

# Feasibility and Evaluation of Surfactants and Gas Lift in Combination as a Severe-Slugging-Suppression Method

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## Summary

An experimental study of severe-slugging suppression by use of a combination of surfactants and gas lift was conducted with a facility comprising a 3-in.-inner-diameter, 65-ft-long,  $-3^\circ$ -inclined flowline, followed by a 45-ft-long vertical-riser system. Air and water were used as fluids. The surfactant used was a foaming agent capable of forming stable foams in all brines for a wide range of pH values. Pressure behavior in the flowline/riser system was monitored, and input-gas-, injection-gas-, liquid-, and surfactant-flow rates were measured continuously. In addition, visual observations were made to identify severe slugging. Effects of the proposed method were quantified with a modified elimination performance index (MEPI) that considered not only pressure fluctuations, but also backpressure effects.

Thirty tests were conducted. The data were analyzed for the severe-slugging suppression of the combination of surfactant and gas lift, the effect of gas lift on surfactant injection, and the effect of the surfactant on the reduction of the gas lift gas. The combination technique with the highest gas lift rate completely eliminated the severe slugging for all tests conducted. Surfactants were able to suppress severe slugging for most of the cases. The performance of the “only-surfactant injection case” increases as the gas/liquid ratio increases. For all of the tests, backpressure reduction was observed. The MEPI is used as the main parameter to assess the performance of the severe-slugging-suppression methods. Gas lift not only contributes to density reduction through volumetric increase of gas in the riser, but it also reduces the mixture density by promoting more foam generation. There were reductions in the gas lift rate from the original maximum gas lift injection rate for all the tests conducted with surfactant injection.

## Introduction

The use of long deepwater risers that conduct production from multiple wellheads on the seafloor to the surface predisposes the system to severe slugging in the riser for a wide range of flow rates and seabed topography. Considering the length of the deepwater risers, the problem is expected to be more severe than in production systems installed in shallower waters. Severe slugging could occur at high pressure, with the magnitude of the pressure fluctuations so large as to cause a shorter natural-flow period, with subsequent consequences such as premature field abandonment, loss of recoverable reserves, and earlier-than-planned deployment of boosting devices.

Severe slugging typically will be experienced in two-phase-flow systems in which a pipeline segment with a downward inclination angle is followed by another segment/riser with an upward incli-

nation angle for relatively low gas- and liquid-flow rates. Sarica et al. (2014) divided the severe-slugging cycle into four steps, as described in Fig. 1. The classic pipe geometry for severe slugging is a slightly downward section upstream of a riser. In Step 1, gas and liquid velocities are low enough to allow stratified flow in the downward-sloping pipe section followed by liquid bridging and accumulation at the bottom of the riser. The hydrostatic pressure of the accumulated liquid initially increases equal to or faster than the buildup of gas pressure upstream of the liquid slug (Step 2). When the gas pressure eventually exceeds the hydrostatic head of the liquid slug, the gas will begin to push the liquid slug out of the riser and start to penetrate the riser (Step 3). The pressure in the gas reduces as the liquid is removed from the riser and the gas expands, increasing the velocities in the riser. After most of the liquid and gas exit the riser, the velocity of the gas is no longer high enough to sweep the liquid upward. Liquid film not swept from the riser starts falling back down the riser (Step 4), and the accumulation of liquid starts again.

Severe slugging will cause periods of no liquid and gas production in the separator followed by very high liquid- and gas-flow rates. The resulting large pressure and flow-rate fluctuations are highly undesirable. Several mitigation techniques are proposed in the literature. A thorough summary of these techniques can be found in Sarica and Tengedal (2000). Surfactant application and gas lift are typically considered to be separate methods. The combination of both can provide a better mitigation of severe slugging by complementing one another.

As mentioned by Sarica and Tengedal (2000), Yocum (1973) was the first to identify multiple severe-slugging-mitigation techniques. These are reduction of the line diameter, splitting the flow into dual or multiple streams, gas injection into the riser, the use of mixing devices at the riser base, choking, and backpressure increase. Here, we will classify severe-slugging-mitigation methods into three groups: passive, active, and hybrids (combination of both passive- and active-mitigation methods).

Passive methods require energy from the system; the most relevant are given as follows:

1. Choking: One of the most common mitigation techniques is the installation of a choke valve at the top of the riser. By choking the flow, the riser operational pressure changes, stabilizing the flow. Several publications regarding choking exist in the literature, as detailed in Sarica and Tengedal (2000). Unfortunately, because of the backpressure created by choking, production is affected, and a minimum amount of energy is required for this method to be successful. This technique can be combined with a feedback control to regulate the largest choke opening that will stabilize the flow.
2. Backpressure increase: This method requires significant pressure increases at the separator or riser head. It is not considered to be as viable an option, even for shallow-water systems, because production-capacity reduction is experienced as a result of the backpressures imposed. The reduction in

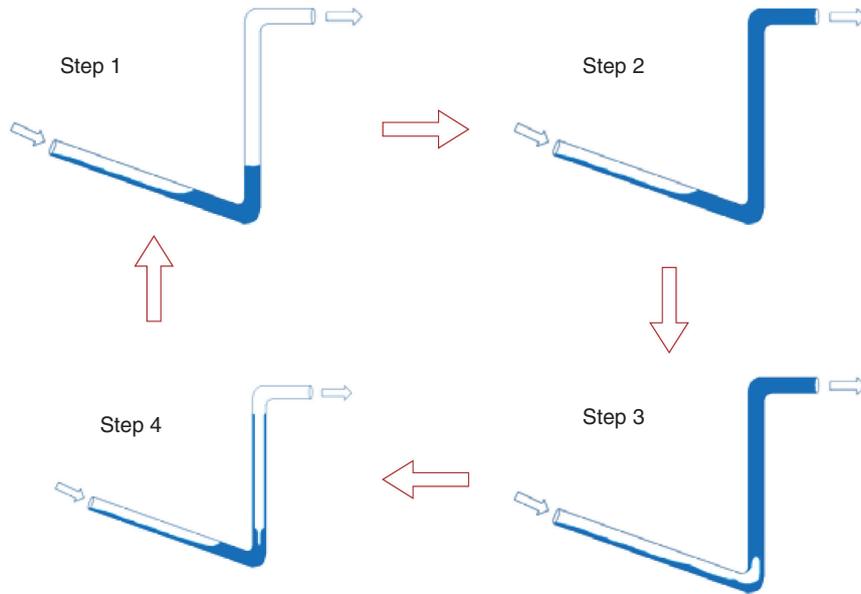


Fig. 1—Schematic of severe-slugging cycle.

Specific gravity	1.02
Viscosity (cp)	30
Flash point (°F)	186
Pour point (°F)	0

Table 1—SI-403 properties.

production capacity is expected to be worse for deepwater-production systems.

3. Self-lifting: Tengesdal et al. (2003) proved the viability of this method, which requires the transfer of pipeline gas (in-situ gas) through a bypass line to the riser at a point above the riser base. The transfer process reduces both the hydrostatic head in the riser and the pressure in the pipeline, consequently mitigating the severe slugging.

All methods included in the preceding classification do not require external energy to operate. Active-elimination methods add energy to the system, overcoming the constraint of passive methods by increasing the complexity and costs. The most common methods in the active category are

1. Gas lift: This is one of the most-used techniques. This method was investigated initially by Pots et al. (1985), and they concluded that the severity of the slug is considerably

reduced by injecting 50% of the inlet gas and it disappears completely by injecting 300%. The drawbacks of this method are the increase in frictional pressure drop, potential problems resulting from Joule-Thomson cooling, and the need for an injection point and an injection system.

2. Multiphase pumping: A multiphase pump can be installed in the riser base, boosting the pressure of the phases. This method reduces the backpressure, but increases the capital expenditure and the operating expenditure (Falcimaigne and Decarre 2008).
3. Subsea separation: After the separation of the gas and liquid phases, the phases are transported to the surface in two separated lines. A pump is usually required to lift the liquid.

Finally, hybrid systems combine passive and active methods. Jansen (1990) compared a hybrid system consisting of choking and gas lift with the performance of each method measured independently. He concluded that the choking and gas lifting combination is the best elimination method by reducing the degree of choking and the amount of injected gas.

Hassanein and Fairhurst (1998) mentioned foam flow as one more possibility for severe-slugging elimination. No further details were provided in their original work. Sarica et al. (2014) showed that by adding surfactant to an air/water system, the severe slugging was reduced considerably. After the surfactant injection, the

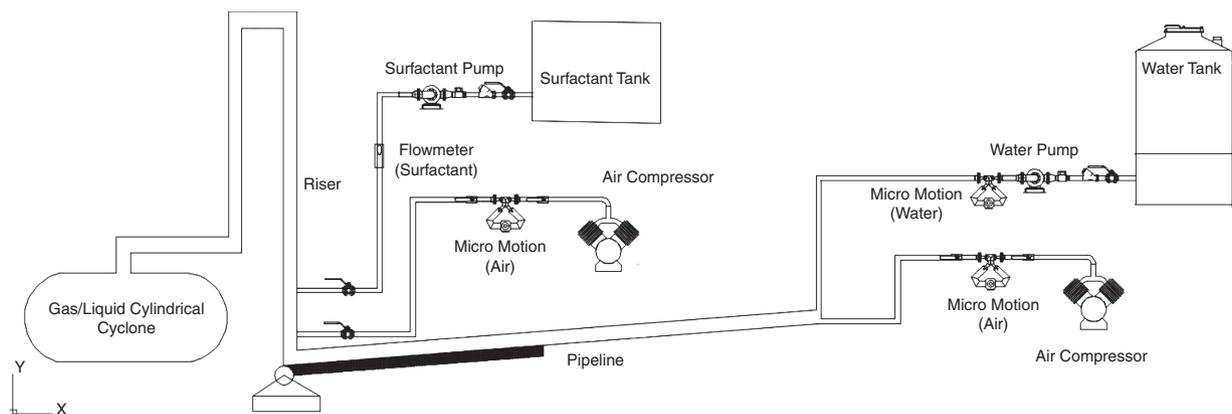


Fig. 2—Schematic of the test facility.

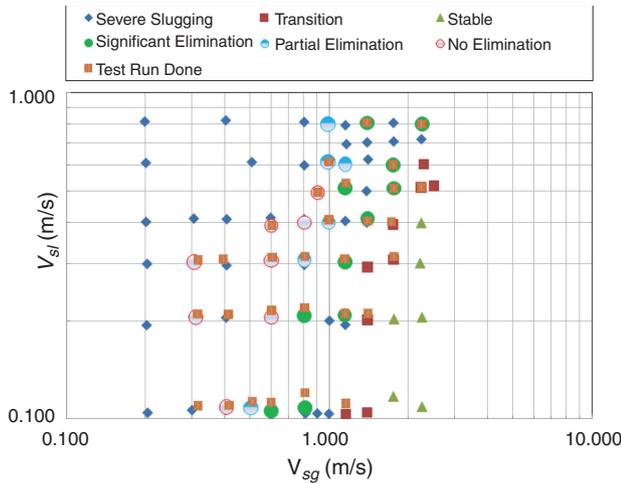


Fig. 3—Test matrix for surfactant and gas lifting tests.

foam is generated by the self-agitation of the phases. No further energy is required or added to the system. The severe slugging is mitigated by changing the flow pattern occurring in the system. This paper presents an extension of the Sarica et al. (2014) study by combining the surfactant injection with the gas lift method and the impact on severe-slugging mitigation.

### Experimental Program

The 3-in. gas/oil/water flow loop at the University of Tulsa Fluid Flow Projects facility was used for this experimental program. Water and compressed air were the working fluids. The water was taken from the municipality of the City of Tulsa. Water was initially in a storage tank and pumped to the system by a Gould centrifugal pump with a capacity of 280 gal/min at 120-psig discharge pressure. Air was supplied by a rotary screw (oil-free) air compressor with a capacity of 677 ft<sup>3</sup>/min at 100 psig. Both air and water phases were measured by Coriolis flowmeters (Micro Motion™).

The foaming agent used in this study was SI-403, which is a blend of surfactants that produces high, stable foams in all brines and in wide ranges of pH. Physical properties of SI-403 are presented in Table 1.

**Facility.** The test sections of the flow loop were a 65-ft pipeline followed by a 48-ft riser. These pipe sections were made of transparent ID R-4000 polyvinyl chloride pipe with an inner diameter of 3 in. The test sections were attached to a tower and boom facility, with the riser mounted on the stationary tower and the downward-sloping pipeline attached to the boom. Because the boom is inclinable, this arrangement permitted the investigation of several pipeline inclination angles. Fig. 2 shows a schematic of the three-phase-flow severe-slugging facility used in this study.

**Instrumentation and Data Acquisition.** Gas and water were measured with Micro Motion™ mass flowmeters. They consist of Coriolis sensors and microprocessor-based transmitters that provide mass-flow, volume-flow, density, and temperature measurement of air and water in real time, exhibiting low pressure drop. The gas-mass flowmeter is located upstream of a regulator valve to minimize pressure fluctuations. It has a nominal range of 0 to 40 lbm/min (0 to 205 scf/min), with standard accuracy of ±0.50% and a repeatability of ±0.25% of the mass-flow rate. The water-flow rate was measured at the inlet of the facility. The water-mass flowmeter has a nominal range of 0 to 1600 lbm/min, with mass-flow accuracy of ±0.10% and a repeatability of ±0.05% of the flow rate.

A custom-made rotameter was used for the low gas-injection rates of 1 to 5% of the main gas rate. The low-gas-injection rotameter has a range of 0.01 to 0.1 m<sup>3</sup>/h at 70°F and 15 psig. For the high gas-injection rates, a Micro Motion mass flowmeter was installed in parallel with the rotameter by use of a bypass. A pressure regulator was installed in the gas-injection flowline to overcome the flow-rate fluctuation caused by severe slugging. For all tests, the upstream pressure was maintained at 70 psig, keeping the gas injection under critical (sonic) flow conditions. The flow rate was very stable.

Two different full-cone-spray-injection nozzles were used. The nozzles have an angle of 60° and orifice diameters of 0.04 and 0.05 in., respectively, for low and high injection rates. It was visually

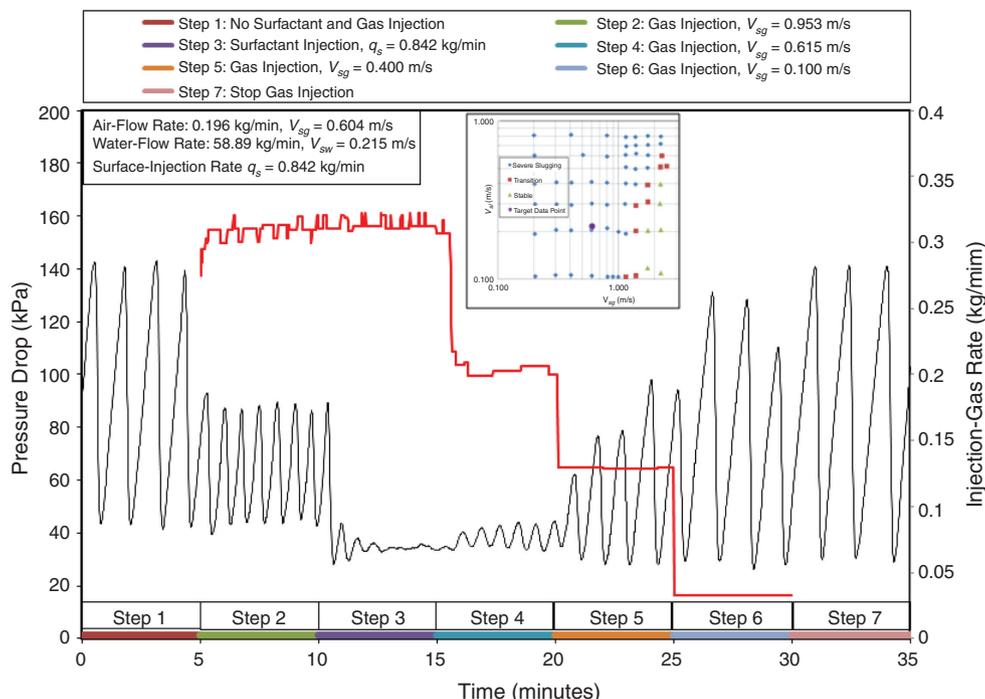


Fig. 4—Typical test-run pressure signature.

Test	$V_{sg}$ (m/s)	$V_{sl}$ (m/s)	$V_{sgo,inj}$ (m/s)							Surfactant Rate (kg/min)	EPI (%)						
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7		Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	
1	1.16	0.11	0	0.92	0.92	0.62	0.42	0.1	0	0.16	46	94	100	92	89	90	
2	1.40	0.21	0	0.92	0.92	0.62	0.40	0.1	0	0.16	44	92	93	95	95	95	
3	1.76	0.32	0	0.95	0.92	0.61	0.42	0.1	0	0.17	41	91	98	95	98	93	
4	1.73	0.4	0	0.94	0.94	0.6	0.43	0.11	0	0.17	38	94	92	87	86	-4	
5	2.24	0.51	0	0.95	0.95	0.6	0.42	0.11	0	0.17	48	96	95	95	81	78	
6	0.32	0.11	0	0.96	0.96	0.62	0.40	0.1	0	0.84	70	100	93	51	5	-13	
7	0.42	0.11	0	0.96	0.96	0.62	0.43	0.11	0	0.84	63	98	99	75	23	-3	
8	0.51	0.11	0	1	1	0.60	0.44	0.11	0	0.84	66	100	95	82	47	-2	
9	0.60	0.11	0	1.0	1.0	0.62	0.43	0.11	0	0.23	60	97	99	95	48	21	
10	0.81	0.12	0	0.96	0.96	0.6	0.41	0.1	0	0.17	52	99	95	94	88	90	
11	0.32	0.21	0	0.96	0.96	0.62	0.44	0.11	0	0.84	56	89	56	22	-8	-20	
12	0.41	0.21	0	0.99	0.99	0.65	0.41	0.1	0	0.84	61	95	60	31	-5	-12	
13	0.60	0.22	0	0.95	0.95	0.62	0.4	0.1	0	0.84	56	98	88	29	3	-14	
14	0.81	0.22	0	0.92	0.92	0.68	0.39	0.1	0	0.24	50	100	97	73	22	15	
15	1.15	0.21	0	0.92	0.92	0.57	0.4	0.1	0	0.16	46	97	97	96	96	93	
16	0.32	0.31	0	0.90	0.90	0.62	0.42	0.1	0	0.84	52	89	40	14	-7	-14	
17	0.40	0.31	0	0.98	0.98	0.62	0.46	0.12	0	0.84	55	99	46	19	-7	-21	
18	0.61	0.31	0	0.98	0.98	0.63	0.46	0.12	0	0.84	51	99	74	29	-1	-12	
19	0.81	0.32	0	0.97	0.97	0.57	0.42	0.21	0	0.81	53	100	95	53	31	-10	
20	1.15	0.31	0	0.94	0.94	0.66	0.42	0.1	0	0.23	44	99	98	88	23	16	
21	0.61	0.39	0	0.97	0.97	0.62	0.43	0.11	0	0.81	49	99	49	19	-6	-16	
22	1	0.41	0	1	1	0.62	0.45	0.11	0	0.84	48	100	97	83	20	19	
23	1.4	0.4	0	0.96	0.96	0.67	0.43	0.11	0	0.17	40	93	80	55	38	28	
24	0.91	0.5	0	0.94	0.94	0.62	0.45	0.11	0	0.84	45	99	80	53	7	-7	
25	1.16	0.53	0	0.91	0.91	0.65	0.38	0.1	0	0.48	45	99	99	93	51	43	
26	1.77	0.51	0	0.92	0.92	0.62	0.42	0.1	0	0.17	45	95	84	72	55	45	
27	1.0	0.61	0	0.95	0.95	0.62	0.45	0.11	0	0.84	42	98	97	55	28	10	
28	1.75	0.6	0	1	1	0.66	0.43	0.11	0	0.52	42	100	100	98	98	97	
29	1.39	0.81	0	0.90	0.90	0.62	0.4	0.1	0	0.52	38	98	99	94	66	55	
30	2.25	0.8	0	0.90	0.90	0.58	0.42	0.11	0	0.16	31	98	92	76	69	47	

Table 2—Severe-slugging-suppression performance.

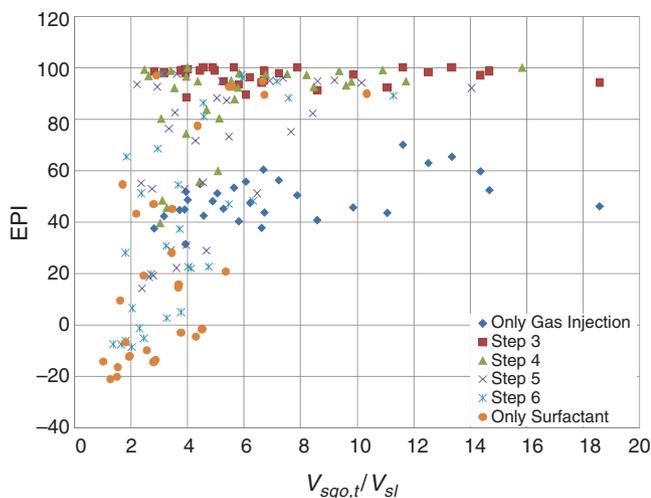


Fig. 5—EPI vs. gas/liquid ratio.

observed that the installed injection nozzles helped the foam generation to some extent, especially at low surfactant-injection rates. However, little difference was seen in the pressure-drop results.

Pressure transducers and differential-pressure transducers were located at the inlet and outlet of the pipeline and along the riser, as shown in Fig. 2. Static pressures were measured at six different points: one in the pipeline, four in the riser, and one in the separator at the top of the riser. Differential pressures were measured in the pipeline and also in the riser. Additional pressure devices were used to monitor the pressure in the three-phase separator, the inlet of the gas line, and the hydrostatic level of the water tank and small separator at the top of the riser. The temperatures of the fluids were measured with resistance-temperature-detector temperature transmitters that were located at the inlet of the gas and liquid lines, which allowed the calculation of the fluid densities.

Signals from the sensors were gathered by an electronic data-acquisition system from National Instruments. The hardware consists of a personal computer and a multifunction input/output (I/O) board. The analog signals from the measurement devices are converted to digital signals by the multifunction I/O board. A data-acquisition program written using LabVIEW™ 7.0 software (National Instruments 2003) provided the necessary interface. The program acquired the data from the sensors, converted and displayed the output signals (in a format of -10 to +10V) in their respective calibrated measurement (i.e., temperature, mass-flow rate), and stored the data in a text file.

Test	$V_{sg}$ (m/s)	$V_{sl}$ (m/s)	$V_{sg,inj}$ (m/s)							Surfactant Rate (kg/min)	BPR (%)						
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7		Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	
1	1.16	0.11	0	0.92	0.92	0.62	0.42	0.1	0	0.16	22	67	67	63	63	62	
2	1.40	0.21	0	0.92	0.92	0.62	0.40	0.1	0	0.16	20	58	56	56	53	53	
3	1.76	0.32	0	0.95	0.95	0.61	0.42	0.1	0	0.17	20	55	54	52	52	50	
4	1.73	0.4	0	0.94	0.94	0.6	0.43	0.11	0	0.17	21	55	51	48	47	4	
5	2.24	0.51	0	0.95	0.95	0.6	0.42	0.11	0	0.17	20	46	44	42	37	35	
6	0.32	0.11	0	0.96	0.96	0.62	0.40	0.1	0	0.84	48	82	75	50	15	1	
7	0.42	0.11	0	0.96	0.96	0.62	0.43	0.11	0	0.84	39	78	75	62	29	11	
8	0.51	0.11	0	1	1	0.60	0.44	0.11	0	0.84	37	76	71	63	44	14	
9	0.60	0.11	0	1.0	1.0	0.62	0.43	0.11	0	0.23	29	72	69	65	45	32	
10	0.81	0.12	0	0.96	0.96	0.6	0.41	0.1	0	0.17	23	74	64	61	57	59	
11	0.32	0.21	0	0.96	0.96	0.62	0.44	0.11	0	0.84	36	71	51	29	8	1	
12	0.41	0.21	0	0.99	0.99	0.65	0.41	0.1	0	0.84	38	74	53	33	7	1	
13	0.60	0.22	0	0.95	0.95	0.62	0.4	0.1	0	0.84	39	75	69	31	13	0	
14	0.81	0.22	0	0.92	0.92	0.68	0.39	0.1	0	0.24	33	72	69	57	27	22	
15	1.15	0.21	0	0.92	0.92	0.57	0.4	0.1	0	0.16	27	65	61	60	58	56	
16	0.32	0.31	0	0.90	0.90	0.62	0.42	0.1	0	0.84	33	65	39	23	7	2	
17	0.40	0.31	0	0.98	0.98	0.62	0.46	0.12	0	0.84	33	70	42	26	7	1	
18	0.61	0.31	0	0.98	0.98	0.63	0.46	0.12	0	0.84	34	72	58	30	9	2	
19	0.81	0.32	0	0.97	0.97	0.57	0.42	0.21	0	0.81	35	73	67	44	29	2	
20	1.15	0.31	0	0.94	0.94	0.66	0.42	0.1	0	0.23	26	66	64	58	21	17	
21	0.61	0.39	0	0.97	0.97	0.62	0.43	0.11	0	0.81	31	68	41	24	8	3	
22	1	0.41	0	1	1	0.62	0.45	0.11	0	0.84	33	70	66	59	24	24	
23	1.4	0.4	0	0.96	0.96	0.67	0.43	0.11	0	0.17	23	56	49	37	26	22	
24	0.91	0.5	0	0.94	0.94	0.62	0.45	0.11	0	0.84	28	66	57	41	13	5	
25	1.16	0.53	0	0.91	0.91	0.65	0.38	0.1	0	0.48	26	65	63	59	39	34	
26	1.77	0.51	0	0.92	0.92	0.62	0.42	0.1	0	0.17	24	53	47	41	32	27	
27	1.0	0.61	0	0.95	0.95	0.62	0.45	0.11	0	0.84	24	61	58	41	25	15	
28	1.75	0.6	0	1	1	0.66	0.43	0.11	0	0.52	24	57	56	55	53	53	
29	1.39	0.81	0	0.90	0.90	0.62	0.4	0.1	0	0.52	19	53	51	48	39	34	
30	2.25	0.8	0	0.90	0.90	0.58	0.42	0.11	0	0.16	16	44	42	35	31	20	

Table 3—BPR.

### Experimental Results

Thirty tests were conducted to investigate the effectiveness of the combination of surfactants and gas lift in severe-slugging mitigation. The operating conditions of these tests are shown in Fig. 3 on the severe-slugging map. In every test, the following order was followed:

- The baseline is established with no gas and surfactant injection (Step 1).
- Maximum gas-injection rate is applied (Step 2).
- Surfactant is injected at an amount greater than the critical micelle concentration (Step 3).
- Gas-injection rate is reduced successively (Steps 4 through 6).
- Gas-injection rate is stopped, but surfactant injection is maintained (Step 7).

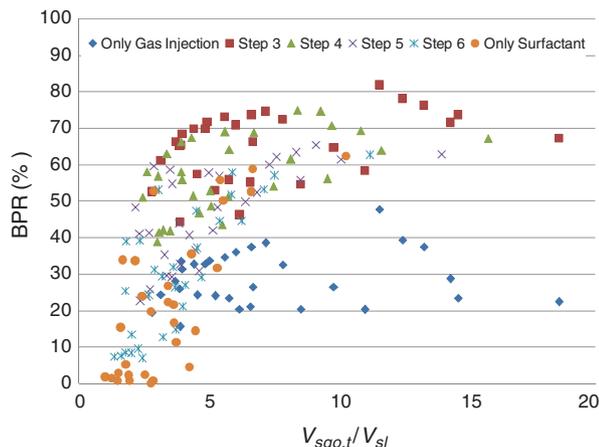


Fig. 6—BPR vs. gas/liquid ratio.

Fig. 4 shows a typical riser-base pressure signature for the preceding described steps. Each consecutive step took approximately 5 minutes. For this particular test case, in Step 1, the severe-slugging conditions were created. Severe slugging was lessened, but not completely eliminated, by gas lift for the considered maximum gas lift injection rate (Step 2). Complete elimination of severe slugging was observed after the application of surfactants (Step 3). In Steps 4 through 6, gas lift rate was reduced by the indicated amounts. As the gas lift rate was reduced, the pressure fluctuations increased progressively. Finally, when the gas injection was stopped, pressure fluctuations greater than those of Step 1 were observed (Step 7).

For all the tests conducted, severe slugging was eliminated for a certain combination of surfactant- and gas-injection rates. Conceptually, this proves that the combination works as an elimination technique if enough gas and surfactant are injected. The primary suppression mechanism of gas lift is simply to increase the total gas-flow rate in the riser, thereby pushing the operating point out of

Test	$V_{sg}$ (m/s)	$V_{sl}$ (m/s)	$V_{sgo,inj}$ (m/s)							Surfactant Rate (kg/min)	MEPI (%)					
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7		Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
1	1.16	0.11	0	0.92	0.92	0.62	0.42	0.1	0	0.16	51	98	100	97	96	92
2	1.40	0.21	0	0.92	0.92	0.62	0.40	0.1	0	0.16	49	97	97	98	98	96
3	1.76	0.32	0	0.95	0.95	0.61	0.42	0.1	0	0.17	46	96	99	98	99	94
4	1.73	0.4	0	0.94	0.94	0.6	0.43	0.11	0	0.17	44	97	96	93	93	-2
5	2.24	0.51	0	0.95	0.95	0.6	0.42	0.11	0	0.17	53	98	97	97	88	81
6	0.32	0.11	0	0.96	0.96	0.62	0.40	0.1	0	0.84	79	100	98	76	19	-13
7	0.42	0.11	0	0.96	0.96	0.62	0.43	0.11	0	0.84	71	100	100	91	45	3
8	0.51	0.11	0	1	1	0.60	0.44	0.11	0	0.84	72	100	98	94	71	6
9	0.60	0.11	0	1.0	1.0	0.62	0.43	0.11	0	0.23	65	99	100	98	71	32
10	0.81	0.12	0	0.96	0.96	0.6	0.41	0.1	0	0.17	57	100	98	98	95	92
11	0.32	0.21	0	0.96	0.96	0.62	0.44	0.11	0	0.84	65	97	79	45	1	-20
12	0.41	0.21	0	0.99	0.99	0.65	0.41	0.1	0	0.84	69	99	81	54	2	-12
13	0.60	0.22	0	0.95	0.95	0.62	0.4	0.1	0	0.84	66	99	96	51	15	-14
14	0.81	0.22	0	0.92	0.92	0.68	0.39	0.1	0	0.24	59	100	99	88	43	24
15	1.15	0.21	0	0.92	0.92	0.57	0.4	0.1	0	0.16	53	99	99	99	98	95
16	0.32	0.31	0	0.90	0.90	0.62	0.42	0.1	0	0.84	61	96	63	34	0	-13
17	0.40	0.31	0	0.98	0.98	0.62	0.46	0.12	0	0.84	63	100	69	40	1	-20
18	0.61	0.31	0	0.98	0.98	0.63	0.46	0.12	0	0.84	61	100	89	50	8	-11
19	0.81	0.32	0	0.97	0.97	0.57	0.42	0.21	0	0.81	63	100	98	73	51	-8
20	1.15	0.31	0	0.94	0.94	0.66	0.42	0.1	0	0.23	52	100	99	95	39	23
21	0.61	0.39	0	0.97	0.97	0.62	0.43	0.11	0	0.81	58	100	70	38	3	-14
22	1	0.41	0	1	1	0.62	0.45	0.11	0	0.84	58	100	99	93	39	30
23	1.4	0.4	0	0.96	0.96	0.67	0.43	0.11	0	0.17	48	97	90	72	54	37
24	0.91	0.5	0	0.94	0.94	0.62	0.45	0.11	0	0.84	54	100	91	72	19	-3
25	1.16	0.53	0	0.91	0.91	0.65	0.38	0.1	0	0.48	53	100	100	97	70	54
26	1.77	0.51	0	0.92	0.92	0.62	0.42	0.1	0	0.17	52	98	91	83	69	53
27	1.0	0.61	0	0.95	0.95	0.62	0.45	0.11	0	0.84	51	99	99	74	46	18
28	1.75	0.6	0	1	1	0.66	0.43	0.11	0	0.52	50	100	100	99	99	98
29	1.39	0.81	0	0.90	0.90	0.62	0.4	0.1	0	0.52	45	99	100	97	79	64
30	2.25	0.8	0	0.90	0.90	0.58	0.42	0.11	0	0.16	37	99	95	85	78	53

Table 4—Severe-slugging-suppression performance by use of MEPI.

the severe-slugging envelope. Surfactants suppress severe slugging by converting the liquid and gas into foam, thereby lifting the liquids and reducing the backpressure. This paper analyzes the data to

see whether the combination of two proven elimination techniques has any additional benefit.

**Evaluation on the Basis of the Elimination Performance Index (EPI).** The following EPI definition proposed by Sarica et al. (2014) was used initially to quantify the elimination performance:

$$EPI = \left[ 1 - \frac{(\Delta p_{max} - \Delta p_{min})_{after}}{(\Delta p_{max} - \Delta p_{min})_{before}} \right] \times 100 \dots\dots\dots (1)$$

Elimination performance is classified into three categories: significant elimination (SE) for  $100 \geq EPI \geq 50$ , partial elimination (PE) for  $50 > EPI > 0$ , and no elimination (NE) for  $EPI \leq 0$ .

Table 2 shows the severe-slugging-suppression performance of gas lift only, surfactant injection only, and a combination of the two for various gas-injection rates. Blue, yellow, and red boxes show SE, PE, and NE, respectively.

Fig. 5 presents the results given in Table 2 in graphical form. The following observations were made from both Fig. 5 and Table 2:

- Step 2: Only gas injection can suppress severe slugging significantly when a sizable amount of gas is injected, as seen from the test results. As seen from Fig. 5, as the total gas/liquid ratio increases, the EPI increases. The total gas/liquid ratio is defined as the ratio of the total superficial gas velocity to the superficial liquid velocity.

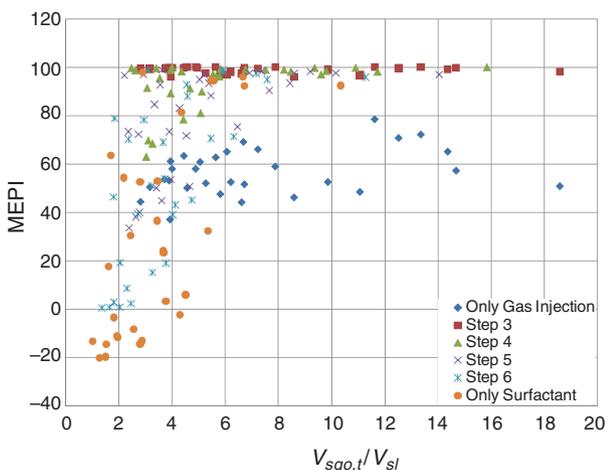


Fig. 7—MEPI vs. gas/liquid ratio.

Test	EPI (%)						MEPI (%)					
	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
1	46	94	100	92	89	90	51	98	100	97	96	92
2	44	92	93	95	95	95	49	97	97	98	98	96
3	41	91	98	95	98	93	46	96	99	98	99	94
4	38	94	92	87	86	-4	44	97	96	93	93	-2
5	48	96	95	95	81	78	53	98	97	97	88	81
6	70	100	93	51	5	-13	79	100	98	76	19	-13
7	63	98	99	75	23	-3	71	100	100	91	45	3
8	66	100	95	82	47	-2	72	100	98	94	71	6
9	60	97	99	95	48	21	65	99	100	98	71	32
10	52	99	95	94	88	90	57	100	98	98	95	92
11	56	89	56	22	-8	-20	65	97	79	45	1	-20
12	61	95	60	31	-5	-12	69	99	81	54	2	-12
13	56	98	88	29	3	-14	66	99	96	51	15	-14
14	50	100	97	73	22	15	59	100	99	88	43	24
15	46	97	97	96	96	93	53	99	99	99	98	95
16	52	89	40	14	-7	-14	61	96	63	34	0	-13
17	55	99	46	19	-7	-21	63	100	69	40	1	-20
18	51	99	74	29	-1	-12	61	100	89	50	8	-11
19	53	100	95	53	31	-10	63	100	98	73	51	-8
20	44	99	98	88	23	16	52	100	99	95	39	23
21	49	99	49	19	-6	-16	58	100	70	38	3	-14
22	48	100	97	83	20	19	58	100	99	93	39	30
23	40	93	80	55	38	28	48	97	90	72	54	37
24	45	99	80	53	7	-7	54	100	91	72	19	-3
25	45	99	99	93	51	43	53	100	100	97	70	54
26	45	95	84	72	55	45	52	98	91	83	69	53
27	42	98	97	55	28	10	51	99	99	74	46	18
28	42	100	100	98	98	97	50	100	100	99	99	98
29	38	98	99	94	66	55	45	99	100	97	79	64
30	31	98	92	76	69	47	37	99	95	85	78	53

Table 5—Comparison of EPI and MEPI.

- Step 7 shows the only-surfactant injection case. Surfactants were able to suppress or lessen the severe slugging for one-half of the cases. In some instances, EPI values indicated worsening of the severe slugging because of a reduction in the minimum pressure drop.
- Step 3 shows the combination of the highest gas-injection rate and the surfactant-injection case. As seen for all the tests conducted, severe slugging was eliminated completely.
- Steps 4 through 6 present the cases with reduced injection-gas rates. As seen from Fig. 5, in general, EPI gets smaller as the total gas/liquid ratio is reduced.

**Backpressure Reduction (BPR).** In both gas lift and surfactant-injection tests, a significant BPR is observed. This effect is not taken into account in the EPI definition. This subsection presents a BPR analysis. Moreover, a new severe-slugging-suppression criterion, modified EPI (MEPI), is proposed to assess both the pressure fluctuation and BPR. The BPR is measured by use of the following expression:

$$BPR = \left( \frac{\Delta p_{\max, \text{before}} - \Delta p_{\max, \text{after}}}{\Delta p_{\max, \text{before}}} \right) \times 100 \quad \dots \dots \dots (2)$$

The experimental results are presented in Table 3 and Fig. 6. The following observations are made:

- In most of the available severe-slugging-suppression techniques, backpressure increase is unavoidable. Backpressure increase inherently reduced the throughput. For all of the tests, BPR was observed (Table 3 and Fig. 6).
- Generally, as the gas/liquid ratio increased, BPR increased. This increase reaches a plateau at high gas/liquid ratios.
- The maximum BPR was obtained in Step 3, where the combination of maximum gas injection and surfactant injection was used. As the gas-injection rate was reduced, slight decreases in BPR were observed.
- The performance of the only-surfactant injection case (Step 7) increased as the gas/liquid ratio increased.
- The only-gas injection case (Step 2) could achieve only approximately 40% BPR, while the introduction of surfactant with varying gas lift flow rates increased BPR to approximately 70%.

**MEPI.** The EPI definition does not consider the variations in backpressure. Therefore, EPI was modified to include the backpressure effects, as given in

$$MEPI = \left[ 1 - \frac{(\Delta p_{\max} - \Delta p_{\min})_{\text{after}} (p_{\text{sep}} + \Delta p_{\max})_{\text{after}}}{(\Delta p_{\max} - \Delta p_{\min})_{\text{before}} (p_{\text{sep}} + \Delta p_{\max})_{\text{before}}} \right] \times 100 \quad \dots \dots \dots (3)$$

Test	$V_{sgo,i}/V_{sgo}$				$\Delta MEPI$ ( $MEPI_{Step i} - MEPI_{Step i-1}$ )				MEPI Initial (Step 7)	MEPI Final (Step 3)
	Step 6	Step 5	Step 4	Step 3	Step 6	Step 5	Step 4	Step 3		
	1	1.09	1.36	1.53	1.80	4	1	3		
2	1.07	1.29	1.44	1.66	2	0	-1	0	96	97
3	1.06	1.24	1.35	1.54	4	-1	1	-3	94	96
4	1.06	1.25	1.35	1.54	95	1	3	1	-2	97
5	1.05	1.19	1.27	1.42	7	9	0	1	81	98
6	1.31	2.24	2.94	4.04	32	56	23	2	-13	100
7	1.26	2.03	2.48	3.31	42	45	9	0	3	100
8	1.21	1.87	2.17	2.96	65	23	5	2	6	100
9	1.18	1.72	2.03	2.68	39	27	1	-1	32	99
10	1.13	1.51	1.74	2.18	3	3	0	2	92	100
11	1.35	2.40	2.95	4.04	20	44	34	18	-20	97
12	1.25	2.00	2.57	3.39	14	51	28	18	-12	99
13	1.17	1.66	2.02	2.58	29	36	45	3	-14	99
14	1.12	1.48	1.84	2.15	19	45	11	1	24	100
15	1.09	1.35	1.50	1.80	4	0	0	0	95	99
16	1.33	2.31	2.94	3.83	13	33	30	33	-13	96
17	1.29	2.16	2.55	3.48	21	39	29	31	-20	100
18	1.19	1.76	2.04	2.56	19	42	39	10	-11	100
19	1.26	1.52	1.70	2.20	59	22	25	2	-8	100
20	1.09	1.36	1.58	1.82	16	56	4	0	23	100
21	1.18	1.71	2.01	2.60	17	35	32	30	-14	100
22	1.11	1.45	1.62	2.00	9	54	6	1	30	100
23	1.08	1.31	1.48	1.68	17	18	18	7	37	97
24	1.12	1.50	1.68	2.06	22	53	19	8	-3	100
25	1.08	1.33	1.56	1.78	16	27	2	0	54	100
26	1.06	1.23	1.35	1.52	16	14	8	6	53	98
27	1.11	1.45	1.62	1.95	29	27	25	1	18	99
28	1.06	1.24	1.37	1.57	1	0	1	0	98	100
29	1.07	1.29	1.44	1.65	15	18	3	0	64	99
30	1.05	1.19	1.26	1.40	26	6	11	3	53	99

Table 6—Analysis of gas injection by use of  $\Delta MEPI$ .

**Table 4** shows the severe-slugging-suppression performance by use of MEPI for gas lift only, for surfactant injection only, and for a combination of the two at various gas-injection rates. Blue, yellow, and red boxes show SE, PE, and NE, respectively. **Fig. 7** presents the results given in Table 4 in graphical form. **Table 5** shows the comparison between EPI and MEPI. Table 5 indicates that the MEPI captures both the pressure fluctuation and the BPRs.

**Effect of Gas Lift.** The primary mechanism of the gas lift in severe-slugging elimination is the reduction of the backpressure by the reduction of the mixture density in the riser. In this subsection, the data are analyzed on the basis of the total gas rate to identify whether there are additional effects to suppress severe slugging by use of gas lift.

When Step 6 (small injection gas with surfactant) is compared with Step 2 (only gas injection with high flow rate), for a majority of the cases, higher MEPIs are observed for Step 6 (see Table 5). This shows that relatively low injection-gas rates, along with surfactants, will perform significantly better than either the case of high gas-injection rate or the case of only surfactant. Gas lift alone could not accomplish the density reductions observed in a majority of the cases in Step 6. This indicates that gas injection not only contributes to density reduction through volumetric increase of gas in the riser, but also reduces the mixture density by promoting more foam generation.

To better analyze the effect of the gas lift, the changes in MEPI from one step to the other were analyzed. **Table 6** presents the data in the form of  $V_{sgo,i}/V_{sgo}$  vs.  $\Delta MEPI$ . Blue, yellow, and red colors show the significant (15 to 100%), slight (5 to 15%), and insignificant or negative (< 5%) changes, respectively. Excluding the six tests with the complete elimination by use of surfactant injection (shown with red continuous blocks in the table), the rest of the tests indicated either significant or slight improvements in MEPI in Step 6, where the gas lift gas-injection rates were within 5 to 33% of the original inlet- or feed-gas-flow rate. As the gas lift rates are increased with Steps 3 through 5, the rate of improvement in MEPI is decreased.

**Effect of Surfactant-Injection Gas Saving by Use of Surfactants.** Surfactant injection can be considered to reduce the required gas lift rate for severe-slugging suppression. In this subsection, the acquired data are analyzed to investigate the gas lift gas-rate reductions.

Reductions in gas lift rates through surfactant injection are analyzed through the differential MEPIs. The Step 2 MEPI is taken as the base. The MEPI differential equal to or close to zero will provide similar elimination results. These differential MEPI values were used to identify the lowest gas lift rate with surfactant injection that will give elimination performance similar to that of the maximum gas lift rate case without surfactant injection. Then, the difference between maximum gas lift and the

Test	$MEPI_{\text{Step } i} - MEPI_{\text{Step } 2}$					Minimum $V_{sgo,inj}$	Step 2 $V_{sgo,inj}$	Injection Gas Rate Saved (%)
	Step 3	Step 4	Step 5	Step 6	Step 7			
1	47	49	46	45	41	0.00	0.92	100
2	48	48	49	49	47	0.00	0.92	100
3	50	53	51	53	48	0.00	0.95	100
4	53	52	49	49	-46	0.11	0.94	88
5	45	45	44	36	29	0.00	0.95	100
6	21	20	-3	-59	-92	0.42	0.96	56
7	29	29	20	-26	-68	0.27	0.96	72
8	28	26	21	-2	-66	0.11	1	89
9	34	35	33	6	-33	0.11	1.01	89
10	42	41	40	38	35	0.00	0.96	100
11	32	13	-20	-65	-85	0.53	0.96	45
12	29	12	-16	-67	-81	0.53	0.99	46
13	33	30	-15	-51	-80	0.51	0.95	47
14	41	40	29	-16	-35	0.24	0.92	74
15	46	46	46	46	42	0.00	0.92	100
16	35	2	-28	-61	-74	0.62	0.9	32
17	36	5	-23	-63	-83	0.62	0.98	37
18	39	28	-11	-52	-72	0.55	0.98	44
19	37	35	11	-12	-71	0.32	0.97	68
20	48	48	43	-13	-28	0.26	0.94	72
21	42	12	-20	-55	-72	0.52	0.97	46
22	42	41	35	-19	-28	0.28	1	72
23	49	42	24	6	-11	0.11	0.96	89
24	46	38	19	-35	-57	0.28	0.94	70
25	47	46	44	17	1	0.00	0.91	100
26	45	39	31	17	1	0.00	0.92	100
27	49	48	23	-4	-33	0.11	0.95	88
28	50	50	49	49	48	0.00	1	100
29	55	55	52	34	19	0.00	0.9	100
30	62	58	48	41	16	0.00	0.9	100

Table 7—Reduction in gas lift rate.

identified gas lift rates was used to estimate the saved gas lift rate as a percentage of the maximum gas lift rate. The results are presented in **Table 7**.

Analysis of the results presented in Table 7 yields the following:

- There were reductions in the gas lift rate from the original maximum gas lift injection rate for all the tests conducted. The minimum reduction was 32%, while the maximum reduction was 100%.
- Significant gas lift gas savings were observed for most cases.
- 100% of the cases indicated that there was no need for gas lift.

### Scaleup

It is expected that the results obtained in this study would scaleup to offshore-oilfield conditions, provided that the mechanisms of foam creation are understood. This proof-of-concept study was able to prove that the combination of surfactant injection and gas lift can eliminate the severe slugging.

A mechanistic scaleup model is needed to properly upscale to oilfield geometries and flow conditions. The mechanistic model should consider turbulent and interfacial forces under kinetic conditions. The desired effect is “sustained foaming in the riser” to prevent severe slugging. This requires sufficient contact between the gas and liquid/surfactant mixture. Sufficient contact will require an appropriate amount of surfactant, the presence of continuous gas in contact with liquid, and agitation or mixing to facilitate sustainable bubble formation.

As discussed in Sarica et al. (2014), the process is a competition between foam generation and the fluid flow in a riser/pipeline system. As an example, for low gas- and liquid-flow rates and the

no gas lift case, the liquid can accumulate up to the top of the riser without any gas entry into the riser at the bottom. During this period, injected surfactant does not create foam. During the blowout phase of severe slugging, most of the liquids are pushed out of the riser in a short time period with some foam creation. Then, for the next cycle, the riser is filled with fresh liquid and the process repeats itself without realizing the desired effect. In this study, it was observed that gas lift gas increased the suppression of severe slugging through the introduction of gas and the agitation for the foam generation.

### Concluding Remarks

In this study, a feasibility analysis of the combination of gas lift and surfactants as a severe-slugging-suppression technique was conducted. Thirty tests were conducted and analyzed to investigate the effectiveness of the combination of surfactants and gas lift in severe-slugging suppression. In every test, the following order was followed:

1. A baseline was established with no gas and surfactant injection.
2. A maximum gas-injection rate was applied.
3. A constant surfactant amount greater than the critical micelle concentration was injected.
4. The gas lift rate was reduced progressively in four steps from maximum to zero.

The data were analyzed for severe-slugging suppression of the surfactant and gas lift combination, the effect of gas lift on surfactant injection, and the effect of the surfactant on the reduction of the gas lift gas. The following conclusions were reached:

- The combination technique with the highest gas lift rate completely eliminated the severe slugging for all tests conducted.
- In general, it was observed that the elimination performance index (EPI) became smaller as the total gas/liquid ratio was reduced.
- Similar to the observations made in Sarica et al. (2014), surfactants were able to suppress severe slugging for most of the cases. For some cases, EPI values indicated worsening of the severe slugging because of the reduction in the minimum pressure drop. The performance of the only-surfactant injection case increased as the gas/liquid ratio increased.
- For all of the tests, backpressure reduction (BPR) was observed.
- Generally, as the gas/liquid ratio increased, BPR increased. This increase reached a plateau at high gas/liquid ratios for the studied gas/liquid ratios.
- The maximum BPR was obtained when a combination of maximum gas injection and surfactant injection was used. This reduction is significant, as indicated by an increase of BPR from 40 to 70% when the gas lift only case is compared with the cases of varying gas lift injection rates and surfactant application.
- The EPI definition does not consider the variations in backpressure. Therefore, a modified EPI (MEPI) is defined to include the backpressure effects. MEPI was used as the main parameter to assess the performance of the severe-slugging-suppression methods.
- Gas lift not only contributed to density reduction through volumetric increase of gas in the riser, but it also reduced the mixture density by promoting more foam generation.
- There were reductions in the gas lift rate from the original maximum gas lift injection rate for all the tests conducted with surfactant injection. The minimum reduction was 32%, while the maximum reduction was 100%.

A mechanistic model is needed to understand the physics of the surfactant effects on severe-slugging suppression. The mechanistic model will be the key to scaleup. The model needs to focus on simulating foam generation and maintenance and its effect relative to the liquid-accumulation rate in the riser/pipeline system. It is speculated that sustainable foam-generation rate needs to be greater than the liquid-accumulation rate for surfactant injection to be successful.

The priority of a followup study should be the understanding of the mechanisms and the development of the models to simulate the flow behavior. Additional testing may be required to determine the effects of different surfactants. The additional testing will also help in the development/improvement of the mechanistic model.

## Nomenclature

- $P_{sep}$  = separator pressure, Pa  
 $V_{sg}$  = superficial gas velocity, m/s  
 $V_{sgo}$  = superficial gas velocity at standard conditions, m/s  
 $V_{sl}$  = superficial liquid velocity, m/s  
 $\Delta p_{max}$  = maximum pressure drop, Pa  
 $\Delta p_{min}$  = minimum pressure drop, Pa

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