Regular Article

PHYSICAL CHEMISTRY RESEARCH
Published by the
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Phys. Chem. Res., *Vol. 6, No. 4, 815-824, December 2018*
DOI: 10.22036/pcr.2018.145537.1529

Effect of Surfactants on Pressure Drop in Vertical Water-Air and Gas Condensate-Air Two-Phase Vertical Flow

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(Received 26 August 2018, Accepted 1 October 2018)

The influence of sodium dodecyl sulfate and Triton X-100 surfactants on the two-phase pressure drop and two phase flow regime of water-air and gas condensate-air in upward vertical pipe were investigated for various gas/liquid flow rates. Sodium dodecyl sulfate and Triton X-100 reduced the pressure drop of single phase water flow by 11% and 29% compared to that of pure water single phase flow at water velocity of 13 m s^{-1}. For condensate single phase flow, sodium dodecyl sulfate and Triton X-100 reduced the pressure drop by 9% and 17% compared with that of condensate single phase flow with no surfactant at gas condensate velocity of 13 m s^{-1}. The maximum efficiency of sodium dodecyl sulfate and Triton X-100 in reducing the pressure drop of water-air system were 67.1% and 79.8%, respectively, compared to that of pure water-air two-phase flow. For gas condensate-air system, the maximum efficiency of sodium dodecyl sulfate and Triton X-100 in reducing the pressure drop was 57.1% and 36.7%, respectively, compared to that of pure condensate-air two-phase flow.

Key words: Vertical flow, Single phase flow, Two-phase flow, Flow regime, Pressure drop, Surfactant

INTRODUCTION

Transport of oil and gas in petroleum industry is associated with the multiphase flow of oil, water and gas in a single pipeline from the production wells to the central gathering station [1]. The length of the pipelines transporting multiphase flow of oil, water, and gas might be many kilometers; thus, a considerable pressure drop might occur in the pipeline. Traditionally, drag reducing agents (DRAs) are exploited to decrease pressure drop along a pipeline which in turn allows an enhanced and more economical production [2]. Polymers, surfactants and fibers are three major types of DRAs. Polymeric DRAs include polyacrylamides, polystyrene, polyisobutylene, carboxy-methylcellulose, and polyethylene oxides. Examples of surfactant DRAs are sodium lauryl cetyl trimethyl ammonium chloride (CTAC), cetyl trimethyl ammonium bromide (CTAB), sodium salicylate, and sodium dodecyl-benzene sulfonate (SDBS). Pulp and nylon fibers exemplify the fiber DRAs [3,4].

Addition of DRAs may alter multiphase flow regime in addition to reduction of pressure drop. For instance, when polymer solution is added in the liquid phase, the region of stratified gas-liquid flow may significantly extend as annular and slug flows change into stratified ones. Moreover, slug frequencies may substantially decrease, disturbance waves get dampened, and the liquid hold-up increases [5-10]. Such delayed transition to slug flow as well as reduction in the slug frequencies may bring up to 50% reduction in corrosion in pipelines [11].

While DRAs offer great economic advantages to the petroleum produces, their effect on flow regime and reduction of pressure drop relies on the physicochemical properties of the fluids. Thus, selection of proper DRA and determination of its optimum concentration for the maximum reduction of pressure drop in a particular system

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Table 1. Properties of Surfactant

Surfactant name	SDS	Triton
Chemical formula	$C_{12}H_{25}NaO_4S$	$C_{14}H_{21}(C_2H_4O)_nOH$, n = 9 or 10
Cloud point (ºC)[a]	>100	63-69
Density at 25 ºC (g l^{-1})	1.01	1.065
Surface tension (dyne cm^{-1})[a]	39.5	30
HLB	6.6	13.5
CMC at 25 ºC (mM)	8.2	0.22-0.24

[a]1% aqueous solution.

Table 2. Properties of Water

Property	Value
pH	7.4
Turbidity (NTU)	5
Hardness (mg l^{-1})	150
TDS	500
Bicarbonate	80-120
Chlorine	200

is essential. In this study, sodium dodecyl sulfate (SDS) and Triton X-100 (Triton) are used as surfactant DRAs. The effect of SDS and Triton concentration on reduction of water and gas condensate surface tension is studied to determine the appropriate range of DRA concentration for experiments. Finally, the effect of SDS and Triton on pressure drop reduction in two-phase water-air and gas condensate-air vertical flow is elucidated at different gas-liquid-ratios (GLRs) as well.

Materials and Methods

Sodium dodecyl sulfate (SDS) and Triton X-100 (Triton) are purchased from Sigma-Aldrich. Properties of SDS and Triton are summarised in Table 1. Tap water and gas condensate from Kangan gas field are used in this study whose properties are listed in Tables 2 and 3, respectively.

A flow regime simulator device was used for the pressure drop measurements and flow visualization. This device consists of a 13 meter horizontal galvanized pipeline and a riser with 3.5 meter of height. A 1.5 meter curved pipe is used for connecting the horizontal pipeline to the riser. The internal diameter of pipe is 2-inches. The liquid phase enters the pipe from a 200 l tank. The flow of water and condensate are supplied by a high flow rate pump (Stream Pumps, China) and a medium pressure compressor (Cermac, Italy). Flow rate of each phase is determined by a rotameter (Azmoon Motamam, Iran). Water/condensate and air flow rates are controlled by rotameters which have a maximum flow rate of 600 l min^{-1} and1000 l min^{-1}, respectively. The pump pushing water/condensate into the pipeline has a

Table 3. Properties of Gas Condensate from Kangan Gas Field

Property	Value	Evaluation method
Specific gravity	0.7228	ASTM D 4052
ºAPI	64.3	ASTM D1298
Kinematic viscosity at 20 ºC (mm^2 s^{-1})	0.6745	ASTM D 445
Pour Point (ºC)	<-39	ASTM D 97
Molecular mass	138	Osmomat
Saturates (%)	91.2	ASTM D 1319
Olefin (%)	0.7	ASTM D 4052
Aromatics (%)	8.17	ASTM D 4052
Vax (%)	0.03	BP 237
Sulfur content (%)	0.03	ASTM D 4294
Nitrogen content (ppm)	<10	ASTM D 5762
Mercaptan (ppm)	104144	UOP 163
H_2S (ppm)	<1	UOP 163
H_2O (ppm)	104	ASTM D 4928

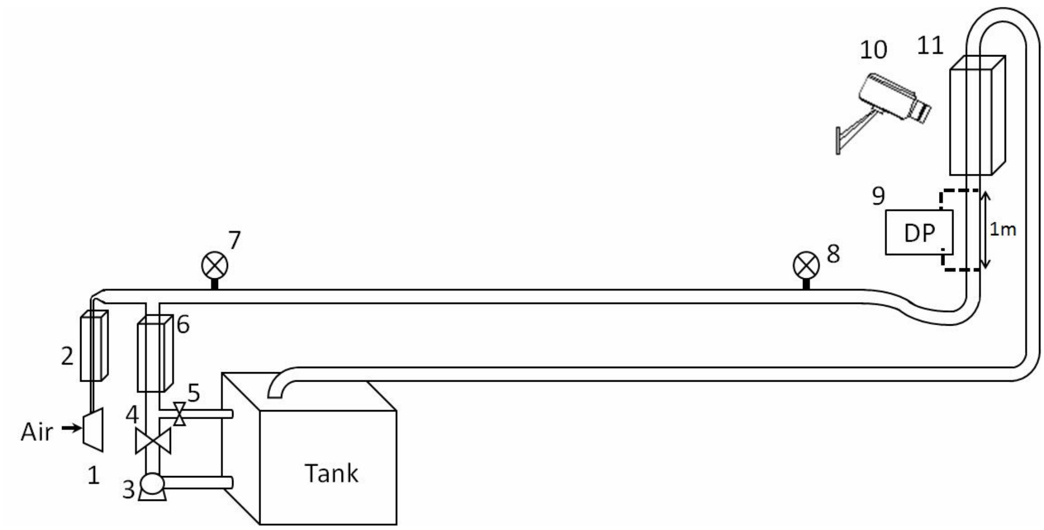

Fig. 1. Schematic diagram of the experimental set up for the measurement of pressure drop in the riser. Different parts of the setup include: 1. compressor, 2. and 6. rotameters, 3. pump, 4. and 5. valves, 7. and 8. pressure gauges, 9. differential pressure gauge, 10. camera, and 11. side glass.

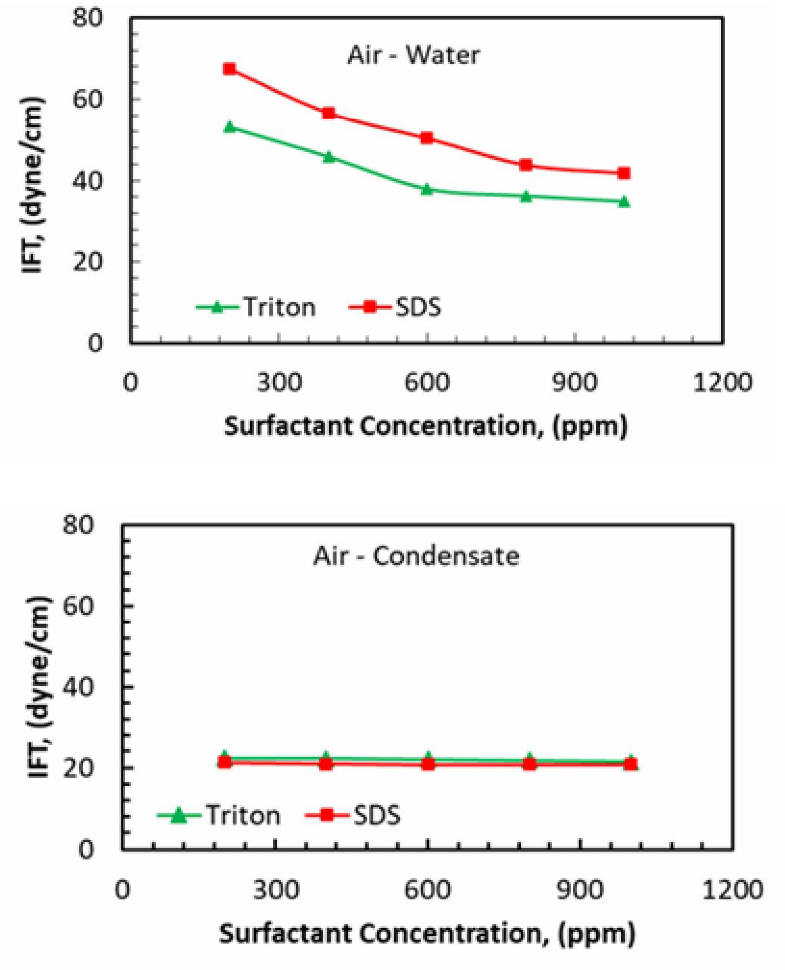

Fig. 2. Effect of surfactant type and concentration on interfacial tension in a) air-water and b) air-condensate system.

constant power; thus, an adjustable recycle stream is utilized to achieve the desired flow rate. Flow rate of compressed air is adjusted by a pressure regulator on the compressor. After flow adjustment, air enters a 1-inch to 2-inch connector, and a 2-inch and then 2-inch T-shaped connector. Water/condensate also enters the T-shape connector where mixing of two phase occurs.

Different flow rates are chosen, and associated pressure drops are measured using a differential pressure gauge. Two-phase flow regimes are visualized using the side glass embedded in the pipeline. SDS or Triton with the desired concentration is added to the tank and the flow experiment is repeated twice for each experimental condition.

Determination of Optimal Concentration of Surfactant

Introduction of the surfactants at the interface of two immiscible phases provides a barrier between the molecules at the interface which in turn decreases the interfacial tension (IFT). However, at critical micelle concentration (CMC), where the interface is filled with the surfactant molecules, further increase in surfactant concentration no longer reduces the IFT and additional surfactant molecules that do not have a chance to adsorb at the interphase from micelles within the liquid phase. Figure 2 shows the results of IFT measurements as a function of SDS/Triton concentration for both air-water and air-condensate systems

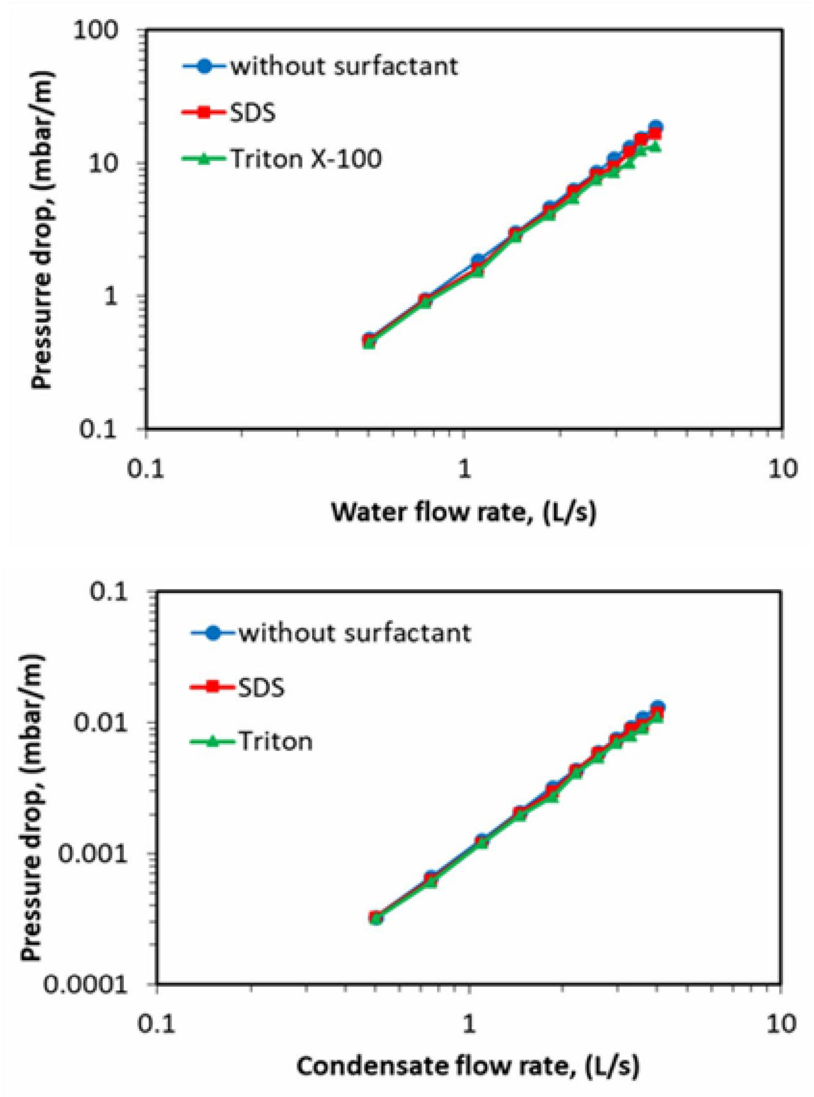

Fig. 3. Effect of surfactant type on interfacial tension in a) air-water and b) air-condensate system.

at 27 °C and 1 bar. It can be seen from Fig. 2 that for air-water system the optimum concentration of Triton and SDS are 600 ppm and 800 ppm, respectively. For air-condensate system the concentration of surfactants has a limited effect on IFT; nevertheless, the optimum concentration for Triton and SDS are measured as 1000 and 800 ppm, respectively. The optimum concentration of surfactants are used for the measurement of pressure drop in the two-phase flow.

Effect of Surfactants on Single Phase Flow

The optimum concentration of surfactant is utilized to show the effect of SDS and Triton surfactants on the pressure drop of single phase water and gas condensate flow. According to Fig. 3a, SDS and Triton can reduce pressure drop of single phase water flow up to 11% and 29% compared to that of pure water single phase flow at high flow rates respectively. Figure 3b illustrates pressure drop of single-phase gas condensate at different flow rates. It can be seen from Fig. 3b that pressure drop in gas condensate is very small compared to that of water. According to Fig. 3b, SDS and Triton can reduce pressure drop of single phase condensate flow up to 9% and 17%

compared to that of condensate single phase flow with no surfactant at high flow rates.

Effect of Surfactants on Two-Phase Flow Pressure Drop

Pressure drop profiles corresponding to the two-phase flow of water-air and condensate-air as a function of superficial gas velocity, V_{sg}, at different superficial liquid velocities, V_{sL}, are presented in Fig. 4. It can be seen from Figs. 4a, 4c and 4e that Triton is more effective than SDS in reducing pressure drop of water-air system. The maximum efficiency of Triton in reducing the pressure drop of water-air system occurs at $V_{sg} = 1$ m s^{-1} where it can reduce pressure drop by 79.8%, 76.5% and 79.6%, for V_{sL} equal to 0.2 m s^{-1}, 0.3 m s^{-1} and 0.6 m s^{-1}, respectively, compared to that of pure water-air two-phase flow. Interestingly, the maximum efficiency of SDS in reducing the pressure drop of water-air system also occurs at $V_{sg} = 1$ m s^{-1} where it can reduce pressure drop by 67.1%, 62.0% and 60.7% V_{sL} equal to 0.2 m s^{-1}, 0.3 m s^{-1} and 0.6 m s^{-1}, respectively, compared to that of pure water-air two phase flow. The profile of pressure drop *vs.* V_{sg} for water-air two-phase flow at different V_{sL} values does not follow a monotonic decrease by increasing V_{sg} neither in the absence nor in the presence of surfactants.

Pressure drop profiles corresponding to the two-phase flow of condensate-air as a function of superficial gas velocity, V_{sg}, at different V_{sL} values are presented in Figs. 4b, 4d and 4e. It can be seen from these figures that the pressure drop of condensate-air system monotonically decreases in all cases regardless of the presence/absence of the surfactant or at a specified V_{sL}. Compared to that of water-air two-phase system, the surfactants have a less pronounced effect on reduction of pressure drop in condensate-air system. SDS is more effective than Triton in reducing pressure drop of condensate-air system. The maximum efficiency of SDS in reducing the pressure drop condensate-air system occurs at $V_{sg} = 1$ m s^{-1} where it can reduce pressure drop by 29.4% at V_{sL} = 0.6 m s^{-1}. For V_{sL} equal to 0.2 and 0.3, the maximum efficiency of SDS in reducing the pressure drop of condensate-air system occurs at $V_{sg} = 0.1$ m s^{-1} where it can reduce pressure drop by 57.1% and 43.8%, respectively, compared to that of pure condensate-air two-phase flow. The maximum efficiency of Triton in reducing the pressure drop of condensate-air system also occurs at $V_{sg} = 1$ m s^{-1} where it can reduce pressure drop by 36.7%, 31.3% and 26.5% for V_{sL} equal to 0.2 m s^{-1}, 0.3 m s^{-1} and 0.6 m s^{-1}, respectively, compared to that of pure condensate-air two-phase flow. The profile of pressure drop *vs.* V_{sg} for condensate-air two-phase flow at different V_{sL} values follows a monotonic decrease by increasing V_{sg}.

Maximum Reduction of Pressure Drop by Surfactants

The effect of Triton/SDS concentration on reduction of pressure drop for water-air two-phase flow is studied using Triton concentrations of 400 ppm, 600 ppm and 800 ppm and SDS concentrations of 600 ppm, 800 ppm and 1000 ppm at V_{sL} = 0.1 m s^{-1}. It can be seen from Fig. 5a that increasing Triton concentration from 400 ppm to 600 ppm has a strong effect on the reduction of pressure drop and reduces the pressure drop from 76.9% to 19.4% of the pure water-air system at V_{sg} = 0.1 m s^{-1}. Further increase in the Triton concentration from 600 ppm to 800 ppm has a marginal effect on reduction of pressure drop of water-air system and incrementally reduces pressure drop from 19.4% to 16.4% of the pure water-air system at V_{sg} = 0.1 m s^{-1}. Similarly, Fig. 5b reveals that increase of SDS concentration from 600 ppm to 800 ppm has a strong effect on the reduction of pressure drop and reduces the pressure drop from 89.3% to 30.0% of the pure water-air system at V_{sg} = 1 m s^{-1}. Further increase in the Triton concentration from 800 ppm to 1000 ppm has a marginal effect on reduction of pressure drop of water-air system and incrementally reduces pressure drop from 30.0% to 25.8% of the pure water-air system at $V_{sg} = 1$ m s^{-1}.

The effect of Triton/SDS concentration on reduction of pressure drop for condensate-air two-phase flow is assessed using Triton concentrations of 800 ppm, 1000 ppm and 1200 ppm and SDS concentrations of 400 ppm, 600 ppm and 800 ppm at V_{sL} = 0.2. It can be seen from Fig. 6a that adding 800 ppm of Triton reduces the pressure drop to 83.3% of the pure condensate-air system at V_{sg} = 0.1 m s^{-1}. Increasing Triton concentration from 800 ppm to 1000 ppm further reduces the pressure drop from 83.3% to 77.1% of the pure condensate-air system at V_{sg} = 0.1 m s^{-1}. Additional increase in the Triton concentration from 1000 ppm to 1200

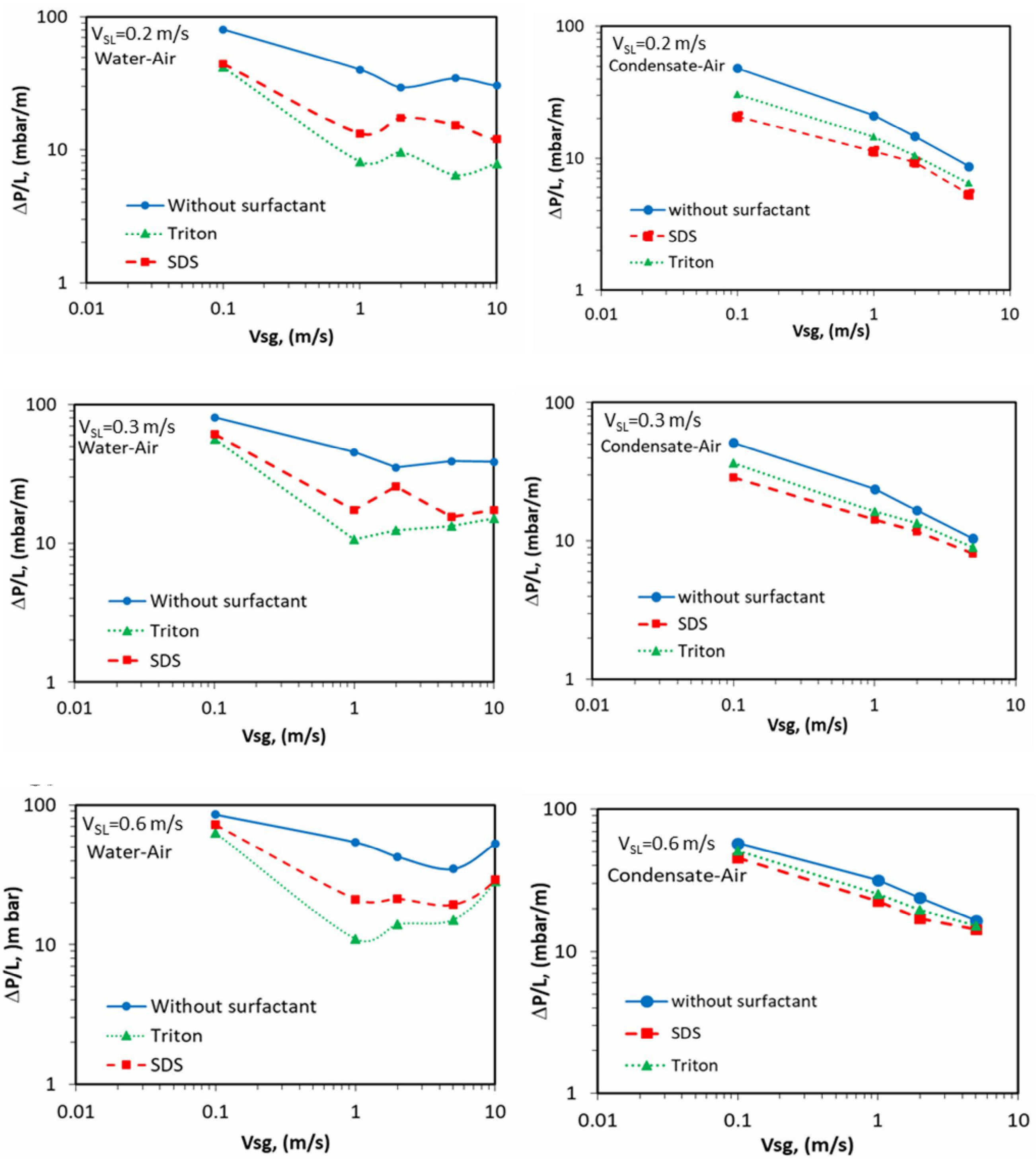

Fig. 4. Effect of surfactant type and concentration on pressure drop in a), c), and e) air-water and b), d), and f) air-condensate system.

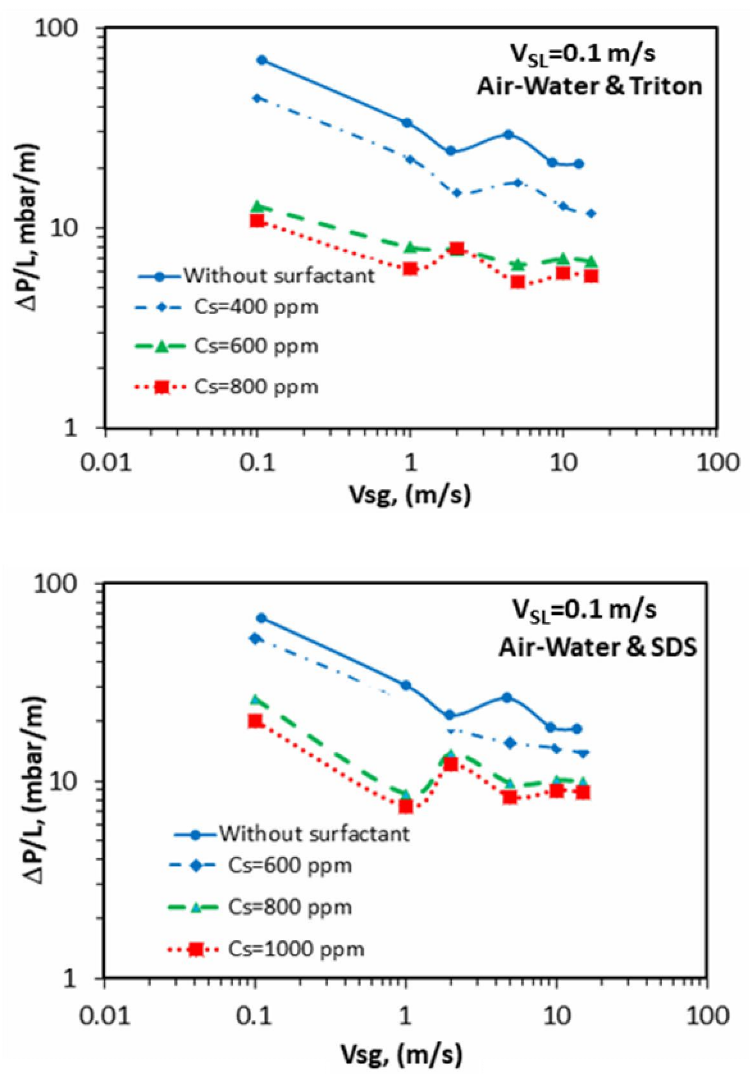

Fig. 5. Maximum reduction of pressure drop by a) Triton and b) SDS in air-water system.

ppm has a marginal effect on reduction of pressure drop of condensate-air system and incrementally reduces pressure drop from 77.1% to 63.3% of the pure condensate-air system at V_{sg} = 0.1 m s^{-1}. Similarly, Fig. 6b shows that adding 400 ppm SDS reduces the pressure drop to 79.9% of the pure condensate-air system at V_{sg} = 0.1 m s^{-1}. Increasing SDS concentration from 400 ppm to 600 ppm further reduces the pressure drop from 79.9% to 50.9% of the pure condensate-air system at V_{sg} = 0.1 m s^{-1}. Additional increase in the SDS concentration from 600 ppm to 800 ppm further reduces the pressure drop of condensate-air system from 50.9% to 42.8% of the pure condensate-air system at V_{sg} = 0.1 m s^{-1}.

CONCLUSIONS

Results of this study revealed that both sodium dodecyl sulfate and Triton X-100 surfactants can drastically reduce pressure drop during two-phase upward flow of water-air and gas condensate-air. Pressure drop profile of water-air system in all cases shows a local maxima at intermediate V_{sg} suggesting a change in the flow regime. On the other hand,

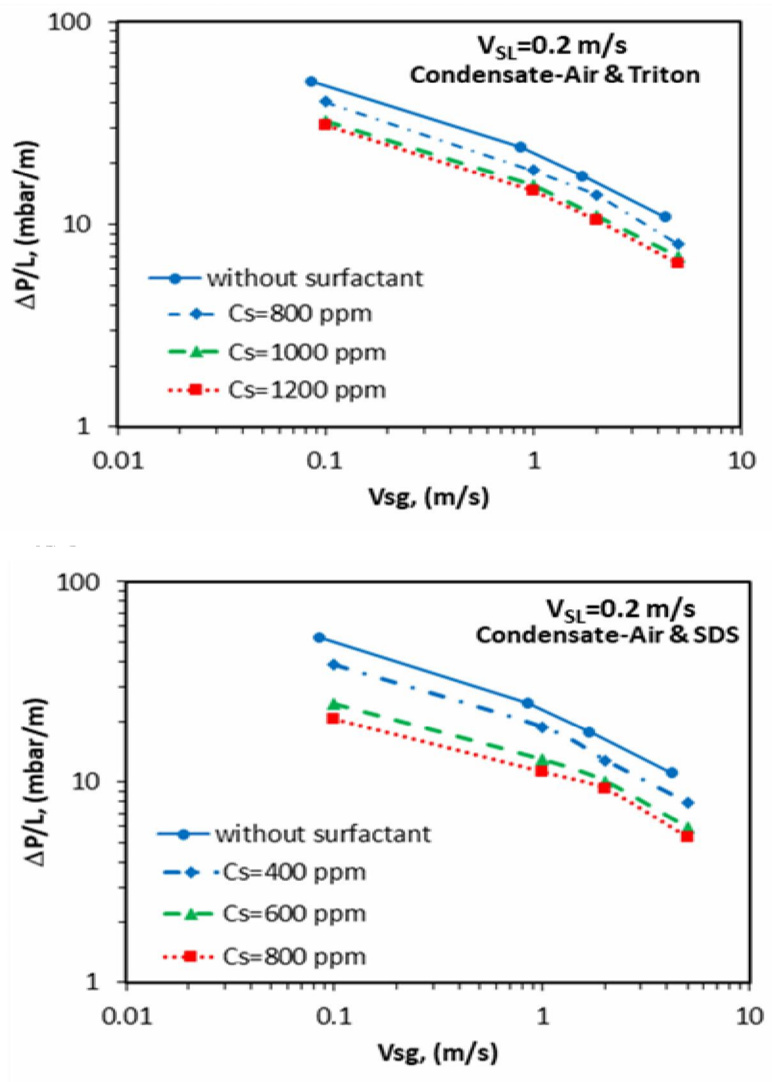

Fig. 6. Maximum reduction of pressure drop by a) Triton and b) SDS in air-condensate system.

pressure drop profile of gas condensate-air system follows a monotonic decrease. Although sodium dodecyl sulfate and Triton X-100 surfactants could reduce the pressure drop of water-air system by 67.1% and 79.8% (57.1% and 36.7% for gas-condensate-air system), the efficacy of surfactants in reduction of pressure drop in two-phase system is greatly affected by the interfacial area of two phases at a given time. The relative flow rate of each phase and two-phase flow regime will determine the interfacial area. Further studies are required to understand the effect of sodium dodecyl sulfate and Triton X-100 surfactants on flow regime.

ACKNOWLEDGMENTS

The authors are grateful to the Shiraz University for supporting this research.

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