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Experimental study on the critical gas velocity of liquid-loading onset in an inclined coiled tube

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ABSTRACT

Coiled tubes have been widely used in gas fields with low permeability because of their small flowing section area and low critical gas rate of liquid loading. An accurate prediction of the critical gas rate in coiled tubes is the basis to optimize the production rate of a gas well. In the current study, an experiment was performed using air and water in pipes with inner diameters of 30 mm and 40 mm at an inclination angle of 15–76° from the horizontal. The pressure gradient at a gas rate of 10–160 m^3/d and a liquid rate of 1–10 m^3/d was measured. Meanwhile, 72 date points of the critical gas velocity of liquid loading were obtained based on observation and pressure gradient fluctuation characteristics. The effects of the inclination angle, pipe inner diameter and liquid velocity on the critical gas velocity were studied. The correlation between the pressure gradient at the liquid-loading condition and the critical gas velocity was also analysed. The Film model (Xiao, 2010) and the Belfroid model were evaluated against these data points. Two correction items were added to the Belfroid model to consider the effect of the pipe inner diameter and liquid velocity based on the experimental data. The performance of the modified model was significantly improved with an average error of 6.58% and an average absolute error of 11.63%.

1. Introduction

Horizontal wells have been widely drilled in gas reservoirs with low permeability because they have a larger drainage area and a higher production rate than vertical wells. However, in some gas fields, such as Daniudi (Zhou and Zhang, 2015), Sichuan and Sulige (Zhao et al., 2012) in China, the wellhead flowing pressure and production rate quickly decrease because of liquid accumulation at the bottom hole. To avoid liquid loading, a coiled tube is widely installed in the large tube with inner diameter (ID) of 75.9 mm at the early stage of production. More than 60 horizontal wells had installed coiled tubes in the Daniudi gas field in the last two years (Lai et al., 2016).

Meanwhile, the coiled tube supplies an injection path for the foaming agent. It is notably important for production engineers to precisely predict the critical gas rate of the liquid-loading onset because they can take appropriate measures to prevent liquid loading and extend the well production life based on the liquid-loading mechanism.

A horizontal well consists of a horizontal section, an inclined section and a vertical section. For a vertical gas well or vertical tube of a horizontal well, Turner et al. (1969) presented a film-movement model and an entrained-droplet model to predict the critical gas velocity of the liquid-loading onset. Based on the field data, they concluded that the entrained-droplet model could predict the loading condition better than the film-movement model. Turner's entrained droplet model was deduced from the force balance of an impending maximum drop in an air stream, which has become the classic method to predict the critical gas rate in vertical gas wells. Coleman et al. (1991) found that the unadjusted entrained droplet model tended to offer a better match in low-pressure gas wells. Later, Nosseir et al. (1997), Li et al. (2002), Zhou and Yuan (2010) and Wang et al. (2015) modified Turner's entrained droplet model based on the single liquid droplet model, which considered the effect of the flow regime, droplet deformation and liquid amount in the gas stream on the critical gas velocity. Meanwhile, investigators (Zabaras et al., 1986; Van't Westende et al., 2007; Belfroid et al., 2008; Van't Westende, 2008) noticed that the liquid loading should be characterized by the film instability, and the liquid droplet model may not be sufficient to predict the liquid-loading onset condition in a vertical gas well.

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For the inclined wellbore of a horizontal well, Van't Westende (2008) measured the critical gas velocity of an ID 50 mm pipe at inclinations of 10, 30, 60 and 80° from the horizontal at Delft University. Van't Westende found that the critical gas velocity first increased and subsequently decreased with the increase of the inclination angle. Yuan (2011) performed an experiment to study liquid loading in a vertical and slightly deviated setting in an ID 76.1 mm pipe at the multiphase flow loop facility of the Tulsa University Fluid Flow Projects (TUFFP). The results from these two experiments confirm the reverse of liquid film at the initiation of liquid loading. The increase in liquid flow rate increases the critical gas velocities.

Yuan (2011) determined the critical gas velocity based on the minimum pressure gradient criterion. In the same flow loop facility, Guner (2012) and Alsaadi (2013) tested the pressure gradient and liquid holdup and determined the critical gas velocity at inclination angles of 2–30° from the horizontal. The results show a significant effect of the inclination angle and liquid velocity on the critical gas velocity. Guner (2012) and Alsaadi (2013) noticed that partial liquid-film reverse flowing continued to occur at a gas velocity with minimum pressure gradient. Thus, both researchers determined the critical gas velocity based on the fully upward film flow.

Fiedler and Auracher (2004) presented an empirical correlation to predict the critical gas velocity of the film flooding point based on experiments, which included an angle correction term. Belfroid et al. (2008) introduced the proposed angle correction term into the Turner model to make it suitable for the inclined wellbore of a horizontal well. Hence, the essence of liquid loading in the Belfroid model is the reversed flowing of the liquid film. Xiao et al. (2010) proposed a film model to predict the critical gas velocity based on the average film thickness. Li et al. (2014) developed a two-variable (liquid velocity and deviation angle) curve-fit model and a mechanistic model based on experimental data from Guner (2012) and Alsaadi (2013). However, neither models consider the effect of the pipe diameter, and they only perform better in an 76.1 mm pipe.

Shi et al. (2014) conducted several groups of experiments to examine the liquid droplet shape in a gas flow wellbore with different inclination angles. Based on the observed droplet shape in the experiment, they proposed an analytical entrained-droplet model to predict the critical gas velocity of liquid loading in vertical, slanted and horizontal wellbores. According to the calculated results, Shi et al. (2014) concluded that the slanted wellbore has the maximum critical velocity, and the liquid most probably accumulates in the horizontal well.

Researchers have measured the critical velocity of liquid loading in inclined pipes with 50 mm and 76.1 mm. With the increasing number of coiled tubes in horizontal gas wells, further investigation of the liquid-loading mechanism in inclined coiled tubes is necessary. The objective of the paper is to present the results of an experiment performed to investigate liquid loading in 30 mm and 40 mm inclined coiled tubes and study the effect of the pipe inner diameters and liquid velocity on the critical velocity of liquid loading. Meanwhile, a new modified model is established based on experimental data.

2. Experiment facility

The existing two-phase (air and water) facility of State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation in Southwest Petroleum University has been modified to conduct the experiments. The experiment facility was constructed in 2014 and sponsored by China Petroleum and Chemical Corporation to study the two-phase flow in horizontal gas wells. The schematic of the test facility is shown in Fig. 1.

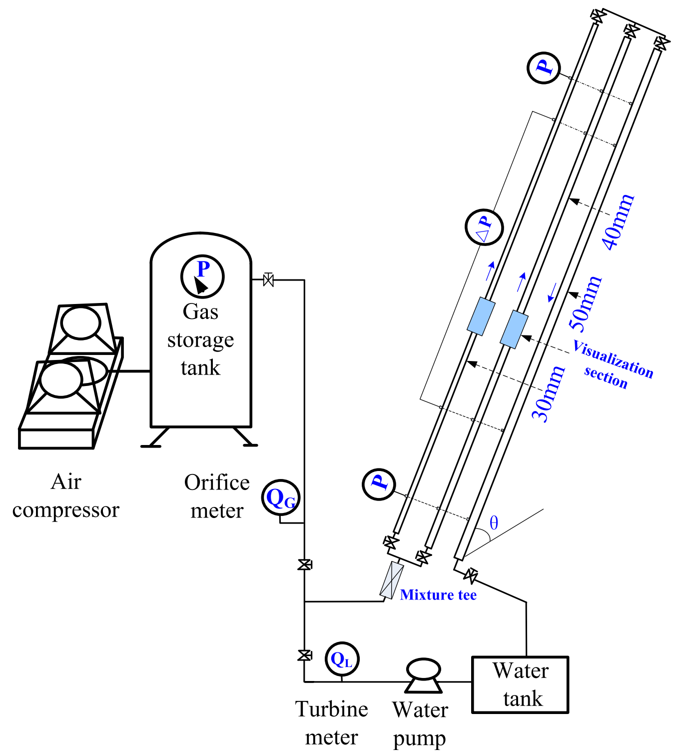

Fig. 1. Schematic of the experiment flow loop.

Three pipes were mounted on a movable ladder-shaped frame, which can be adjusted to any angle between vertical and horizontal. When it was adjusted to a certain angle, the movable frame was placed onto another vertical fixed frame to avoid swinging. Three pipes were made of transparent PVC material with a length of 8 m and a thickness of 5 mm; the inner diameter is 30, 40 and 50 mm. The 50 mm pipe was used for fluid returning.

Compressed air flowed through the gas storage tank, orifice meter, and valve into a mixture tee 2 m below the pipe entrance. The water supplied by a pump flowed through a turbine meter and into the mixture tee. The mixture tee was connected to the 30 mm and 40 mm pipes. The gas-liquid mixture flowed upward along the 30 mm or 40 mm pipes to the top and downward along 50 mm to the water tank. The mixture was separated at the water tank, where the gas was discharged into the atmosphere, and the water was recycled into a bump. In the current experiment, the pressure gradient and critical gas rate of the liquid-loading onset in the 30 mm and 40 mm pipes were measured. The inner diameter of the experimental pipe is almost identical to those of coiled tubes with inner diameters of 31.8 mm and 41.9 mm, which are widely used in gas wells.

In our experiment, two pressures at the bottom and top of the inclined pipe and the pressure drop of 4 m distance were tested. The pressure transducer has a range of 0–600 kPa with a precision of 0.5%. The differential pressure transducer has a range of 0–40 kPa with a precision of 0.5%. The turbine meter has a range of 0~1 m^3/h with a precision of 0.5%. The orifice meter has a range of 0–400 m^3/h with a precision of 0.25%.

The experiment was conducted with six different inclination angles: 15, 30, 40, 50, 67 and 77° from the horizontal. The superficial liquid rate was 1, 2, 4, 6, 8 and 10 m^3/d, which corresponded to liquid velocities of 1.64, 3.27, 6.55, 9.82, 13.1 and 16.4 cm/s in the 30 mm pipe and 0.92, 1.84, 3.68, 5.53, 7.37 and 9.21 cm/s in the 40 mm pipe, respectively. The gas rate was 10–160 m^3/h in the 40 mm pipe and 10–120 m^3/h in the 30 mm pipe with an average