EFFECTS OF SWIRL ON FLOW PATTERNS AND LIQUID UNLOADING OF GAS–LIQUID TWO-PHASE VERTICAL FLOW UNDER STAGNANT CONDITIONS

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Liquid loading is a common problem in low-production gas wells faced in many producing regions around the world. Recently, swirl flow has been applied to remove the accumulated liquid. However, the effect of swirl on the flow characteristics in gas–liquid two-phase flow is largely unexplored, which is important for the application of swirl flow in the natural gas industry. Therefore, the effects of swirl on flow patterns and liquid unloading in gas–liquid two-phase vertical flow under stagnant conditions are investigated by visualization experiment in this work. A dimensionless parameter is proposed to quantitatively describe the capability of liquid unloading. The results show that interface morphology varies along the streamwise direction under stagnant liquid situations. In the case of slug flow, a swirler can suppress the fallback of falling liquid film. In the case of churn flow with relatively high gas velocity, the churn flow can be transformed to swirling annular flow once out of the swirler. The swirl is beneficial in unloading liquid when the gas velocity is relatively high. The critical gas velocity, which is defined as the minimum gas velocity to prevent the onset of liquid load up in the gas well, can be reduced in the swirl flow compared with that in non-swirling flow. In addition, the initial position of the liquid level has an influence on liquid unloading, and a swirler located below the initial position of the liquid level performs better in unloading liquid.

KEY WORDS: swirl flow, liquid unloading, flow pattern, stagnant condition

1. INTRODUCTION

The production of natural gas is usually accompanied by the production of liquids. When the reservoir pressure is relatively high at the early stage, these liquids can be transported to the surface by natural gas. However, during the period of gas production, the reservoir pressure declines, leading to decreasing gas velocity. When the gas velocity is below a certain value (called the critical gas velocity) the gas fails to carry the liquids to the surface, leading to the fallback of some liquid that accumulates at the bottom of the wellbore. The phenomenon is called liquid loading and is a common problem faced in low-production gas wells in many producing regions around the world. Accumulated liquid significantly reduces the production capacity and can eventually kill the well (Liu et al., 2018b; Wang et al., 2015). Many technologies have been proposed to remove liquids from wells (Shooshtari and Shahsavand, 2013; Veeken and Belfroid, 2011; Ali et al., 2005).

Swirl flow has been successfully used to modulate flow patterns and is widely used in practical industries, such as in heat transfer enhancement, phase separators, and pneumatic conveying (Lim et al., 2017; Liu et al., 2018a). In recent years, it has also been used in natural gas exploitation, such as in the measurement of the two-phase flow rate (Surendra et al., 2009) and severe slugging mitigation (Xing et al., 2013). Swirling flow induced by a downhole vortex...
tool has been used recently to remove liquid from the bottom of the wellbore (Ali et al., 2005; Zhou et al., 2019). This new technology has been applied in gas fields and performs well in removing liquid. However, the field tests show that the vortex tool loses efficiency in some liquid loading gas wells due to the effect of swirl on the gas–liquid two-phase flow, and this effect has been largely unexplored. Although some numerical and experimental studies on the vortex tool are available, most of them focus on the effectiveness and structure of vortex tools (Zhou et al., 2019; Wu et al., 2016; Bose, 2007; Ali et al., 2005). Unfortunately, the effect of swirl on the flow characteristics in vertical gas–liquid two-phase flow is less clear, especially on the flow patterns and liquid unloading capability, which is important in the application of swirl flow on liquid unloading.

In the presence of centrifugal force in gas–liquid two-phase swirling flow, the flow characteristics (such as the flow pattern, pressure drop, and heat transfer) are different from those in the non-swirling flow (Funahashi et al., 2018; Liu and Bai, 2014, 2019b). Under the effect of swirl, dispersed bubbles are transformed to gas column (Qian et al., 2018; Yin et al., 2017; Liu and Bai, 2015). In a vertical pipe with twisted tape, the Taylor bubbles, liquid slug in the slug flow swirl, and the gas in the liquid slug concentrate on the pipe center (Chang and Yang, 2009). Churn flow can be transformed to swirling annular flow (Liu and Bai, 2019a). In a horizontal pipe, stratified flow and wavy flow can be transformed to swirling annular flow under the effect of swirl (Rocha et al., 2015; Krishna, 2009). In swirling annular flow, most droplets are thrown to the pipe wall leading to a thicker liquid film (Yue et al., 2019; Liang et al., 2017; Liu et al., 2018a). The flow pattern map in horizontal and vertical pipes is different from the pattern in non-swirling flow, where some special flow patterns occur such as swirling gas column flow, swirling intermittent flow, and swirling annular flow (Liu and Bai, 2014, 2019b; Shuli et al., 2012; Kanizawa and Ribatski, 2012). However, the effect of swirl on the flow patterns and liquid unloading capability, which is important in the application of swirl flow in the natural gas industry, is largely unexplored.

When the liquid accumulates at the bottom of the well, the natural gas has to pass through the accumulated liquid, and carries the liquid to the surface. In the wellbore, water is stagnant in the test section, and this flow is different from the gas–liquid two-phase flow studied in most published works. However, the effect of swirl on gas–liquid two-phase vertical flow under stagnant conditions is largely unexplored, which is important in the application of swirling flow in removing liquid in natural gas wells.

In this paper, the effects of swirl on flow patterns and liquid unloading in gas–liquid two-phase vertical flow under stagnant conditions are investigated using visualization experiments. To compare the capability of liquid unloading in swirl and non-swirl flow, a dimensionless parameter is proposed to quantitatively describe the capability of liquid unloading. Although fundamental, this study has strong applicative implications since the flow configuration mimics the behavior of a vortex tool applied in natural gas wells.

2. EXPERIMENTAL SETUP

2.1 Flow Loop

The experiments were conducted in a flow loop constructed using transparent acrylic pipes (62 mm in diameter), as also reported in our previous works (Liu and Bai, 2014, 2015), and only the main features are presented here. To facilitate the visual observation, the test section was made from transparent acrylic pipe, as shown in Fig. 1. The test section with a total vertical height of 11 m was consisted of five 2-m-long segments and one 1-m-long segment with a swirler connected by flanges. The swirler, fixed at 4 m from the bottom of the test section, was made of polymethyl methacrylate. The most important part of the swirler was the helical tape twisted along a hub. The diameter of the hub was 38 mm and the diameter of the swirler was 58 mm. The helical tape twisted 360° with a vertical length of 197 mm, and the thickness of the helical tape was 5 mm. The structure of the swirler is given in Fig. 1.

Air and water at room temperature were used as the working fluid in the setup. Air supplied from a compressed air supply (Atlas Copco Gxe7FF air compressor) was measured by two Coriolis mass flow meters in order to cover a wide range of gas flow rates and minimize measurement errors, and all of the meters had an accuracy of 0.5%. The maximum relative uncertainty of the gas mass flow rate was 1.61%. The air was injected into the test section through a porous pipe wall section. Water entered the test section at the bottom of the pipe. After passing through the test section, the air/water mixture was separated using a separator. Water was sent back to the tank and air was released.
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FIG. 1: Diagram of the experimental setup and swirler structure (unit: mm); the z-axis is positive in the upward direction, and the origin point is located at the inlet of the swirler

into the atmosphere. A pressure transmitter was used to measure the pressure above the swirler ($z = -0.1$ m), as shown in Fig. 1.

2.2 Experimental Procedures

Liquid loading in natural gas wells is a common problem faced in many producing regions around the world. To ensure maximal production in gas wells, removing the liquid that accumulates at the bottom of the well is very important. To investigate the effect of swirl on liquid unloading, some stagnant liquid was allowed to accumulate at the bottom of the pipe in order to simulate loading liquid in a gas well, in which the inlet velocity of the liquid phase in the test section was zero.

2.2.1 Liquid Unloading

First, water is introduced into the pipe using a water pump. Once the liquid level reaches the designed height (above or below the swirler), the control valve on the inlet water line is closed and the water pump is turned off such that the water becomes stagnant in the test section. Then, the gas phase is introduced into the pipe. Once the gas flows in the test section, two conditions are possible: either there is a zero or non-zero liquid flow rate at the outlet/top of the test section, as shown in Fig. 2. According to the two conditions observed in the experiment, two parameters are recorded to evaluate the effect of swirl on liquid unloading:

1. Highest/average position the liquid can reach: When the gas velocity is relatively low the liquid cannot move out of the test section, leading to the zero-net liquid flow rate between the inlet and outlet of the test section.
FIG. 2: Measurement of liquid unloading capability: (a) zero liquid flow rate at the outlet of the test section; (b) non-zero liquid flow rate at the outlet of the test section

Liquid remains in the pipe at the highest position that the liquid can reach. Since the highest position varies with time, the average position is also proposed to evaluate the effects of swirl on liquid unloading.

2. Reduced volume of the liquid ($V$): When the gas velocity is relatively high, some liquid flows out of the test section, leading to the non-zero liquid flow rate at the outlet/top of the test section. Therefore, the amount of liquid in the pipe is reduced. The reduced volume of the liquid is finally recorded when the flow rate at the outlet section is zero and the amount of liquid in the pipe remains constant. Under this condition, dimensionless parameter $V/V_0$ is proposed to evaluate the effects of swirl on liquid unloading, where $V$ is the reduced volume of the liquid and $V_0$ is the total liquid volume at the initial time.

To investigate the effect of swirl on liquid unloading in a vertical pipe, a dimensionless parameter, the relative liquid unloading ability (RLUA), is proposed with consideration of the two conditions mentioned previously:

$$RLUA = \frac{(\Delta h_2 - \Delta h_1)}{\Delta h_1}$$ (1)

As shown in Fig. 2, in the case of a zero liquid flow rate at the outlet, $\Delta h_1$ represents the maximum/average height of the liquid in the non-swirling flow carried by the gas phase, and $\Delta h_2$ represents the maximum/average height of the liquid in the swirling flow. In the case of a non-zero liquid flow rate at the outlet, $\Delta h_1$ indicates the reduced height of the liquid carried by the gas in the non-swirling flow, and $\Delta h_2$ indicates the reduced height of the liquid carried by the gas in the swirling flow.

2.2.2 Critical Gas Velocity

The critical gas velocity is an important parameter in liquid uploading of gas wells. It can be defined as the minimum gas velocity needed to prevent the onset of liquid load-up. In our experiment, the critical gas velocity is defined as
the minimum velocity at which liquid film can be observed moving upward in the whole pipe (Veeken and Belfroid, 2011; Yusuf et al., 2010; Veeken et al., 2009). When the gas velocity reaches the critical gas velocity, all of the liquid can be finally carried out of the test section.

2.3 Experimental Conditions

The superficial gas velocity \( u_{sg} \), which is a parameter commonly used in gas–liquid two-phase flow, is defined as \( u_{sg} = \frac{Q_g}{A} \), where \( Q_g \) is the volume flow rate of the gas phase \( (m^3/s) \) and \( A \) is the cross-sectional area of the circular pipe (m\(^2\)). The range of gas superficial velocities in the experiment was 0.24–14.39 m/s, where slug/churn/annular flow in the non-swirling flow could be observed. In the case of extremely small gas velocity, the flow pattern in the pipe was bubble flow. This case is not investigated here, since the gas well is nearly killed when the flow pattern in the pipe is bubble flow. The gauge pressure at the swirler inlet measured by a pressure transmitter was from 0.025 to 0.063 MPa (the absolute pressure was from 0.126 to 0.164 MPa). Except for the investigation of the effects of the initial liquid level position on liquid unloading (Section 4.3), the initial position of the liquid level in our experiment was 1 m below the inlet of the swirler \( (z = -1 \text{ m}) \). The original point of the \( z \)-axis was at the inlet of the swirler, as shown in Fig. 1.

3. EFFECTS OF SWIRL ON FLOW PATTERNS

3.1 Non-Swirling Flow Pattern under Stagnant Conditions

Although the liquid flow rate at the inlet of the test section was zero, the flow patterns in the gas–liquid two-phase non-swirling flow were the same as the flow patterns in the flow with a non-zero liquid flow rate at the inlet. In our work, the gas velocity was relatively high and three typical flow patterns were observed once the flow was out of the swirler \( (z = 0) \): slug flow, churn flow, and annular flow. For relatively low gas velocity \( (u_{sg} = 0.92 \text{ m/s}) \), the slug flow was characterized by a series of long bubbles, and liquid slugs with dispersed bubbles were observed. With increasing gas velocity \( (u_{sg} = 10.95 \text{ m/s}) \), the slug flow was gradually transformed to churn flow, where the liquid slugs in the slug flow disappeared, the gas phase was continuously surrounded by liquid film oscillating up and down in the pipe wall, and more droplets were entrained by the gas phase. By continuing to increase the gas velocity \( (u_{sg} = 13.74 \text{ m/s}) \), the churn flow was transformed into annular flow, where the liquid film in the pipe wall swirled upward and the gas core and entrained droplets moved upward. The morphologies of the air–water interfaces for these flow patterns are shown in Fig. 3.

In gas–liquid two-phase flow with a zero liquid flow rate at the inlet, the interface morphology varied along the streamwise direction, as shown in Fig. 4. This phenomenon is special and different from that in the flow with a non-zero liquid flow rate at the inlet. At relatively low gas velocity, the flow pattern in the whole vertical pipe was

![FIG. 3: Typical flow patterns in the non-swirling flow with zero liquid flow rate at the inlet \((z = 0)\): (a) slug flow \((u_{sg} = 0.92 \text{ m/s})\); (b) churn flow \((u_{sg} = 10.94 \text{ m/s})\); (c) annular flow \((u_{sg} = 13.74 \text{ m/s})\)](image-url)
slug flow. With increasing gas velocity \((u_{sg} = 13.74 \text{ m/s})\), the flow pattern was different since the amount of liquid decreased along the streamwise direction under the effect of gravity force: once out of the swirler \((z = 0)\) churn flow occurred; along the streamwise direction \((z = 4 \text{ m})\) annular flow occurred; and at the outlet/top of the test section droplets entrained by the gas phase were thrown to the pipe wall, leading to the formation of falling liquid film in the pipe wall.

### 3.2 Swirling Flow Pattern under Stagnant Conditions

Once the fluid was out of the swirler, the swirl intensity was strong and flow patterns were observed, as shown in Fig. 5. In the case of relatively low gas velocity \((u_{sg} = 0.66 \text{ m/s})\), slug flow was observed in the swirling flow
downstream from the swirler ($z = 448–680$ mm). The altered flow pattern was between liquid slug and gas slug with deformed large bubbles. Since the gas velocity was low, centrifugal force acting on the flow was weak. Taylor bubbles in the gas slug were deformed, which led to the appearance of deformed large bubbles surrounded by falling liquid film downstream from the swirler, reduced bubble diameter, and changes in the shape of the bubbles over time. Dispersed bubbles in the liquid slug failed to coalesce with each other and moved upward without an obvious swirling motion. In this flow, the velocity of the liquid slug was relatively low. When the fluid passed through the swirler, the flow area was greatly reduced, leading to increased flow velocity. Once the fluid was out of the swirler, the flow area increased, the flow velocity of the liquid slug was reduced, and the liquid slug fell back to the upstream region of the swirler.

When the gas velocity was increased to the value of 2.42 m/s, although the flow pattern remained slug flow, the liquid slug remained downstream from the swirler without fallback, as shown in Fig. 6, where it can be seen that the gas velocity in the swirler is high enough to suppress the liquid phase fallback to the upstream region of the swirler. When the gas velocity was increased to the value of 6.89 m/s, the flow pattern upstream of the swirler was churn flow. Once the fluid was out of the swirler, swirling annular flow was observed near the outlet ($z = 0–1.6D$). Large waves were observed in the liquid film of the swirling annular flow. This swirling flow was quickly transformed to non-swirling flow due to the swirl decaying along the streamwise direction ($z > 1.6D$), as shown in Fig. 6. At the top of the test section, many small droplets (on the order of millimeters for the droplet diameter) were thrown to the upper pipe wall, and then the falling liquid film was formed.

When the gas velocity continued to increase and reached the value of 12.35 m/s, obvious swirling annular flow was observed at the outlet of the swirler, and the flow remained at a length of approximately 30–40 cm (4.8–6.5$D$) along the streamwise direction. Then, the swirling annular flow was gradually transformed to annular flow without swirl, and large waves were observed on the liquid film. Falling liquid film also existed at the top of the pipe. No liquid phase accumulated at the bottom of the pipe, while some liquid phase accumulated at the outlet of the swirler.

**FIG. 6:** Effects of swirl on flow patterns with increasing gas velocity in the case of zero liquid flow rate at the inlet of the test section
4. EFFECTS OF SWIRL ON THE LIQUID LOADING CHARACTERISTICS

4.1 Liquid Unloading

Under stagnant conditions, two cases were observed: zero liquid flow rates at the outlet/top of the test section when the gas velocity was relatively low, and non-zero liquid flow rates at the outlet when the gas velocity was relatively low. The two cases were studied, respectively, to understand the effects of swirl on liquid unloading: zero liquid flow rates at the outlet with relatively low gas velocity, and non-zero liquid flow rates at the outlet with relatively high gas velocity.

4.1.1 Zero Liquid Flow Rate at the Outlet with Relatively Low Gas Velocity

Since the axial position of the maximum liquid level fluctuated, both the average and maximum height of the liquid level were measured in the experiment, as shown in Fig. 7, where it can be seen that as the gas velocity increases the interfacial force between the gas and liquid phases increases and the average and maximum heights of the liquid level also increase. Compared with the height of liquid level in non-swirling flow, both the average and maximum heights of the liquid level in the swirling flow are lower. It can be concluded that the swirl is not beneficial for liquid loading in the case of relatively low gas velocity.

4.1.2 Non-Zero Liquid Flow Rate at the Outlet with Relatively High Gas Velocity

The volume of the residual liquid at the bottom of the test section was measured to describe the effect of swirl on liquid loading. The dimensionless relative liquid volume parameter uploaded by gas ($V/V_0$) was used, where $V$ is the volume of the liquid uploaded by the gas phase, and $V_0$ is the volume of the liquid at the initial time. Results of $V/V_0$ between swirling and non-swirling flows are shown in Fig. 8. In Fig. 8, it can be seen that at relatively low gas velocity ($u_{sg} < 1.92$ m/s), the value of $V/V_0$ in swirling flow is lower than the value in non-swirling flow; however, when the gas velocity increases to the value of 1.92 m/s, the value of $V/V_0$ in swirling flow equals the value in non-swirling flow, and when the gas velocity continues to increase ($u_{sg} > 1.92$ m/s), the value of $V/V_0$ in swirling flow is higher than the value in non-swirling flow. The flow pattern changes during the process: at relatively low gas velocity the flow patterns in non-swirling flow is slug flow, while the flow pattern in swirling flow is slug intermittent flow, which

![Graph](image)

**FIG. 7**: Effects of swirl on the average and maximum height of the liquid level with relatively low gas velocity under stagnant conditions: (a) non-swirling flow; (b) swirling flow

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FIG. 8: Effects of swirl on relative liquid volume uploaded by gas \( (V/V_0) \), where \( V \) is the volume of the liquid uploaded by the gas phase and \( V_0 \) is the volume of the liquid at the initial time.

alternates between deformed large bubbles and liquid slug and some liquid film falls back to the upstream region of the swirler; however, with increasing gas velocity, the flow pattern in non-swirl flow remains slug flow, while the swirling intermittent flow in the swirling flow is observed downstream from the swirler and the liquid film without fallback to the upstream region of the swirler. Also, with a continued increase in the gas velocity, the flow patterns in non-swirling flow is churn flow and the highest position of oscillating liquid film varies, while in the swirling flow, once the oscillating liquid film passes through the swirler, the swirler suppresses the liquid film fall back to the region upstream of the swirler, and then the gas velocity (which is greatly increased in the swirler) can carry more liquid out of the pipe. Therefore, the value of \( V/V_0 \) in swirling flow is higher than the value in non-swirling flow at relatively high gas velocity.

It can be concluded that the swirl is beneficial in unloading liquid when the gas velocity is relatively high. The reason for this is closely related to the morphology of the gas–liquid interface. According to the results on the interface morphology presented in Section 3, the flow pattern upstream of the swirler with low gas velocity is slug flow, and the swirler fails to suppress the liquid phase downstream from the swirler fallback to the area upstream of the swirler at relatively low gas velocity. With increasing gas velocity the swirler can suppress the liquid phase in slug flow at relatively high gas velocity; with a continued increase in the gas velocity the slug flow is gradually transformed into churn flow upstream of the swirler and the churn flow can be transformed into swirling annular flow once it is out of the swirler. This variation of the interface morphology is beneficial in unloading liquid by swirl with increasing gas velocity.

4.2 Critical Gas Velocity

The experiment showed that when the gas velocity was close to (but lower than) the critical gas velocity, liquid accumulated at the bottom of the pipe and the flow pattern at the lower part of the pipe was churn flow characterized by liquid film oscillating up and down, which was gradually transformed into annular flow along the streamwise direction. With increasing gas velocity, the liquid film moved upward; meanwhile, the amount of liquid accumulating at the bottom of the pipe was small and gradually vanished. Then, the gas velocity was recorded as the critical gas velocity in our experiment.

In the case of swirling flow, when the gas velocity reached the critical gas velocity, liquid film was not observed nearby the swirler \((z/D = 0–4.8)\). Along the streamwise direction, swirling liquid film was obviously observed. Compared with the critical gas velocity in the non-swirling flow, the critical gas velocity in the swirling flow was reduced by 14.2%, as shown in Fig. 9. The critical gas velocity in the swirling flow was lower than the velocity in
the non-swirling flow, indicating that under the effect of swirl the critical gas velocity can be reduced in the case of the flow with a zero liquid flow rate at the inlet. This result agrees with the results presented in Fig. 8, indicating that swirl is beneficial for liquid unloading at relatively high gas velocity.

4.3 Influence of the Initial Position of the Liquid Level

The effect of the initial position of the liquid level on liquid unloading was studied, as shown in Fig. 10. Six positions were studied: the liquid levels were 1, 2, and 3 m below the inlet of the swirler (at liquid level positions $z/D = 23.4$, $39.5$, and $55.6$, respectively); and 2, 1.5, and 1 m above the outlet of the swirler (at liquid level positions $z/D = 32.3$, $24.2$, and $16.1$, respectively). The effects of the initial position on liquid unloading are shown in Fig. 10. The $X$-coordinate denotes the gas velocity, while the $Y$-coordinate is the RLUA parameter used to describe the liquid unloading capability. Figure 10 shows that, compared with the RLUA value when the initial position of the liquid level is below the swirler ($z/D = 23.4$, $39.5$, and $55.6$), the RLUA value is higher when the initial position of the liquid level is above the swirler ($z/D = 32.3$, $24.2$, and $16.1$). This indicates that the swirl has a better effect on liquid unloading when the swirler is below the initial position of the liquid level. In addition, the effects of the initial position of the liquid level on the critical gas velocity were studied, and we found that the initial liquid level has no effect on the critical gas velocity.

4.4 Analysis of the Performance of Swirl on Liquid Unloading

4.4.1 Effects of Swirl on Slug Flow

For slug flow upstream of the swirler the flow velocity was relatively low. When the mixture passed through the swirler the flow area in the swirler was greatly reduced, leading to an increase in the flow velocity. The gas–liquid mixture was injected into the fluid once it was out of the swirler. However, at relatively low gas velocity the mixture velocity was still low once it passed through the swirler. Falling liquid film downstream from the swirler fell back to the upstream region of the swirler, leading to the swirler performing badly in relation to unloading liquid. With increasing gas velocity, the gas velocity was high in the swirler and was injected into the fluid downstream from the swirler. Due to the high gas velocity, the falling film in the liquid slug accumulated in the region downstream of the swirler without fallback to the upstream region of the swirler. Then, the swirler performed well in relation to liquid unloading since the fallback of liquid phase was suppressed.
4.4.2 Effects of Swirl on Churn Flow

With increasing gas velocity, slug flow was transformed to churn flow, characterized by liquid film oscillating up and down upstream of the swirler. The flow velocity increased when the fluid passed through the swirler, leading to the accumulation of liquid film downstream from the swirler. Meanwhile, under the effect of centrifugal force the thickness of liquid film was more uniform along the circumferential direction, and this was beneficial with respect to the gas carrying the liquid film.
For churn flow with relatively high gas velocity, churn flow was observed to transform to swirling annular flow once it was out of the swirler. Since the flow area in the swirler sharply decreased, the flow velocity increased and the phase distribution in the swirler was redistributed. The liquid film swirled upward under the effect of swirl, and the droplets entrained by the gas were thrown into the liquid film in the pipe wall. This is beneficial in liquid unloading. Therefore, the swirl flow performed well with respect to unloading liquid when the gas velocity was relatively high.

5. CONCLUSIONS

The effects of swirl on flow patterns and liquid unloading in gas–liquid two-phase vertical flow under stagnant conditions were investigated by visualization experiments in this study. To quantitatively describe the liquid unloading capability, a dimensionless parameter, the relative liquid unloading ability, was proposed. The major conclusions reached from this study are summarized as follows:

1. In gas–liquid two-phase flow under stagnant liquid situations, the interface morphology varies along the streamwise direction; this is different from flow with non-zero gas and liquid velocity. Two cases of zero and non-zero flow rates at the outlet/top of the test section were observed.

2. In the case of slug flow with relatively high gas velocity, the swirler can suppress the fallback of falling liquid film in the gas slug; In the case of churn flow with relatively high gas velocity, the flow can be transformed to swirling annular flow once it is out of the swirler.

3. The swirl is beneficial in unloading liquid when the gas velocity is relatively high and not beneficial in liquid loading with relatively low gas velocity. Under the effect of swirl, the critical gas velocity is reduced compared with that in non-swirling flow.

4. According to the RLUA parameter, the initial position of the liquid level has an influence on liquid unloading. Swirl performs better in unloading liquid when the swirler is located below the liquid level at the initial time.

All of these elements are very important in better understanding the behavior of swirl flow used to remove liquid in natural gas wells. One of the next challenges would be to establish a theoretical model to investigate the effect of swirl on liquid film in order to help understand the effect of swirl on the critical gas velocity under such conditions.

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REFERENCES

Bose, R., Unloading Using Auger Tool and Foam and Experimental Identification of Liquid Loading of Low Rate Natural Gas Wells, PhD, Texas A&M University, College Station, TX, 2007.
Krishna, M.S.R.V., Investigation of Swirl Flows Applied to the Oil and Gas Industry, PhD, Texas A&M University, College Station, TX, 2009.


