International Journal of Multiphase Flow 83 (2016) 183–201

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Effect of surfactants on liquid loading in vertical wells

Abdulkamil Ajani[a,*], Mohan Kelkar[b], Cem Sarica[a], Eduardo Pereyra[a]

[a] McDougall School of Petroleum Engineering, College of Engineering and Natural Sciences, The University of Tulsa, 800 South Tucker Drive, Tulsa, OK 74104, USA
[b] Williams Endowed Professor and Chairman, McDougall School of Petroleum Engineering, The University of Tulsa, 800 S Tucker Drive, Tulsa, OK 74104, USA

ARTICLE INFO

Article history:
Received 8 July 2015
Revised 8 February 2016
Accepted 22 March 2016
Available online 12 April 2016

Keywords:
Vertical pipes
Gas well deliquification with surfactants
Flow regimes in foam flow
Pressure gradient
Liquid holdup
Critical velocity under foam flow

ABSTRACT

Most gas wells produce some amount of liquid. The liquid is either condensate or water. At high rates, the gas is able to entrain liquid to the surface; however, as gas well depletes, the liquid drops back in a gas well (called liquid loading) creating a back pressure on the reservoir formation. Addition of surfactants to the well to remove liquid is one of the common methods used in gas wells. Liquid loading in vertical gas wells with and without surfactant application was investigated in this study. Anionic, two types of amphoteric (amphoteric I and amphoteric II), sulphonate and cationic surfactants were tested in 2-inch and 4-inch 40-feet vertical pipes. Pressure gradient and liquid holdup are measured. Visual observation with a high speed camera was used to gain insight into the direction of foam flow in intermittent flow and foam film flow under annular flow conditions.

Liquid loading is initiated when the liquid film attached to the wall in annular flow starts flowing downwards. Introduction of foam causes the gas velocity at which film reversal occurs to decrease; this shift increases with increasing surfactant concentration and it is more pronounced in 2-inch pipe than in 4-inch pipe. That is, the benefit of surfactants is much more pronounced in 2-inch pipe than in 4-inch pipe. The reason for postponement of liquid loading is reduction in the liquid holdup at low gas velocities which reduces the liquid holdup in foam flow compared to air-water flow. However, at higher gas velocities, the pressure drop in 2-inch compared to 4-inch pipe increases rapidly as the surfactant concentration increases. The selection of optimum concentration of the surfactant is a balance between the reductions in the gas velocity at which liquid loading occurs compared to increase in the frictional loss as the concentration increases. We provide guidelines about the selection of the surfactant concentration.

Visual observations using high speed camera show differences in the behavior under foam flow conditions. Unlike air-water flow, the liquid film attached to the wall is replaced by thick foam capturing the gas bubbles. The type of roll waves which carry the liquid in 2-inch pipe is different than what was observed in 4-inch pipe. Compared to 4-inch pipe, the roll waves in 2-inch pipe are much thicker. This partly explains the differences in 2-inch versus 4-inch pipe behavior.

1. Liquid loading

The reservoir pressure and the corresponding gas rate in a well are expected to decline with time. As this occurs, gas and condensate wells accumulate liquids in the wellbore during gas production. Fig. 1 shows the approximate flow regimes as gas velocity decreases in a vertical gas/liquid well and the well progresses through the stages of liquid loading.

In Fig. 1, a well flowing as a mist of liquid in gas will have a relatively low gravity-pressure drop. However, as the gas velocity begins to drop the flow regime in the well becomes slug flow and then bubble flow. As this transition occurs, a larger fraction of the tubing is filled with liquid. The liquids accumulated in the wellbore will cause additional hydrostatic pressure on the reservoir; this results in reduction of available transportation energy thereby affecting the production capacity. The higher the percentage of liquid in the column, the higher is the back pressure. When the liquid height creates a back pressure equal to the formation pressure, gas production drops to zero.

Source of liquid in a gas well include condensate when the gas well is producing from either wet gas or retrograde condensate reservoir. It can also come from the formation water which condenses in the well bore, or an underlying aquifer (Lea and Nickens, 2004). A liquid loaded well may still produce for a long time. Symptoms for recognizing a liquid loaded well are as follows:

---

[*] Corresponding author. Tel.: 918 814 4276.
E-mail addresses: ayantayo-ajani@utulsa.edu (A. Ajani), mohan@utulsa.edu (M. Kelkar), cem-sarica@utulsa.edu (C. Sarica), eduardo-pereyra@utulsa.edu (E. Pereyra).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.03.019
0301-9322/

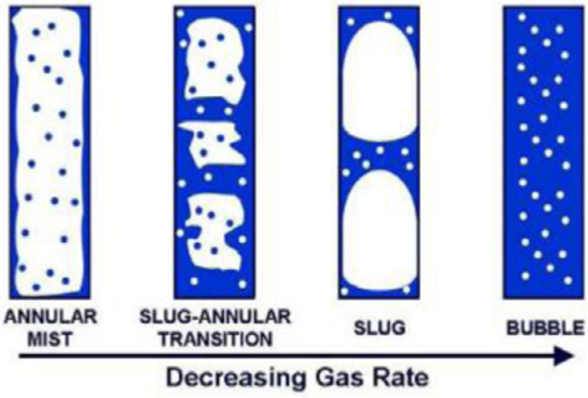

Fig. 1. Flow regimes of a naturally flowing vertical gas well as it progresses through the stages of liquid loading (Bondurant, Dotson and Oyewole, 2007).

- Increasing difference between the tubing and casing flowing pressures with time, measurable without packers present.
- Sharp changes in gradient on a flowing-pressure survey.
- Sharp drop in a decline rate.
- Slugging at the well head, upstream of any liquid knock-out device or separator, where this has not occurred before.
- A wireline pressure survey or sonic fluid level shot down the tubing while the well is producing gas shows the existence of a gassy liquid level in the tubing (Guidelines and Recommended Practices, http://alrdc.com, 2014).

One of the most important challenges operators of marginal gas wells tackle is maintaining sustained production from these wells. One of the strategies is to use surfactant or foam. In general, foam is applicable to wells producing large amount of water and relatively small amount of condensate.

In this paper, brief background review of surfactants is provided in terms of their definition, advantages in gas well deliquification, how they work and selection criteria. Current criteria for predicting onset of liquid loading in air-water foam flow are reviewed. Previous studies on hydrodynamics of air-water foam flow are also presented. This study presents the pressure drop, liquid holdup and foam flow regimes for five different surfactants. The (Luo, 2013) residual pressure gradient approach was extended to predict the transition from annular to intermittent flow in air-water foam flow.

2. Foam assisted lift

2.1. Surfactants: structure and advantages in gas well deliquification

Surfactants are usually organic compounds that are amphiphilic, meaning they contain both hydrophobic groups (their tails) and hydrophilic groups (their heads). Therefore, a surfactant molecule contains a water insoluble (or oil soluble component) and a water soluble component. Surfactant molecules will migrate to the water surface, where the insoluble hydrophobic group may extend out of the bulk water phase, either into the air or, if water is mixed with oil, into the oil phase, while the water soluble head group remains in the water phase. This alignment and aggregation of surfactant molecules at the surface, acts to alter the surface properties of water at the water/air or water/oil interface (Surfactant, Wikipedia, 2014).

The advantages of using surfactants for gas well deliquification are as follows:

- Cost effectiveness (low set-up and operating cost)
- Versatility for different completions and environments
- To boost mechanical artificial lift methods
- Tolerance of particulates, pressure and high temperature
- Rapid response from wells
- Automated continuous programs
- Customized foamer combination products can control downhole corrosion, scale or paraffin problems (Heuvei and Adelizzi, 2014).

2.2. How surfactants unload liquid from gas wells

When foamers are applied to gas wells, they act as surface active agents which reduce surface tension of liquid by adsorbing at the liquid-gas interface. They also reduce the interfacial tension between oil and water by adsorbing at the liquid-liquid interface. Many surfactants can also assemble in the bulk solution into aggregates. Examples of such aggregates are vesicles and micelles. Surface tension falls with surfactants addition till the surfactant molecules begin to form micelles in bulk solution. The concentration at which surfactants begin to form micelle is known as the critical micelle concentration (CMC).

The reduction in surface or interfacial tension allows for gas dispersion rate to increase hence forming a foam structure. Foam assisted lift can be accomplished by dropping soap sticks, or by injecting surfactant in the well through capillary strings. Surfactants migrate to the interface where their hydrophilic and hydrophobic portions change the surface characteristics. The foam created consists of small gas bubbles surrounded by thin lamella within which water and condensate are held as shown in Fig. 2.

The swarm of gas bubbles increases gas holdup, hence the gravitational gradient is reduced. The gas slippage under air-water foam flow is lower compared to air-water flow, this causes the gas to be produced with the liquid in the lamella; hence foam postpones the transition from annular to slug flow. In addition to reducing gravitational gradient, foam also increases frictional gradient. As explained later, this also helps the postponement of liquid loading.

2.3. Surfactants selection criteria

For proper selection of products, different laboratory tests are often conducted on surfactants to determine their foaming characteristics and unloading potential at different surfactant concentrations, temperatures, water composition and water/hydrocarbon ratios (Heuvei and Adelizzi, 2014. Schinagl, Caskie, Green, Docherty and Hodds, 2007. Solesa and Sevic, 2006. Willis, Horsup and Nguyen, 2008. Xu and Yang, 1995). These laboratory tests include surface tension tests (static or dynamic), stability test and unloading rig test. Parameters determined from these tests include reduced surface tension due to surfactant in solution, maximum foam height/foam volume, half-life, drainage of liquid and volume of liquid unloaded with time. The best surfactant for a particular application is selected based on a combination of aforementioned parameters from the laboratory tests. The concentrations of surfactants used in this study are based on results from surface tension tests, foam stability and liquid unloading tests conducted on a Bench top facilities (Ajani, 2014).

3. Prediction of liquid loading in air-water foam flow

The Turner's eqation (Turner, Hubbard, and Duckler, 1969) serves as a basic model for estimating the minimum critical velocity required to maintain annular flow in a flowing gas well without application of surfactant. This equation is written as below

$$v_{G,T} = 6.558\left[\frac{\sigma\left(\rho_L - \rho_G\right)}{\rho_G^2}\right]^{0.25} \tag{1}$$