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Linear and non-linear analysis of flow instability in gas-lift wells

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ABSTRACT

Linear and non-linear analyses of flow instability in continuous gas-lift wells were performed in this study. The linear analysis is based on a modified gas-lift stability criterion that takes into account compressibility of the mixture below the injection point and is applicable to saturated reservoirs. The analysis of non-linear dynamics and stability of the well was performed using direct numerical integration in the time domain of the governing equations describing the gas-lift system. The transient gas-lift well model developed comprises of a model of transient three-phase gas–oil–water flow in the wellbore, a transient model of gas flow in the casing annulus, and a pseudo-steady flow model in the reservoir. The multiphase flow model used is based on the drift-flux theory. Stability boundaries predicted by both linear and non-linear analysis were compared with field data published in a previous study; both types of analysis reproduced the data. The effects of the main well design and flow parameters on the frequency and amplitude of the oscillations during heading in a typical gas-lift well were studied. It was found that flow instability results in the oil production loss, which depends on severity of heading. The largest reduction in oil production takes place in case of the most severe heading in the well (flow instability with the largest amplitude of production rate oscillations). An increase in the lift gas consumption is required to compensate for the production losses caused by heading. An increase in the depth of the injection point may result in heading and an increase in the operating costs caused by the increase in the lift gas consumption. An increase in the separator pressure has a destabilizing effect. At high separator pressures the well can experience two modes of instabilities: casing heading and density-wave oscillations.

1. Introduction

Flow instability (heading) in continuous flow gas-lift wells has been the subject of many studies over the last three decades (Alhanati et al., 1993; Asheim, 1988; Blick et al., 1988; Fairuzov et al., 2004; Grupping et al., 1984a, 1984b; Hu, 2004; Hu and Golan, 2003; Poblano et al., 2002). Heading is the reason of many problems in the operation of oil production facilities (Alhanati et al., 1993) and finally leads to an increase in the operating costs. Two types of instabilities in gas-lift systems have been identified: casing heading and density-wave instability. The former is associated to variations of the injected gas flow rate caused by variations of the density of the multiphase fluid in the tubing downstream the injection point (Asheim, 1988). The flow in a gas-lift well can be also unstable even the downhole gas injection rate is constant due to density-wave oscillations (Hu, 2004; Hu and Golan, 2003). Self-excited pressure and flow rate oscillations in the tubing may either diverge (result in the complete loss of liquid production and gas recirculation) or reach a self-sustained periodic mode (heading).

Two different approaches have been proposed in the literature to analyze gas-lift instability. The linear analysis has been used to develop flow stability criteria in terms of flow and well design parameters by different authors (Alhanati et al., 1993; Asheim 1988; Blick et al., 1988). In this type of analysis, the response of the system, which is initially at equilibrium, to an infinitesimal perturbation of tubing pressure at the injection point is predicted. To obtain practical analytical criteria, several strong simplifications in the description of the system are made. The stability criteria can be used to develop gas-lift stability maps (Fairuzov et al., 2004; Poblano et al., 2002), which significantly reduce the time required for the analysis. The disadvantage of the linear stability analysis is that it only predicts the onset of instability and cannot be used to model the operation of well in the unstable region.

The second approach to studying flow instability in gas lift-wells, the non-linear analysis, is usually based on numerical modeling of multiphase flow in the tubing. This technique has been used to develop active control systems to eliminate heading (Dalsmo et al., 2002; Eikrem et al., 2002, 2004; Hu and Golan, 2003; Jansen et al., 1999; Scibilia et al., 2008; Sinègre et al., 2005).

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Nomenclature

C_D	discharge coefficient
C_S	flow coefficient
d	orifice size, L, m (ft)
ΔH	vertical distance between the injection point and the perforated interval, L, m (ft)
f	friction factor
g	acceleration of gravity, L/t^2, m/s^2 (ft/s^2)
J	productivity index, L^4t/m, std. m^3/s Pa (scf/s psi)
K	production choke's loss coefficient
k	ratio of specific heats
M	molecular weight, M, kg/kg mol (lbm/lbm mol)
m	mass flow rate, m/t, kg/s (lbm/s)
p	pressure, m/Lt^2, Pa (psia)
q	flow rate, L^3/t, m^3/s (ft^3/s)
R	universal gas constant, L^2m/Tt^2M, N m/kmol K (ft lbf/lbm mol R)
T	temperature, T, K (R)
t	time, t, s
V	volume, L^3, m^3 (ft^3)
v	velocity, L/t, m/s (ft/s)
x	axial coordinate, L, m (ft)
y	ratio of downstream and upstream pressure of the downhole gas-lift orifice valve
z	gas compressibility factor

Subscripts

avg	average
c	casing
ch	downhole gas-lift orifice valve
f	reservoir fluids
g	gas
i	injection point
L	liquid
m	mixture
o	oil
R	reservoir
r	relative
sc	standard conditions
sv	surface gas-lift valve
t	tubing
w	water

Greeks

α	holdup
γ	specific gravity of gas
ρ	density, m/L^3, kg/m^3 (lbm/ft^3)

The non-linear analysis can be used to study the system behavior when the operating parameters of a gas-lift well exceed the stability limits. The non-linear well models predict the amplitude and frequency of oscillations of flow parameters (tubing and casing pressure, liquid and gas flow rates, liquid holdup, etc.) The main disadvantage of this method is that is time-consuming. Also, it takes a lot of efforts to obtain an agreement between the model predictions and field data for all operating conditions of a well.

In this paper, the results, obtained using the linear gas-lift stability theory for an offshore gas-lift well with unstable flow due to casing heading, are compared to those of a non-linear analysis. The analysis of non-linear dynamics and stability of the well was performed using direct numerical integration in the time domain of the governing equations of multiphase flow in the tubing. Stability boundaries predicted by both linear and non-linear analysis are compared with field data using gas-lift stability maps. The effect of the main well design and flow parameters on the frequency and amplitude of the oscillations during heading is studied. Density-wave instability in a well with constant gas injection rate is also analyzed.

2. Linear stability analysis

In the present study, the linear analysis was carried out using two gas-lift stability criteria proposed by Asheim (1988). The first Asheim's stability criterion can expressed in the following form:

$$F_1 = \frac{(-1/q_{fi})\cdot(\delta q_{fi}/\delta p_{ti})}{(-1/q_{gi})\cdot(\delta q_{gi}/\delta p_{ti})} > 1 \tag{1}$$

The flow is stable when the inequality given by Eq. (1) is satisfied. To obtain this criterion, Asheim assumed that flow is incompressible below the injection point and the production rate at the perforated interval is a linear function of the bottomhole flowing pressure. These assumptions cannot be used for the modeling of gas-lift wells producing below the bubblepoint pressure. To take into account the presence of gas below the injection point, the derivative of the wellbore fluid flow rate with respect to the tubing pressure at the injection point can be calculated as follows:

$$\frac{\delta q_{fi}}{\delta p_{ti}} = \frac{\delta q_{fi}}{\delta p_{wf}}\frac{\delta p_{wf}}{\delta p_{ti}} \tag{2}$$

The first derivate from the right hand side of Eq. (2) can be easily calculated from the Vogel's equation (Vogel, 1968). The second derivative can be calculated either numerically using a correlation of two-phase flow or analytically assuming that the flow is homogeneous and the pressure gradient due to friction is negligible, i.e. $p_{wf}=p_{ti}+\rho_{m,avg}g\Delta H$. In the homogeneous flow, the mixture density is only a function of pressure and the calculation of its derivative with respect to pressure is straightforward. In this work, the gas solubility required for the calculation of the no-slip holdup was calculated using the Standing correlation (Standing, 1957). To take into account the design of gas injection system the original second criterion proposed by Asheim (1988) was used. Both criteria were used to carry out the linear stability analysis.

3. Non-linear analysis

A transient gas-lift well model was developed to perform the non-linear stability analysis. It comprises of a model of transient three-phase gas–oil–water flow in the wellbore, a transient model of gas flow in the casing annulus, and a pseudo-steady flow model in the reservoir.

The drift flux model (Kim and Doster, 1991; Liles and Reed, 1978; Xiao et al., 1994) was used to simulate multiphase flow in the well. The proposed model is based on three mass conservation equations (for mixture, oil, and water) and the mixture momentum equation (Appendix A). The flow patterns considered are bubble flow and slug flow. The thermodynamic properties of