Journal of Natural Gas Science and Engineering 33 (2016) 573–586

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

# Plastic bag model of the artificial gas lift system for slug flow analysis

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ARTICLE INFO

*Article history:*
Received 12 January 2016
Received in revised form
16 May 2016
Accepted 18 May 2016
Available online 25 May 2016

*Keywords:*
Artificial gas-lift system
Casing-heading
Slug flow
Plastic bag model
Third-order model

ABSTRACT

Artificial gas-lift systems are commonly used to enhance the production rate of mature oil wells. However, the technology is subject to casing-heading instability resulting in slug flow occurrence, which may significantly reduce the production rate and impose negative influences on downstream equipment. In order to analyze the casing-heading or slug flow phenomenon, a novel mathematical model for describing the behaviors of the gas-lift system is proposed, which is referred to as the 'plastic bag model'. The plastic bag model is realized by discretizing the differential equations describing the gas lift dynamics simultaneously with respect to both time and space, and the 'homogenous assumption' across the whole tubing is no longer necessary. Therefore, compared with the third-order models and the recently proposed high-order model, the plastic bag model can provide more accurate results in both stable and unstable modes. Moreover, the plastic bag model is much more computationally efficient compared with some other methods of solving nonlinear partial differential equations. Simulations for the plastic bag model are conducted, and comparisons between the plastic bag model and the third-order model are provided.

## 1. Introduction

In many oil fields, the reservoir pressure decreases with time, which results in the reduction of production rate to unsatisfactory level. The artificial gas-lift technique is among the most commonly used to enhance oil production, especially in mature oil wells (Scibilia et al., 2008; Salahshoor et al., 2013; Camponogara and Nakashima, 2006). In gas-lift wells, gas is injected into the tubing which decreases the density of the oil/gas mixture and reduces the downhole pressure caused by the weight of oil in the tubing, such that the production rate of oil is increased. A recent survey demonstrates that the gas-lift is responsible for more than 70% of the total oil production in Brazil (Plucenio et al., 2012). Although the gas-lift technology is used in many oil fields, there are still some challenging problems due to the dynamic interaction between the injected gas in the casing and the oil/gas mixture in the tubing (Scibilia et al., 2008). The most critical issue is the possibility of occurrence of large and regular oscillations of flows and pressure in the gas-lifted wells (Jepsen et al., 2013), which is referred to as the casing-heading instability problem in the oil and gas production process (Jansen et al., 1999). This mode results in the 'slugging flow problem' which is possible in a multi-phase fluid flow (Sun et al., 2002).

The problem of slug or casing-heading instability has several adverse consequences, which include production loss compared with stable flow regime, poor separation of downstream oil/gas mixture and possibility of damage to down-hole and surface equipment (Miresmaeili et al., 2015; Mahdiani and Khamehchi, 2015). Therefore, for years engineers and researchers from both academia and industry have been putting efforts into finding ways to stabilize the gas-lift system. And many mathematical models have been developed to describe the behaviors of the gas-lift dynamics. For example, hydrodynamic models are developed to characterize the 'slug flow' that travels along the pipe (Dukler and Hubbard, 1975; Fernandes et al., 1983). For the purpose of controller or observer design, the most commonly used models are third-order ordinary differential equation (ODE) based models built upon the mass balance principle (Scibilia et al., 2008; Jepsen et al., 2013; Imsland, 2002; Imsland et al., 2003; Eikrem et al., 2004a, 2004b, 2008; Aamo et al., 2004; Aamo et al., 2005; Jahanshahi et al., 2008; Garcia, 2013; Hussein et al., 2015). The advantages of those third-order models include the possibility of capturing the dynamics of the casing-heading phenomenon, and providing an insight into methods of controller and observer design. However,

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http://dx.doi.org/10.1016/j.jngse.2016.05.055
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they use the assumption of ‘homogenous mixing’ along the tubing, which means that the gas is mixed with the oil uniformly along the whole tubing and mixing happens immediately after gas enters tubing. It is not difficult to understand that this assumption is valid only in steady states, and may not be able to produce accurate dynamics of the behavior of the gas-lift system when the casing-heading phenomenon occurs. In addition, due to the ‘homogenous assumption’, the slug flow regime cannot be observed.

In addition to these simple ODE models, commercial software tool such as the Fluent, Comsol and OLGA (Bendiksen et al., 1991) can also be used to develop detailed and relatively complex models for the gas-lift system, which are based on nonlinear partial differential equations (PDE). Although these simulation-oriented models can provide much more accurate results compared with those third-order ODE models (further referred to as third-order model for simplicity), they suffer from the difficulty of mathematical analysis and trial-and error sensitivity analysis (Di Meglio et al., 2010). Besides, these PDE models are often very time-consuming due to their low computational efficiency.

In order to solve the above mentioned issues, we propose a novel model based on our previous work (Hussein et al., 2015), which is referred to as the ‘plastic bag model’. It can be used for analysis of casing-heading phenomenon in gas-lift systems, control design and optimization. The model involves a new approach to the discretization of the partial differential equations describing dependence of process variables on the depth and those describing dependence of process variables on time. The model considers amounts of gas and oil supplied to the tubing over a certain time step as virtually enclosed in a plastic bag of cylindrical shape. Therefore, flow of oil/gas mixture in the tubing is considered as motion of discrete masses of oil and gas mixture virtually wrapped by a series of ‘plastic bags’. Bags are stretchable; pressures and densities in each “plastic bag” and conditions at the boundaries between neighboring bags obey the state equations of oil/gas mixture (Hussein et al., 2015). This is a distinctive feature of the proposed model, and therefore we name it as the ‘plastic bag model’. With the upward movement of the oil/gas mixture in the tubing, all bags move up and can change the size due to the change of pressure; top bags are emptied and new bags are added at the bottom. In this approach, the ‘homogenous assumption’ of the third-order models along the whole tubing is no longer required, and the slug flow regime can be clearly identified. In addition, the plastic bag model is much more computationally efficient compared with some software such as Fluent.

The paper is structured as follows. In Section 2, our previous work on the third-order model is briefly reviewed, followed by the detailed presentation of the proposed plastic bag model in Section 3. In Section 4, simulation results and discussions regarding the plastic bag models are provided, so are the comparisons between the third-order model and the plastic bag model. In Section 5, conclusions are given.

## 2. The third-order model

In this section, the third-order model developed for a vertical gas-lifted well in our previous work (Hussein et al., 2015) is briefly introduced, which is illustrated in Fig. 1. Note that in this model, only two-phase flow, i.e. oil and gas is considered. Yet water content can easily be accounted for by changing the properties of the liquid.

The ideal gas law is assumed to hold, and according to the momentum balance of gas, the pressures at the injection point and top of annulus, i.e. $p_{ai}$ and $p_{at}$, can be calculated as per (Imsland, 2002):

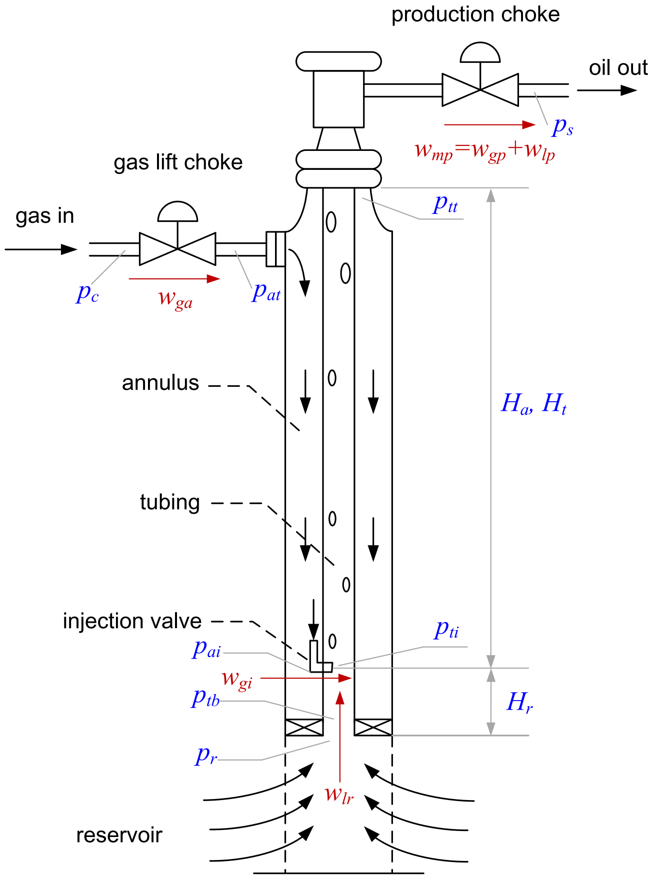

**Fig. 1.** Schematic of the simplified third-order model.

$$p_{ai} = \frac{m_{ga}g}{A_a}\frac{1}{1-e^{-\frac{gM}{RT_a}H_a}} \tag{1}$$

$$p_{at} = p_{ai}e^{-\frac{gM}{RT_a}H_a} = \frac{m_{ga}g}{A_a}\frac{e^{-\frac{gM}{RT_a}H_a}}{1-e^{-\frac{gM}{RT_a}H_a}} \tag{2}$$

Denote the gas/oil mass ratio in the tubing as $\lambda = m_{gt}/m_{lt}$, and with the ‘homogeneous assumption’, $\lambda$ is constant across the entire tubing. Then, pressures in the tubing can be computed as follows

$$p_{ti} = \frac{(m_{gt}+m_{lt})g}{A_t}\frac{1}{1-e^{\frac{(m_{gt}+m_{lt})g-aA_tH_t}{A_tb}}} \tag{3}$$

$$p_{tt} = \frac{(m_{gt}+m_{lt})g}{A_t}\frac{e^{\frac{(m_{gt}+m_{lt})g-aA_tH_t}{A_tb}}}{1-e^{\frac{(m_{gt}+m_{lt})g-aA_tH_t}{A_tb}}} \tag{4}$$

$$p_{tb} = p_{ti} + \rho_l g H_r \tag{5}$$

where $a = \rho_l g(1+\lambda)$ and $b = \lambda\rho_l T_t/M$ are intermediate variables. In addition, the density of the oil/gas mixture at the top of the tubing, $\rho_m$, can be calculated by

$$\rho_m = \frac{1+\lambda}{\lambda\frac{RT_t}{p_{tt}M}+\frac{1}{\rho_l}} \tag{6}$$

Detailed derivations for Eqs. (3)–(6) can be found in (Hussein et al., 2015).