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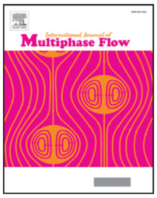

Foam flow in vertical gas wells under liquid loading: Critical velocity and pressure drop prediction

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ABSTRACT

Foam lift is one of the most cost effective methodologies for unloading gas wells. The surfactants are either injected intermittently or continuously to lift the liquid to the surface. By reducing the gravitational gradient and increasing the frictional gradient, the critical velocity at which liquid loading occurs is shifted to lower gas velocities. Currently, we do not have a methodology to predict the critical velocity (at the transition boundary of annular and intermittent flow) and the pressure drop under foam flow conditions.

To address this, we measured several foam flow characteristics in both small scale and large scale facilities. Small scale facility involved measurement of foam carryover capacity as a function of time and surfactant concentration. Large scale facility involved measurement of liquid holdup, pressure drop, fraction of gas trapped in foam and foam holdup in 40-ft 2-in. and 4-in. tubing.

We developed closure relationships for liquid hold up, foam holdup, fraction of gas trapped in the foam and interfacial friction factor by combining the small scale data with the data collected in the large scale experiments. These closure relationships are applicable to four different surfactants tested. A new transition criterion was developed and successfully used to predict onset of liquid loading under foam flow. Using a force balance over the gas core in annular flow, we developed a new procedure to calculate the pressure drop under foam flow conditions. We compared our model results with actual measurements in the large scale facility. Our model was reasonably able to predict the pressure drop within ±30%. The reason for such a large variance is that the small scale facility was not able to capture all the characteristics of the foam which were observed in the large scale facility. It is very difficult to reproduce the foam characteristics exactly in two different experiments. This is discussed further in this paper.

The procedure developed is the only one currently available to calculate the pressure drop under the foam flow conditions using the small scale data. It is superior to conventional annular flow pressure drop prediction models which are currently available in the literature.

1. Introduction

Foaming agents are used globally for removal of water from loaded wellbores. Regrettably, no model exists to predict the critical velocity and pressure drop under foam flow conditions. Hence, marginal gas well operators are unable to accurately predict the performance of the wells under foam flow conditions.

Several papers have been published in the literature to evaluate the performance of foam flow. Our focus is on the prediction of critical velocity and pressure drop under foam flow in vertical gas wells suffering from liquid loading problems. Most of the papers in the literature have concentrated on the application of foam under field conditions. Limited work on theoretical understanding of foam flow, critical velocity and the pressure drop under foam flow conditions are reported in the literature.

Soni et al., (2009) compared the results of a simple drift flux model with actual pressure drop observations under foam flow conditions. Foregoing authors obtained their result by assuming a different surface tension value for each well. While the results are promising, no information was provided about the surfactants used and their concentration.

Although widely used, no models exist to predict critical velocity (velocity needed to unload the well) and pressure drop in gas wells operated under foam flow. The objectives of this study are as follows:

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Nomenclature

a, b, c, n1	Constants, (-)
d	Pipe diameter, (m)
g	Accelaration due to gravity, (m/s^2)
L	Pipe length, (m)
n	Exponent in foam viscosity, (-)
A_C/A_G	Area of core/Area of gas in core, (m^2)
A_F	Area of foam film, (m^2)
A_p	Area of pipe, (m^2)
C_F	Coefficient in foam friction factor, (-)
d_F	Hydraulic diameter of foam film, (m)
d_C	Hydraulic diameter of the core, (m)
f_g	Fraction of gas trapped in foam, (-)
f_I	Interfacial friction factor, (-)
f_F	Foam friction factor
h_F	Foam holdup, (-)
h_g	gas void fraction, (-)
H_L	Liquid holdup, (-)
n_F	Exponent in foam friction factor, (-)
q_{gc}	Volumetric flowrate of gas in the core, (m^3/s)
q_g *in foam*	Volumetric flowrate of gas in foam, (m^3/s)
$q_{g(Total)}$	Total volumetric flowrate of gas, (m^3/s)
q_L	Volumetric flowrate of liquid, (m^3/s)
Re	Reynolds number, (-)
S_I	Perimeter of interface, (m)
S_F	Perimeter of foam film, (m)
μ_C/μ_G	Core or gas viscosity, (Kg/m.s)
μ_F	Foam viscosity, (Kg/m.s)
μ_L	Liquid viscosity, (Kg/m.s)
v_F	Velocity of foam film, (m/s)
v_C/v_G	Core or gas velocity, (m/s)
τ_I	Interfacial shear stress, (Pa)
τ_{wF}	Foam film wall shear stress, (Pa)
δ_F	Foam film thickness, (m)
θ	Pipe inclination angle, (degrees)
ρ_F	Foam density, (Kg/m^3)
ρ_C/ρ_G	Core or gas density, (Kg/m^3)
ρ_L	Liquid density, (Kg/m^3)
ρ_F	Foam density, (Kg/m^3)
v_{SL}	Superficial liquid velocity, (m/s)
v_{Sg}	Superficial gas velocity, (m/s)
$\tilde{\delta}_F$	Dimensionless foam film thickness, (-)
$\tilde{\delta}_{F,\ MIN}$	Dimensionless critical foam film thickness at the minimum point, (-)
π	pie (3.142)
$(\frac{dP}{dL})_F$	Pressure gradient in foam film, (Pa/m)
$(\frac{dP}{dL})_C$	Pressure gradient in the gas core, (Pa/m)
$\frac{\Delta P}{\Delta L})_{Experiment}$	Experimental pressure gradient, (Pa/m)
$\left.\frac{v_{lr\ \ ss}}{v_{lr\ \ ss}}\right]_{6.2\ mm/s}$	Unloading potential at 6.2 mm/s bench top experiment gas sparge rate, (-)

- To develop closure relationships for the following variables under foam flow: liquid holdup, foam holdup, fraction of gas trapped in the foam and interfacial friction factor under foam flow.
- To develop mechanistic models for calculating the critical velocity under foam flow.
- To build a mechanistic model for predicting pressure drop under foam flow.

In this study, experimental data are collected under foam flow conditions for five different surfactants in 2 and 4-in. 40-ft vertical pipes at different superficial gas and liquid velocities. Surfactants tested are Anionic, two different Amphoteric, Sulphonate and Cationic.

We conducted three bench top tests using the five surfactants listed above. These tests are surface tension, stability and liquid unloading tests. The value of optimum concentration of each surfactant is obtained from these tests. We also conducted large scale tests at and around the optimum concentration for all five surfactants. This has become necessary because operators will apply the surfactants at the optimum concentration in order to maximize its benefits. The bench top and large scale tests will be briefly discussed in this study.

From the unloading rig test in the bench top test, we defined unloading potential for each surfactant. This is the unloading benefit associated with using a higher concentration of the surfactant.

The unloading potential from the bench top test was used alongside superficial liquid and gas velocities from the large scale experiments to develop a closure relationship for liquid holdup under foam flow. Using this and other data from large scale facilities, we developed closure relationships for foam holdup, fraction of gas trapped in foam (foam quality), and interfacial friction factor.

Using aforementioned closure relationships, the Barnea, (1986b) transition criterion for air-water flow was modified for foam flow to obtain the critical velocity. Hence, experimental data points in the annular flow regime are identified. These are the data points for which, we predicted the pressure drop. The force balance over the gas core in annular flow was solved to obtain the pressure gradient under foam flow for the two interfacial friction factor closure relationships developed. The models developed are verified with the experimental data.

2. Experimentation

Two sets of experimental facilities were used in conducting this study: the bench top facilities and the large scale facility. The bench top facilities are a tensiometer for surface tension tests, a vertical acrylic pipe for stability tests and liquid unloading tests. Out of the small scale tests, only the liquid unloading test will be briefly discussed in this study. This is because the results from this test are used to determine liquid unloading potential. This is the variable used to connect foam characteristics in the small scale facility to the large scale facility in our models. The facility description and detailed explanation of the procedure for the surface tension and stability tests can be found in the work of Ajani, (2014). The composition of surfactants investigated as shown in Table 1.

2.1. Small scale facility-liquid unloading test

Fig. 1 shows a picture of the unloading rig facility. The facility is divided into three sections: the air supply section, the main test cell and the weighing section.

The gas source is an air compressor which supplies compressed air at pressures above 80 psi. The air supply line to the facility has a pressure regulator to reduce the pressure to 18 psi, after this, an air filter was installed to remove dust particles from the air. The dry air is passed through a Rosemount flow controller which has a precision +/−0.0001 LPM. Upon exit from the flow meter, the air is passed through a three way valve which either diverts the incoming gas to the atmosphere (before the test starts) or diverts the air into a checkvalve at the base of the column (when the test is in progress). The check valve prevents backflow of the test solution into the air line.

The main test cell is a 2.00“ inner diameter 3-ft vertical transparent acrylic pipe with 0.263” wall thickness. It is equipped with a 22 μm 2-in. diameter 0.125-in. thick ceramic sparger at its base.