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Effect of surfactant additive on vertical two-phase flow

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ABSTRACT

The effect of surfactant on vertical gas–liquid two-phase flow was experimentally simulated in a low pressure apparatus. Liquid holdup reduction, pressure drop reduction and drag reduction caused by a surfactant additive were investigated. The flow patterns cover bubbly, slug, churn and annular-mist flows. The results show that the maximum liquid holdup reduction induced by the surfactant additive is high up to 88.6% which appears in churn flow. The maximum pressure drop reduction induced by the surfactant additive is high up to 96.5% which occurs in slug flow. Drag reduction caused by the surfactant additive is unexpectedly beyond 100% in some cases of vertical two-phase flow at high gas–liquid ratios. The frictional pressure drops are found to be negative for some vertical two-phase pipe flows at high gas–liquid ratios, challenging the general sense that the frictional pressure drop should be positive in pipe flow. The surfactant additive does not have significant effect on the transition of two-phase flow pattern. But the surfactant additive makes considerable impact on the detailed configurations of two-phase flow. The surfactant-assisted flow improvement is dependent on gas–liquid ratio, gas velocity and two-phase flow pattern.

1. Introduction

In gas wells, there is a critical gas rate below which liquid falling back will take place (Turner et al., 1969). This phenomenon is well known as gas well liquid-loading, where the gas production efficiency becomes very low. If a gas well has a liquid-loading problem, the use of surfactant additives to improve liquid deliverability is a promising remedy method to enhance the gas production.

Two kinds of chemical compounds are related to fluid delivery. One is drag reducing polymer, the other is surfactant. The drag reduction with drag reducing polymer is significant for a horizontal multiphase pipeline in which the frictional pressure drop is dominant in the total pressure drop. A lot of study on the drag reduction with polymers has been carried out in multiphase flow (Manfield et al., 1999; Al-Sarkhi, 2010). In the vertical tubing of gas well, the gravitational pressure drop (or static head) is dominant in the later life of production and hence the attention should be paid to liquid holdup reduction which is termed as deliquification in field operation.

The importance of deliquification has been gaining recognition in worldwide gas production locations (Bondurant et al., 2008). Numerous deliquification methods have been developed (Simpson, 2006; Lea et al., 2008). Among them, the deliquification with chemical surfactants or foamers is of great significance to many operators, because it is a very simple and inexpensive method.

Surfactants usually cause foaming in a gas–liquid system. As a liquid carrier, foam has been employed for liquid removal in gas wells for decades (Lea and Tighe, 1983; Saleh and Al-Jamaey, 1997). Surfactants or foamers have the deliquification capability by decreasing the critical gas velocity required to lift the liquid (Campbell et al., 2001; Lea et al., 2008; Farina et al., 2012). As a rule of thumb, field experience has shown that foaming flow can reduce the critical velocity by about two thirds. The presence of hydrocarbon condensate, brine, particles and demulsifier will reduce the effectiveness of the foam unloading (Yang et al., 2007).

The industry interest in deliquification with foam has increased dramatically. The scientific interest in flow improvement with surfactant has precipitated some published literarture on the subject. Surfactants are flow improvement additives by reducing the tension at interface and the friction at pipe wall. The effects of surfactant additives upon the pressure drop in two-phase flow have been reported by researchers. Liu and Scott (2000) performed experimental investigation for the effects of trace amounts of surfactants on zero net-liquid flow in a vertical acrylic pipe. They found that the reduction of the total pressure drop of vertical zero net-liquid flow can be reduced up to 80% by surfactant. Rozenblit et al. (2006) experimentally studied the vertical air–water two-phase flow and heat transfer with surfactant in a vertical tube of 2.5 cm in diameter. They showed that the pressure drop reductions increase with increasing superficial gas flow rates, reaching their maximal values at slug-churn transition. The application of foam to unload gas wells generally is governed by

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Nomenclature

D	inside diameter of pipe (m)
GLR	gas–liquid ratio
g	acceleration due to gravity (m/s^2)
H_L	liquid holdup
$H_{L\text{-}additiive}$	liquid holdup with surfactant additive
H_s	liquid holdup in the liquid slug
k	coverage factor
L	length of pipe segment (m)
Q_G	gas volume flow rate (m^3/s)
Q_L	liquid volume flow rate (m^3/s)
R_f	drag reduction
R_H	liquid holdup reduction
$R_{\Delta P}$	pressure drop reduction
U	expanded uncertainty
u_A	standard uncertainty obtained from Type A evaluation
u_B	standard uncertainty obtained from Type B evaluation
u_c	combined standard uncertainty
v_{SG}	superficial gas velocity (m/s)
v_{SL}	superficial liquid velocity (m/s)
v_t	translational velocity of slug (m/s)

Greek symbols

ΔP	total pressure drop in the absence of surfactant additive (Pa)
$\Delta P_{additive}$	total pressure drop in the presence of surfactant additive (Pa)
ΔP_f	frictional pressure drop in the absence of surfactant additive (Pa)
$\Delta P_{f\text{-}additive}$	frictional pressure drop in the presence of surfactant additive (Pa)
φ_f	weighting coefficient for drag reduction
φ_H	weighting coefficient for liquid holdup reduction
θ	inclination angle from horizontal (deg)
ρ_G	gas density (kg/m^3)
ρ_L	liquid density (kg/m^3)

two operating limits: economics and the success in reducing bottomhole pressure (Lea et al., 2008). The pressure drop reduction with surfactant is thus important both academically and industrially.

Surfactant additives may also influence two-phase flow pattern. Spedding and Hand (1997) reported that the addition of surfactant suppressed the transition from stratified smooth flow to stratified wavy flow in a horizontal pipe. Wilkens et al. (2006) found that the addition of surfactant reduced the occurrence of slug in horizontal gas–liquid flow. Duangprasert et al. (2008) investigated the influence of surfactant additive on the two-phase flows in a vertical tube. They found that the addition of surfactant has some impact on the boundary of bubble–slug transition, but the boundaries of the churn, annular and mist flows remain nearly the same for both cases with and without surfactant. Tzotzi et al. (2011) examined the effect of surface tension on flow pattern transitions for gas–liquid two-phase flow in horizontal and near-horizontal pipes. As indicated by their results, the transitions to wavy flow, pseudoslugs, atomization, and annular flow are shifted to lower gas velocities but the transition to slug flow is not affected by the reduction of surface tension with liquid surface tension reduced from 72 to 35 mN/m.

The main issues/challenges of foam flow in connection to the field operation wait for being investigated further. The challenges include the complex components of produced liquids, the reasonable evaluation of surfactant candidates, the effectiveness of surfactant additive at different gas–liquid ratios (GLR), and the success in unloading liquids but failure in reducing bottomhole pressure. Even though some attentions have been paid to the two-phase flow with surfactant, little study in literature has been concerned with the liquid holdup reduction, pressure drop reduction and drag reduction caused by surfactant additive in vertical two-phase flow at high gas–liquid ratios. The study here will aid to reveal some special phenomena occurring in surfactant-assisted gas–liquid flow and suggest the possible approach to address the challenge of gas well deliquification with foaming and foam flow.

2. Experimental apparatus and procedure

An experimental apparatus was constructed to simulate the effects of surfactant additive on the reductions of total pressure drop, frictional pressure drop and liquid holdup for the vertical two-phase flow. The gas was air and the liquid was an aqueous solution with 1000 ppm surfactant additive.

The additive employed in the experiments is an anionic and water-soluble surfactant commercially designated as HY–3. As a foaming agent applied in oil and gas fields, HY–3 is a complex surfactant in which the main ingredients are heavy alkylbenzene sulfonates. The critical micelle concentration of the surfactant HY–3 is 1000 ppm (parts per million) by weight, at which the surface tension of the aqueous solution reaches the minimum value. The concentration of surfactant additive is thus chosen as 1000 ppm in the experiments. At the temperature 22 °C, the surface tensions are 0.072 N/m and 0.033 N/m for the water with 0 ppm additive and the aqueous solution with 1000 ppm additive, respectively. The effects of the surfactant additive on the viscosity and density of the aqueous solution are negligible.

The schematic diagram of the apparatus is shown in Fig. 1. The apparatus consists of a liquid (surfactant solution) supply system, a gas supply system, a test section, a data acquisition system (DAQ) and some valves, platinum resistance thermometers and pressure transmitters.

The liquid supply system includes a liquid tank (1), a stirrer (2) installed in the liquid tank, a gas–liquid separator (3), a low rate liquid rotometer (4), a middle rate liquid rotometer (5), a high rate liquid rotometer (6) and a liquid bypass (7) indicated in Fig. 1.

The air supply system includes a compressor (8), a buffer tank (9), a low rate orifice gas flow meter (10), a middle rate orifice gas flow meter (11) and a high rate orifice gas flow meter (12) indicated in Fig. 1.

The test section is comprised of a gas–liquid mixer (13), a check valve (14), a vertical test section (15), a differential pressure transmitter (16) and a vertical ruler (17) indicated in Fig. 1. The test section is a vertical plexiglass pipe with inner diameter of 0.04 m and length of 5.6 m. The distance is 4 m over which the pressure drop was measured by differential pressure transmitter in the test section.

The temperatures and pressures at different locations were measured with platinum resistance thermometers and pressure transmitters, respectively. The standard uncertainty of the thermometers is 0.1 °C. The accuracy for the differential pressure transmitter and pressure transmitters is 0.2. The accuracy of the liquid rotometers is 1.0. The accuracy of the orifice gas flow meters is 1.0. The vertical ruler was used for the measurement of liquid