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Experimental study of aqueous foam generation and transport in a horizontal pipe for deliquification purposes

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A R T I C L E I N F O

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A B S T R A C T

This work presents and analyses the results of experimental activities aimed at a preliminary characterization of foamy flows for pipeline dewatering, in order to assess whether the addition of surfactants may effectively reduce the liquid holdup in horizontal pipelines. Static tests were run to compare the foam cycle (generation and decay) for three commercial surfactants and to choose the most suitable one. Dynamic tests with the selected product were performed in a 20 m long, 60 mm i.d. Plexiglas® pipe, where a 0.3% wt. solution of surfactant in tap water was pumped after mixing with an air flow at nearly atmospheric pressure and temperature. Superficial velocities ranged between 0.03 m/s and 0.05 m/s for water and between 1.5 m/s and 11.5 m/s for air, which would determine stratified/stratified wavy flows in the case of pure water-air flow, i.e. the benchmark case. Due to the presence of the surfactant, foam formed in the mixing section, which implied a significant change in the flow patterns that were photographically recorded and classified into three main types: plug, stratified wavy and stratified with foam entrainment, as far as the air superficial velocity was increased at constant water superficial velocity. The associated pressure drop, linearly distributed along the pipeline, resulted greater than the benchmark value in all the operating conditions, with a dramatic increase (even more than 100%) for plug flows. On the other hand, the percentage relative difference was found to lower with increasing the air superficial velocity, apart for stratified wavy flows where it seemed to keep constant at about 3.3%. Finally, a theoretical model for stratified flows was used to relate the pressure drop to the void fraction in order to get at least an approximate indication of the liquid load reduction due to the surfactant addition, which ranged between 6% and 39%.

1. Introduction

Natural gas, along with oil and coal, is considered a traditional energy source for humanity, which is gaining a greater share, mainly due to its cleanliness compared to other fossil fuels. Particularly, in the last decade, natural gas consumption has increased by 22%, which places natural gas at the third place in the ranking of energy sources, with a prospective growth in the near future [4]. Two issues mainly affect pipelines used to transport natural gas from the production well to the treatment plant: gas hydrate formation and water accumulation [23]. Gas hydrates are crystalline compounds that form when water gets in contact with some gas molecules at specific temperature and pressure conditions. The formation of gas hydrates was studied from the early '30s [15]as it was found to be one of the major causes of oil and natural gas pipelines blockage. Actually, the combination of high pressure and low temperature in the transportation pipelines sets the conditions to form hydrates. Different techniques have been implemented to avoid or at least limit these drawbacks. In particular, three methods are commonly adopted to prevent hydrate formation: temperature control, water removal and addition of inhibitors. While the feasibility of the former solution is severely limited by cost and technical issues, the other solutions were successfully applied. In most of the fields producing natural gas, hydrate prevention is accomplished by using thermodynamic inhibitors, in particular mono-ethylene glycol (MEG), which has also beneficial effects in limiting corrosion [7]. On the other hand, to reduce liquid loading especially in horizontal pipelines, injection of surfactants to produce foams has been recently considered and seems a promising alternative to traditional techniques that

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Nomenclature

i.d.	inner diameter [mm] or [in]
f	friction factor [-]
BUT	build-up time [s]
CT	collapse time [s]
C	volume fraction (cut) [-]
HLT	half-life time [s]
J	superficial velocity [m/s]
MAPE	mean absolute percentage error [-]
MEG	mono-ethylene glycol
MPE	mean relative percentage error [-]
R	pressure relative increase [-]
Re	Reynolds number [-]
S	perimeter [m]
SF	mass of surfactant [kg]
U	cross-section average velocity [m/s]
W	mass of water [kg]

Subscripts

a	air
i	interface
w	water
G	gas
L	liquid

Greek Symbols

γ	circumferential angle [rad]
ε	void fraction [-]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
σ	surfactant concentration [kg/kg]
τ	shear stress [Pa]
Ω	cross section [m^2]

involve the use of pigs and compressors [9,8,31,20]. Moreover, foam generation in oil wells enables longer and more stable production. The effect of surfactants on upward gas-liquid pipes flow at various inclinations, with particular regard to the pressure gradient, has been recently studied by van Nimwegen et al. [27–29].

The flow of aqueous foams, i.e. dispersions of bubbles in water with a specific structure [16], is relevant to a wide variety of engineering contexts, for example mining and mineral processing, petroleum industry, manufacturing and material science, biological and medical applications, personal care products, food processing, etc. [1]. Foam formation and transport is either desired, owing to its rheology, e.g. the ability in transporting a solid phase like in mineral flotation [22]or unwanted like in environmental water treatment [18]. Accordingly, the scientific literature is very rich of contributions devoted to the detailed characterization of chemical and physical properties of foams: for an overview, the reader may address some extensive treatises [1,21,24] and recent review papers [10,13]. Considering fluid dynamics, it has been noticed [5] that uniform foams, i.e. without bottom liquid film due to drainage, have been mostly taken into account. In this case, self-lubrication takes place due to a very thin liquid layer, which is formed by the breaking of the foam cells at the pipe wall. The description of the motion usually represents the foam as a non-Newtonian fluid [16,30] and several power-law statements of the stress-strain relationship were proposed for engineering applications: most of them are addressed in Stevenson [24], Dollet and Raufaste [10], Briceno and Joseph [5]. However, such a description may be very poor since in various experiments foam is not uniform, but the motion exhibits flow patterns similar to the ones commonly encountered in two-phase flows. For instance, Briceno and Joseph [5] studied the flow of an aqueous foam in a 5/8 in. inner diameter pipe made of transparent Plexiglas® and 1.2 m long. The foam has been generated by supplying air to a water stream with previously dissolved surfactants in a foam generator essentially consisting of a packed bed. According to the superficial velocities of the phases, different flow patterns have been observed, including stratified flow and transition to slug flow. More recently, Bogdanovic et al. [3] tested various surfactants at different concentrations in stainless steel 0.5 and 1 in. nominal diameter pipes, about 3.7 m long, observing two different flow regimes: the so called "high-quality regime", characterized by slug flow with oscillating pressure response, and the "low-quality regime" with uniform foam and stabilized pressure response. Gajbhiye and Kam [14] adopted the same approach and extended the characterization recognizing that foam rheology in the high quality regime depends on both gas and liquid velocities, whereas in the low quality regime only gas velocity matters. Finally, other authors observed wet foamy flows with stratification of partially shared or unshared layer of foam on top of a liquid layer [6,2,26]. The variety of foamy two-phase flows in the oil and gas sector may be even larger as it will be also shown in this paper, but there is a fundamental lack of both experimental data and modelling approaches, particularly as far as large diameter pipes are concerned. For these reasons, this work presents and analyses the results of experimental activities aimed at a preliminary characterization of foamy flows for pipeline dewatering, in order to assess whether the addition of surfactants may effectively reduce the liquid holdup in horizontal pipelines. Static tests were run to compare the foam cycle (generation and decay) for three commercial surfactants and to choose the most suitable one. Dynamic tests with the selected product were performed in a 20 m long, 60 mm i.d. Plexiglas® pipe, where a 0.3% wt. solution of surfactant in tap water was pumped after mixing with an air flow at nearly atmospheric pressure and temperature.

2. Static tests

2.1. Experimental setup and operating conditions

Three surfactants, two of them provided by CHIMEC SpA and the other one by DAJAN Srl, were considered: to avoid commercialism, in the following they will be randomly denoted as A, B and C. Compositions and properties are reported in Table 1. Measured values of the equilibrium surface tension at 20 °C as a function of the

Table 1
Surfactant characteristics.

	Component	Concentration	Density at 20 °C [kg/m^3]	Dynamic viscosity at 20 °C [Pa·s]
Surfactant A	Alkyl polyglycol ethers	55–65%	980 ± 20	< 0.1
	Propan-2-ol	10–20%		
Surfactant B	Ammonium lauryl ether sulfate	5–10%	1020 ± 20	< 0.1
	Polyglycerol alkyl ethers	50–60%		
	Propan-2-ol	10–20%		
	2-Butoxyethan-1-ol	< 5%		
Surfactant C	Ethane-1, 2-diol	15–25%	1035 ± 5	< 0.01
	Alkyldimethyl-betaines	15–25%		