Journal of Natural Gas Science and Engineering 57 (2018) 349–358

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Experimental and modeling studies on the prediction of liquid loading onset in gas wells

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ARTICLE INFO

Keywords:
Liquid loading
Liquid-film reversal
Critical gas velocity
Mechanistic model
Angle-correction term
Film thickness

ABSTRACT

Liquid loading is a major problem that limits production of gas wells. When liquid loading occurs, the gas well will suffer a rapid decrease in gas flow rate and eventually cease. An accurate prediction of liquid-loading onset is vital for operators to optimize production or take other measures in time. Through a careful review of previous studies, it's more reasonable to relate liquid-loading onset to liquid-film reversal rather than liquid-droplet reversal. However, few mechanistic approaches based on liquid-film reversal are available to predict the critical gas velocity. Furthermore, these models have complicated calculation and conservative results. This paper develops a more comprehensive and simpler analytical model for prediction of liquid-loading onset on the basis of liquid-film-reversal criterion. To reach this goal, experimental investigation has been conducted to analyze the effect of inclined angle and liquid velocity on the critical gas velocity. The Belfroid et al. (2008) angle-correction term has been adopted in the new model to predict critical gas velocity in inclined pipes. After validation against laboratory and field data from the published literature, this model has better performance compared with other models. Considering its simple form and high accuracy, the new model can provide a convenient approach for gas production engineers to predict critical gas flow rate.

1. Introduction

In gas wells, liquid loading is one of the main problems restricting natural gas production. When a well suffers liquid loading, the gas velocity is no longer sufficient to lift liquid to the surface. Generally, in the early stage of gas production, the high gas flow rate is capable of carrying liquid upward as film attached to the tubing wall and entrained droplets in the gas core. As the reservoir pressure declines, the decreasing gas production rate results in partial backflow of liquid, leading to liquid accumulation at the bottom of the wellbore. As a consequence of liquid loading, the rapid increase in hydrostatic pressure prevents production. Therefore, to keep a gas well producing with liquid unloading, the gas velocity should be above a critical value, which corresponds to the onset of liquid loading.

The earliest and most widely used model for prediction of liquid-loading onset was proposed by Turner et al. (1969). Based on the force balance of the largest droplet entrained in the gas core, they derived a semi-empirical equation by assuming the critical Weber number value of 44 and the drag coefficient value of 0.44. For security, an upward adjustment of 20% is added to the equation. By matching gas wells with low-wellhead pressure, Coleman et al. (1991) suggested that the 20% upward adjustment of Turner et al. (1969) model was unnecessary. Afterward, Nosseir et al. (2000), Li et al. (2002), Guo et al. (2005), Wang et al. (2015), and Fadili and Shah. (2017) have made some modifications to Turner's model by considering the impact of flow pattern, drag coefficient, liquid-droplet shape, kinetic energy, Weber number, and inclination on the critical gas velocity, respectively. Although droplet-reversal models have good acceptance in prediction of liquid-loading onset for their simple expressions, there is no direct evidence from experiments and gas wells to verify the connection between droplet reversal and liquid loading.

To shed light on liquid-droplet behavior in liquid loading, Van't Wenstende et al. (2007) conducted annular/churn air–water upward flow experiments in a 50-mm pipe. They found that the measured droplet diameter is much smaller than that assumed in Turner's model and no droplets were observed flowing counter-currently with gas flow. Furthermore, the experimental results of Sawant et al. (2008) and Alamu (2012) demonstrate that the droplet entrainment rate is much lower than that of the film when annular/churn flow is transforming. Especially in inclined pipes, droplets cannot be transported along the

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https://doi.org/10.1016/j.jngse.2018.07.023
Received 12 February 2018; Received in revised form 21 June 2018; Accepted 23 July 2018
Available online 26 July 2018

pipe for a long distance (Wang et al., 2018). Therefore, liquid-film reversal seems to be more reasonable for explaining the mechanism of liquid-loading onset.

With the aim of better understanding liquid-loading initiation, some experimental studies have been conducted based on liquid-film reversal. Yuan et al. (2013) conducted an experimental investigation in a 3-in pipe at inclined angles of 0°, 15°, and 30° from vertical. They applied minimum pressure gradient criterion to determine the critical gas velocity. Actually, they thought that the minimum pressure gradient corresponded to the liquid-film reversal, which is consistent with the studies of Hewitt et al. (1985) and Zabaras et al. (1986). However, Skopich et al. (2015) found that the liquid-film reversal differs from the minimum pressure gradient point in different pipe diameters by observing small bubbles entrained in the film. Guner (2012), Alsaadi (2013), and Wang et al. (2016) have conducted experimental research on the effect of pipe inclination on the critical gas velocity. They also determined the liquid-film reversal by direct observation. These experimental studies sought to identify the effect of pipe diameter, liquid velocity, and inclination on the critical gas velocity. However, these studies lacked analysis of the mechanism involved and were not systematic.

Different from the entrained-droplet criterion, it's more complicated to model liquid loading based on liquid-film reversal. Waltrich et al. (2015) experimentally investigated the liquid-film reversal and concluded that the empirical flooding correlation proposed by Wallis (1969) has good performance for prediction of liquid-film reversal. Subsequently, Riza et al. (2015) proposed a practical approach to deal with liquid loading which is considered to occur corresponding to churn/annular transition. They used the criterion given by Taitel et al. (1980) for the churn-annular transition. Based on the original Turner et al. (1969) criterion, Belfroid et al. (2008) and Wang et al. (2016) have added angle-corrected and liquid-corrected empirical terms for better understanding liquid loading, respectively. In spite of the simple form of these empirical correlations, they disconnect the critical gas velocity from fluid properties, such as the liquid flow rate and viscosity. Afterward, Luo et al. (2014) proposed a mechanistic model for prediction of liquid-loading onset in an inclined pipe based on the Barnea (1986) model. The Luo et al. (2014) model established an empirical equation for the non-uniform film distribution along the circumferential position. Later, Li et al. (2014) and Wang et al., 2018 modified the Luo et al. (2014) correlation for better performance in inclined pipes. Note that one of the most important parameters in these models is the average film thickness, which must be obtained from the Barnea (1986) model in vertical pipes.

Although many researchers have tried to model liquid-loading onset based on liquid-film reversal, a few mechanistic models are available currently. Due to the complicated form and calculation process of these film-reversal models, it's hard for gas production engineer to make a quick judgment about whether the gas well is suffering liquid loading.

The main objective of this study is to develop a more convenient and comprehensive model for prediction of liquid-loading onset in vertical and horizontal gas wells. To reach this goal, experimental investigation has been conducted to analyze the effect of liquid velocity and inclined angle on critical gas velocity and the angle-correction term has been adopted in the new model. The new model was validated against the experimental measurement and field data from the published literature.

2. Experimental setup

The current experiments were conducted at the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation of the Southwest Petroleum University. The experimental test setup consisted of a 5-m visual Perspex pipe with an inner diameter of 30 mm and a thickness of 5 mm. The schematic of the flow loop is shown in Fig. 1. The top of the pipe is tied with a movable block installed on a fixed vertical steel frame and the bottom is supported by a sliding support, which ensures that any desirable inclined angle between vertical and horizontal can be obtained.

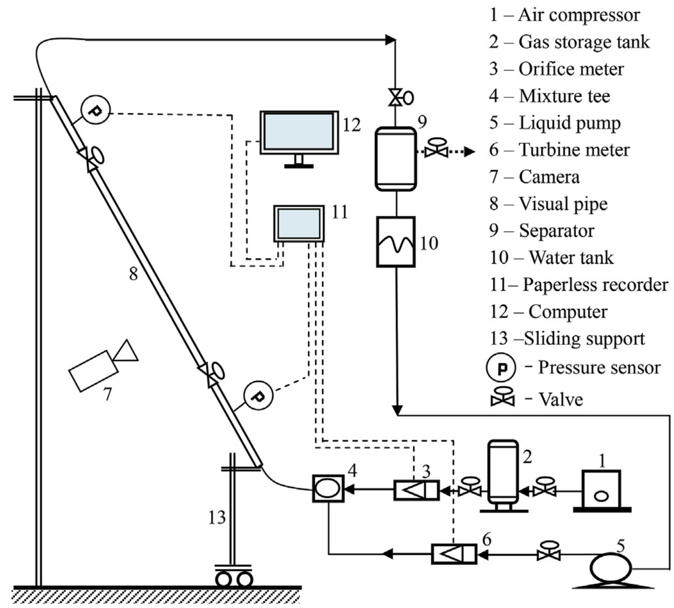

Fig. 1. Schematic of the experimental flow loop.

During the experiments, air supplied by the air compressor was stored in a gas storage tank. The air flow rate was controlled by a valve downstream from the tank and subsequently measured by an orifice meter with a range of 0–200 m^3/h and an accuracy of 1%. Meanwhile, the water was supplied by a pump and measured by a turbine meter with a range of 0–0.3 m^3/h and an accuracy of 2%. After the air and water were fully blended in a mixture tee, the air–water mixture flowed into the test section. The water was then recycled by a gas–liquid separator connected to the test-section outlet while the air was discharged.

To acquire a better understanding of two-phase flow, two pressure sensors were installed, one at the 1-m downstream entrance and the other at the 0.5-m upstream exit of the pipe. Liquid holdup was obtained by measuring the liquid volume with two quick-closing valves, which were located at distances of 1.5 and 4 m from the entrance of the pipe, respectively. In addition, liquid-film flow direction was recorded by using an Ultima APX high-speed camera (Fastcam Company). Note that all the measured data can be recorded by a paperless recorder linked to a computer.

In this study, 120 tests were conducted in a 30-mm pipe for vertical and inclined two-phase flow. The test matrix is designed to cover the transition boundary of churn and annular flow since the liquid loading is related to churn/annular transition. The superficial gas velocity varied from 5 to 28 m/s and the superficial liquid velocities were 0.01, 0.03, and 0.05 m/s. The inclined angles were 90°, 75°, 45°, and 15° from the horizontal. The transition boundary in the vertical pipe is predicted by Barnea (1986), Taitel et al. (1980), and Wallis (1969) models. In the inclined pipe, the maximum velocity for the transition boundary is predicted based on the angle-correction term proposed by Belfroid et al. (2008). Fig. 2 presents the test matrix and annular/churn transitions predicted by different models in the 30-mm ID pipe with a pressure of 0.1 MPa and an air density of 1.293 kg/m^3.

3. Experimental results and analysis

3.1. Recognition of liquid-loading onset

Based on liquid-film-reversal criterion, the widely accepted approach to determining the initiation of liquid loading in experiments is