:

$$\tau_p=\frac{\rho_p d_p^2}{18\mu_q} \quad (8)$$

In the equation, d_p is the diameter of droplets or bubbles of p phase.

Schiller and Naumann model has been chosen:

$$f=\frac{C_D \mathrm{Re}}{24} \quad (9)$$

In the equation, Drag coefficient C_D was determined by the type:

$$C_D=\begin{cases}24\left(1+0.15Re^{0.687}\right)/Re & Re\le1000\\ 0.44 & Re>1000\end{cases} \quad (10)$$

In this calculation, lift force is ignored because of the too small influence of the lift force to resistance. The virtual mass force is ignored because of its too small value.

◆ **turbulence model**

In the calculation, the mixed turbulence model was chosen. Describe the model equation is as follows:

$$\frac{\partial}{\partial t}(\rho_m k)+\nabla\cdot(\rho_m \vec{v}_m k)=\nabla\cdot\left(\frac{\mu_{t,m}}{\sigma_k}\nabla k\right)+G_{k,m}-\rho_m\varepsilon \quad (11)$$

$$\frac{\partial}{\partial t}(\rho_m \varepsilon)+\nabla\cdot(\rho_m \vec{v}_m \varepsilon)=\nabla\cdot\left(\frac{\mu_{t,m}}{\sigma_\varepsilon}\nabla \varepsilon\right)+\frac{\varepsilon}{k}\left(C_{1\varepsilon}G_{k,m}-C_{2\varepsilon}\rho_m\varepsilon\right) \quad (12)$$

Numerical Algorithm

The Euler two-phase flow model was used to model a steady flow. Phase Coupled SIMPLE (PC-SIMPLE) algorithm was employed for the pressure and velocity coupling. The pressure equation was discrete by PRESTO algorithm, while the momentum equation was calculated with the third order MUSCL format. The second-order windward format is applied to turbulent kinetic energy and dissipation rate. The standard wall function is used on the wall. When residual epsilon $\varepsilon_i < 10^{-3}$, there is the computed convergence.

Boundary Conditions

(1) two phase flow inlet boundary conditions: a given speed of gas phase and liquid phase, bubbles were distributed evenly at the entrance, the diameter of bubble is 1 um, the gas volume rate of the second phase bubbles is given; Turbulence intensity I is 5%, the hydraulic diameter $D_H=d$; (2) the outlet boundary conditions: free outflow discharge; (3) solid wall boundary conditions: the no slip boundary condition.

CALCULATION RESULTS AND ANALYSIS

Taking 10 sections from the model, the distance apart the local generator are z1 = 10 mm(A), z2 = 20 mm(B), z3 = 40 mm(C), z4 = 60 mm(D), z5 = 80 mm(E), z6 = 100 mm(F), z7 = 200 mm(G), z8 = 400 mm(H), z9 = 600 mm(I), z10=800 mm(J). Details are shown in table 1.

Table 1: gas volume fraction contour.

No.	Section	Distance(mm)	Code name
1	z1	10	A
2	z2	20	B
3	z3	40	C
4	z4	60	D
5	z5	80	E
6	z6	100	F
7	z7	200	G
8	z8	400	H
9	z9	600	I
10	z10	800	J

There are four conditions in the simulation, shown in table 2. The range of gas volume fraction is 0.167-0.728.

Table 2: The flow conditions

No.	β	W_{sl} (m/s)	W_{sg} (m/s)
1	0.167	1	0.201
2	0.334	2	1.005
3	0.573	2	2.68
4	0.728	1	2.68

Liquid Superficial Velocity(W_{sl})=1 m/s, Gas Superficial Velocity(W_{sg})=0.201 m/s

The liquid flow Q_l = 1.5 m^3/h, namely the liquid superficial velocity W_{sl} = 1 m/s. The gas superficial velocity W_{sg} = 0.201 m/s, the gas phase flow Q_g = 0.3 m^3/h. The entrance gas volume fraction β = 0.167.

Fig.1 presents the distribution of gas volume fraction in centre section x=0, which along with the vertical direction of pipeline. The gas volume fraction of gas phase in the centre of pipeline is very large, the maximum value reaches 0.87, which is 0-50mm behind the outlet of impeller. For spiral flow, in order to balance centrifugal force for generation of the pressure drop, the static pressure is large in the location which has large centrifugal force, the static pressure is small in the location which has small centrifugal force. The centrifugal force and static pressure is small due to the value of tangential velocity closing to 0 in the centre of the vortex. In Fig.2, Fig.2(a) shows the non-dimensional contours of pressure in section z=15mm, the centre of vortex is also the centre of low pressure in the two phase flow. The pressure difference between the inside and outside of the vortex is obvious, and there is a large range of low pressure zone, and lots of light bubbles is inhaled to the vortex, which led to the large void fraction, shown in Fig.3(a). Fig2(b) shows the non-dimensional contours of pressure in section z=100mm, small range of low pressure zone result in low gas volume fraction, the maximum value is about 0.18, shown in Fig.3(b). The liquid phase is mostly distributes around the wall of the pipeline due to larger centrifugal force than gaseous phase results in liquid phase swing to the wall of the pipeline. In this condition, the liquid phase which has large volume fraction mixing with the gaseous phase in the centre of the pipeline due to the lower void fraction in the inlet.

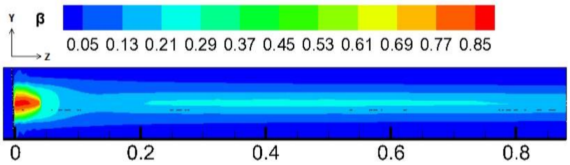
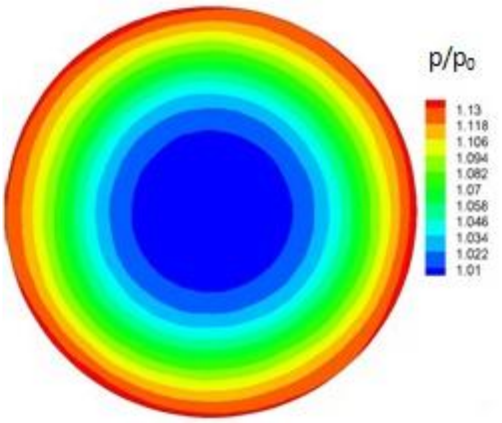
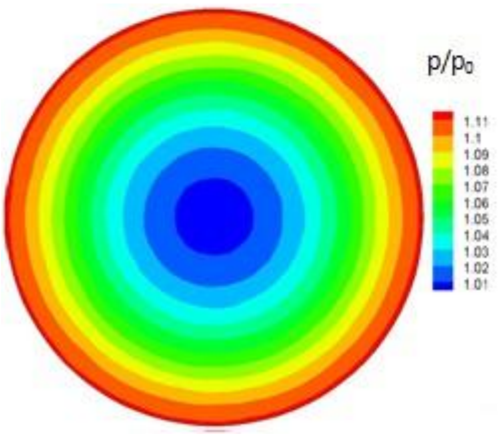


Figure 2: gas volume fraction contour (unit: mm)

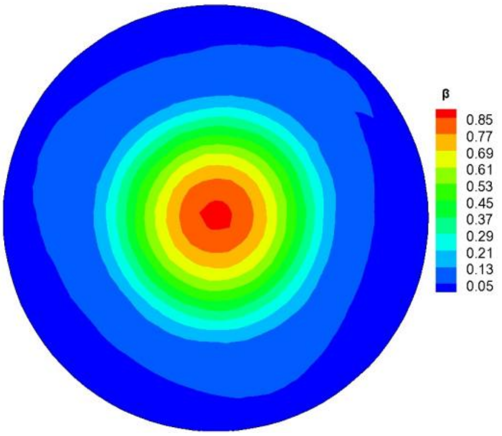


(a)

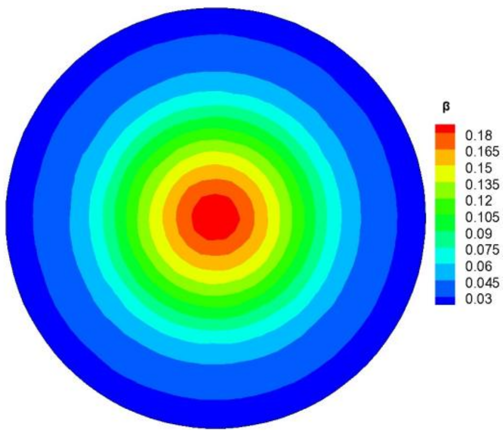


(b)

Figure 2: dimensionless stress contour: (a) z = 15 mm section, (b) z = 100 mm section

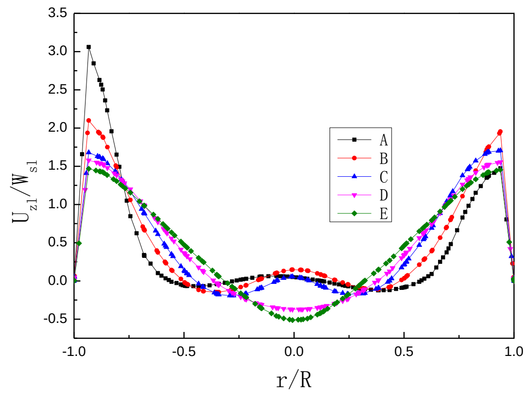


(a)

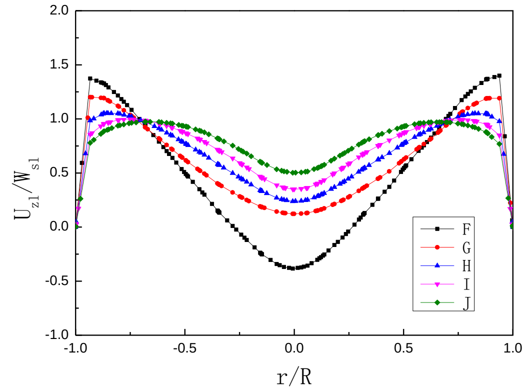


(b)

Figure 3: gas volume rate contour: (a) z = 15 mm section, (b) z = 100 mm section

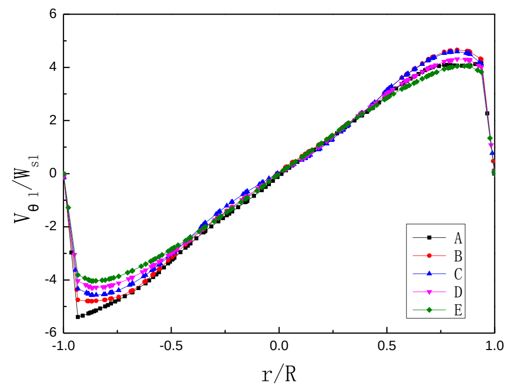


(a)A(10)B(20)C(40)D(60)E(80) unit: mm

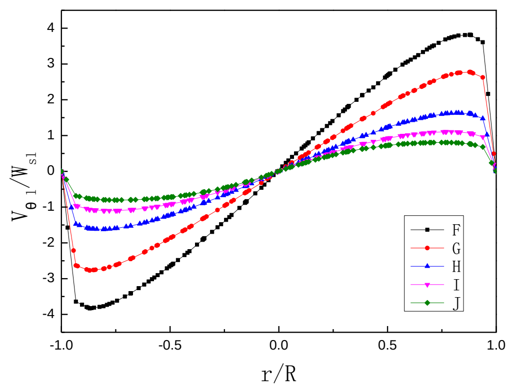


(b) F(100)G(200)H(400)I(600)J(800) unit: mm

Figure 4: liquid axial velocity distribution: (a) section A - E, (b) section F - J



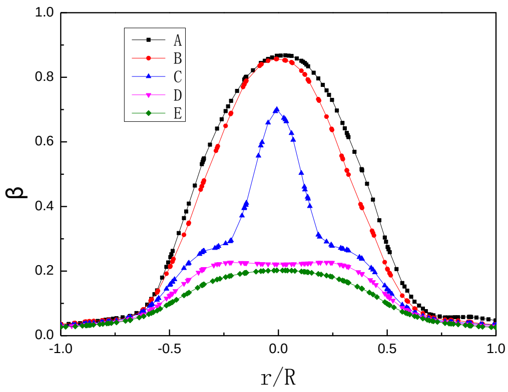
(a) A(10)B(20)C(40)D(60)E(80) unit: mm



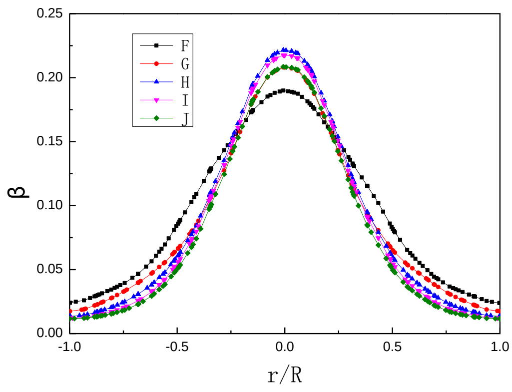
(b) F(100)G(200)H(400)I(600)J(800) unit: mm

Figure 5: liquid tangential velocity distribution: (a) section A - E, (b) section F - J

Fig.4 and Fig.5 presents the non-dimensional axial and tangential velocity of the liquid phase in different section along with the flow direction. By comparison, the distribution of two phase flow and single phase have the same form. But for two phase flow, the axial and tangential velocity decreased in the condition of low gas volume fraction in the inlet due to the complicated interaction between the bubble and liquid phase, which results in large energy loss. Due to the effect of centrifugal force generated by vortex, the maximum velocity forms at the wall of the pipeline. In addition, the liquid with different density moves to the different location, and the flow trend to orderly. In the downstream of the flow, tangential velocity and centrifugal force decreased, the momentum of the flow transported along with the axial direction. When the reflux disappears, the axial velocity in the centre of the pipeline increased, the distribution curve of the axial velocity trends to smooth, the flow trend to homogeneous flow.



(a) A(10)B(20)C(40)D(60)E(80) unit: mm



(b) F(100)G(200)H(400)I(600)J(800) unit: mm

Figure 6: gas volume fraction distribution: (a) section A - E, (b) section F - J

Fig.6 presents the distribution of the gas volume fraction, the shape of the gas volume fraction distribution is close to symmetric parabolic. The larger gas volume fraction in the A and B section is near the outlet of impeller. From the centre to the wall the gas volume fraction decreased gradually, for the section G, the gas volume fraction is close to stabilizing and decreases slowly. For this condition, the mixing is poor for the gas and liquid phase due to low gas volume fraction.

W_{sl}=2 m/s, W_{sg}=1.005 m/s

The liquid flow Q_l = 3 m^3/h, corresponds to the liquid superficial velocity W_{sl} = 2 m/s. The gas superficial velocity W_{sg} = 1.005 m/s, the gas phase flow Q_g = 1.5 m^3/h. The entrance gas volume fraction β = 0.334.

The gas volume fraction is very large in the centre of the pipeline, the maximum value reaches 0.92. The gas volume fraction decreased gradually from the centre to the wall. To the section G, the gas volume fraction is close to stabilizing which decreases slowly, and mixing of gas-liquid two-phase is sufficient. Compared to single-phase flow, complex interaction of gas liquid two phase flow lead to flow energy loss, and the axial and tangential velocity become small.

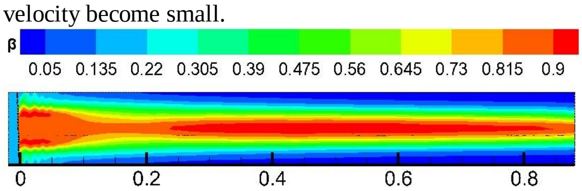


Figure 7: gas volume fraction contour (unit: mm)

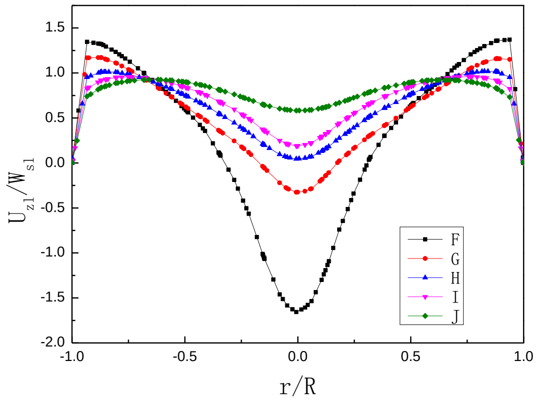


Figure 8: liquid axial velocity distribution: section F – J F(100)G(200)H(400)I(600)J(800) unit: mm

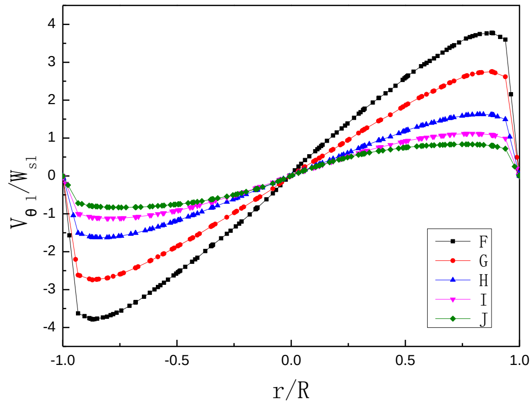


Figure 9: liquid tangential velocity distribution: section F – J

F(100)G(200)H(400)I(600)J(800) unit: mm

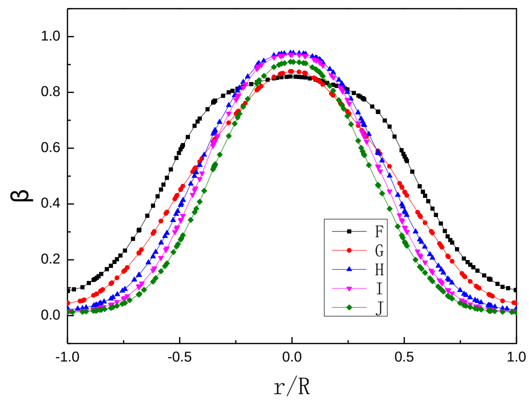


Figure 10: gas volume fraction distribution: section F – J

F(100)G(200)H(400)I(600)J(800) unit: mm

W_{sl}=2 m/s, W_{sg}=2.68 m/s

The liquid flow Q_l = 3 m^3/h, corresponds to the liquid superficial velocity W_{sl} = 2 m/s. The gas superficial velocity W_{sg} = 2.68 m/s, the gas phase flow Q_g = 4 m^3/h. The entrance gas volume fraction β = 0.573.

The gas volume fraction is very large in the centre of the pipeline, the maximum value reaches 0.97. The gas volume fraction decreased gradually from the centre to the wall. To the section H, the gas volume fraction is close to stabilizing which decreases slowly. Under the conditions, a large number of gas accumulates in the centre of the circular tube due to the high gas volume fraction, and the content of the liquid phase is less, which opposes two phase mixing. Because of the high liquid superficial velocity, each phase axial and tangential velocity value is large.

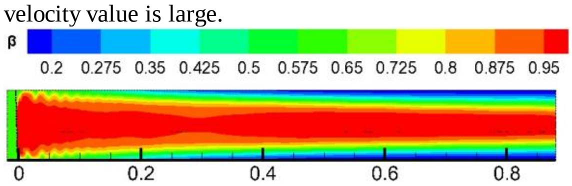


Figure 11: gas volume fraction contour (unit: mm)

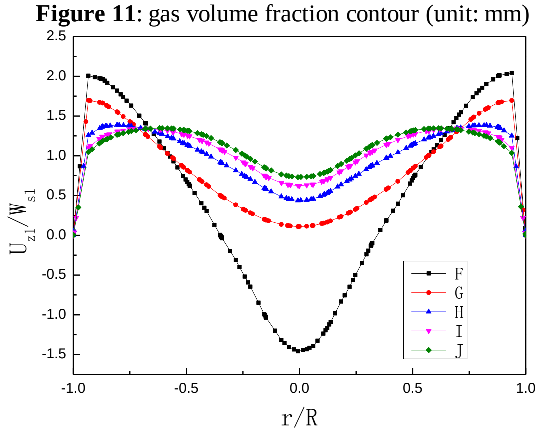


Figure 12: liquid axial velocity distribution: section F – J F(100)G(200)H(400)I(600)J(800) unit: mm

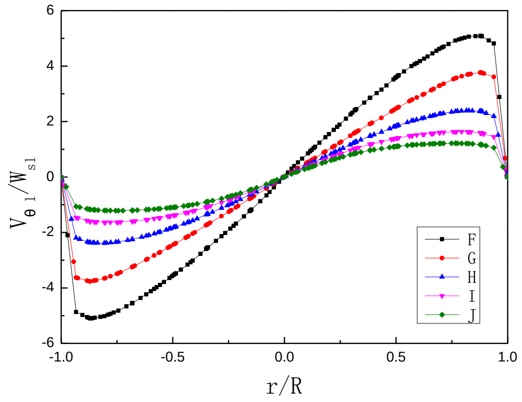


Figure 13: liquid tangential velocity distribution: section F - J

F(100)G(200)H(400)I(600)J(800) unit: mm

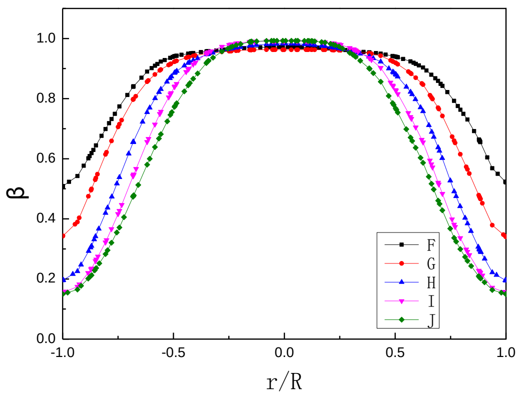


Figure 14: gas volume fraction distribution: section F-J

F(100)G(200)H(400)I(600)J(800) unit: mm

W_{sl}=1 m/s, W_{sg}=2.68 m/s

The liquid flow Q_l = 1.5 m^3/h, corresponds to the liquid superficial velocity W_{sl} = 1 m/s. The gas superficial velocity W_{sg} = 2.68 m/s, the gas phase flow Q_g = 4 m^3/h. The entrance gas volume fraction β = 0.728.

Fig.15 is gas volume fraction distribution of centre section x = 0, Fig.18 is gas volume fraction distribution of section F - J. The gas volume fraction in the pipe centre is 0.98, and gas volume fraction from - 0.5 R to 0.5 R on every section F - J is 0.98. The gas volume fraction decreased gradually from the centre to the wall, gas volume fraction in the wall is 0.62, which is a minimum. Under the conditions, a large amount of gas accumulate is in the centre of the circular tube due to the high gas volume fraction, and the content of the liquid phase is less, which opposes two phase mixing. Because of the high liquid superficial velocity, each phase axial and tangential velocity value is large.

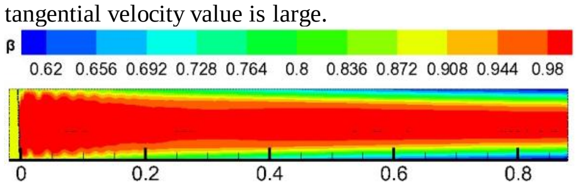


Figure 15: gas volume fraction contour (unit: mm)

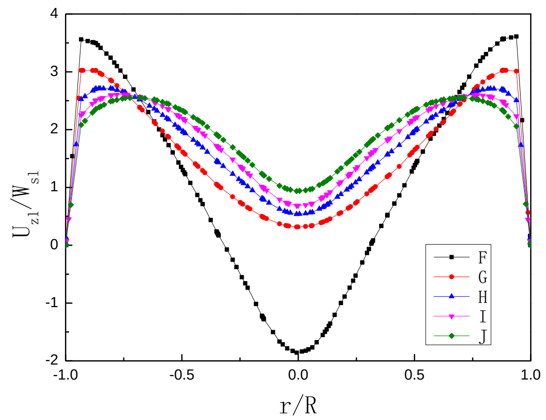


Figure 16: liquid axial velocity distribution: section F – J F(100)G(200)H(400)I(600)J(800) unit: mm

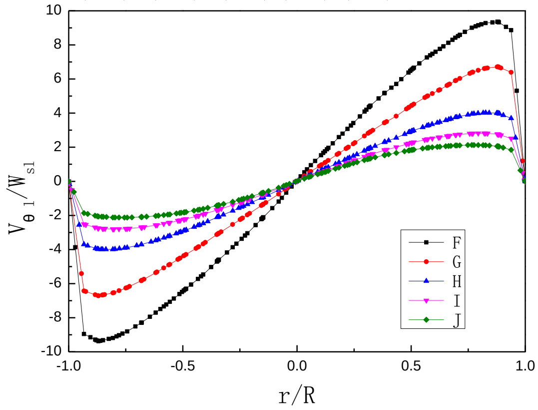


Figure 17: liquid tangential velocity distribution: section F – J

F(100)G(200)H(400)I(600)J(800) unit: mm

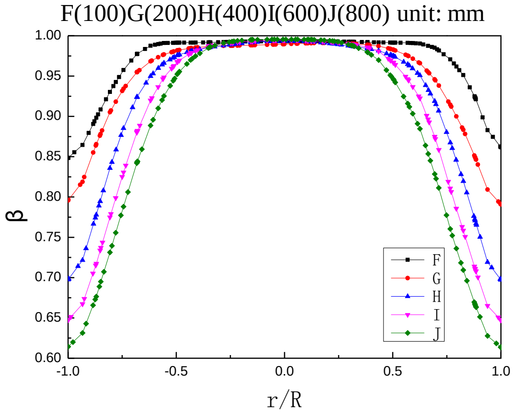


Figure 18: gas volume fraction distribution: section F – J F(100)G(200)H(400)I(600)J(800) unit: mm

CONCLUSION

In this paper, gas hydrate formation rate that was increased using gas liquid two phase spiral flow has been investigated, the flow characteristics of the spiral gas-liquid two phase flow in a horizontal pipe are simulated, and the research conclusions are as follows: (1) In various working conditions, gas flow downstream with liquid, there are almost non-existent speed difference between gas and liquid, and the velocity distribution of each phase is same as single phase flow. (2) When gas volume fraction is 0.167 or 0.728, the intense interaction between gas and liquid leads to more flow loss and larger pressure drop. (3) The too low or too high gas volume rate is bad for the mixing of two phase, and the most suitable range of gas volume fraction is 0.35 - 0.5.

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