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Experimental study of drag reduction by a polymeric additive in slug two-phase flow of crude oil and air in horizontal pipes

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Abstract

In this study the effect of the presence of a drag reducing agent (DRA) on the pressure drop in cocurrent horizontal pipes carrying slug two-phase flow of air and crude oil is investigated. An experimental set-up is erected. The test section of the experimental set-up is consisted of: a smooth pipe of polycarbonate with 10.3 m long and 2.54 cm ID, a rough pipe of galvanized iron with 8.8 m long and 2.54 cm ID and a rough pipe of galvanized iron with 8.8 m long and 1.27 cm ID. The employing DRA is a Polyalpha-olefin (Polyisobutylene). The percent drag reduction (%DR) is calculated using the obtained experimental data, in presence of the DRA. The results show that addition of DRA could be effective up to some doses of DRA after which the pressure drop is kept constant. A %DR of about 40 is obtained for some experimental conditions.

Keywords: Multiphase flow; Non-Newtonian fluids; Polymer; Drag reduction; Slug flow; Fluid mechanics

1. Introduction

It has been known since the late 1940s (Toms, 1948) that the addition of small concentrations of high molecular weight polymer to water or other solvent can produce large reductions in frictional pressure drop for turbulent flows past a surface, leading to the possibility of increased pipeline capacities and faster ships. Two-phase gas–liquid flow is frequently encountered in many industrial units such as distillation columns, pipelines, boiler tubes, condensers, evaporators, and chemical reactors. Offshore production has necessitated transportation of both gas and liquid phases over long distances before separation. This type of flow has many unique features, which must be evaluated in each situation. However, one phenomenon which is nearly always undesirable is the high axial pressure gradient, resulting substantial energy consumption per unit volume of liquid throughput. It can be seen from the literature survey that although some studies have been done on drag reduction by polymer solution in single phase flow, but a few attempts have been made to study the effect of polymer solutions in reducing the high axial pressure drop in two-phase flow. Experimental evidences show that the polymer increases the thickness of the viscous sub layer and the transition zone. The mechanism of this boundary layer effect is not yet fully understood, but supporting experimental evidences have been given by Fortuna and Hanratty (1971), Rudd (1971), Kumor and Sylvester (1972) and Astria (1969).

Among the investigators in this field, Savins (1964), Seyer and Metzner (1969), Patterson et al. (1969), Virk (1975), Lester (1985), Zakin (1971), Yoon and Ghajar (1987, 1988, 1989) and Mowla et al. (1991) could be mentioned. Sylvester and Brill (1976), conducted a study of multiphase drag reduction in an air–water two-phase flow using polyethylene oxide at 100 ppm. In 1995 Mowla et al. (1995), considered the effects of polymer additives on two-phase flow drag reduction for air–water system. Kang and Jepson (1999, 2000) and Dass et al. (2000), have studied drag reduction in horizontal or slightly inclined slug flow and annular entrained flow of oil and carbon dioxide.

The present study involves the drag reduction by a DRA in slug flow regime of air and oil in smooth and rough pipes. Slug flow is selected for two reasons: firstly, it is an important flow regime as far as transport processes are concerned. Secondly, because of the unusual nature of slug flow, that is, alternating sections of gas and liquid, it is possible to use single phase drag

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reduction information combined with two-phase flow data for analysing the physical structure of slug flow.

2. Definition of the drag reduction

Drag reduction is a flow phenomenon by which small amount of additives, e.g. a few parts per million (ppm), can greatly reduce the turbulent friction factor of a fluid. The aim for the drag reduction is to improve the fluid-mechanical efficiency using active agents, known as DRA. In multiphase flow, percent drag reduction (%DR) is defined as the ratio of reduction in the frictional pressure drop when the flow rates are held constant to the frictional pressure drop without DRA, multiplied by 100, as shown in Eq. (1).

$$\%\mathrm{DR} = (\Delta p_f - \Delta p_{fdra})/\Delta p_f \times 100. \tag{1}$$

In this equation Δp_f is the pressure drop in the absence and Δp_{fdra} is the pressure drop in the presence of DRA.

3. Drag reducing agents

The additives, which cause drag reduction, can be split into three groups: polymers, surfactants and fibers. Surfactants can reduce the surface tension of a liquid. Fibers are long cylinder-like objects with high length to width ratio. They oriented themselves in the main direction of the flow to reduce drag. General guidelines for the selection of a DRA for a given multiphase flow application do not exist. The most important requirement is that the DRA is soluble in the liquid. In addition to the solubility of the chemical, it is known that the following properties influence the performance of the polymer:

- High molecular weight ($M > 1\,000\,000\,\mathrm{g/mol}$).
- Shear degradation resistance.
- Quick solubility in the pipeline fluid.
- Heat, light, chemical, biological degradation resistant.

4. Experimental procedure

The main purpose of this work was studying the drag reduction in two-phase flow of oil and natural gas as occurred in oil and gas industries. A literature review indicated little actual data on drag reduction in two-phase flow. Therefore an experimental apparatus was set up for obtaining drag reduction data at various polymer concentrations. The test section of the experimental set-up was consisted of: a smooth pipe of polycarbonate with 10.3 m long and 2.54 cm ID, a rough pipe of galvanized iron with 8.8 m long and 2.54 cm ID, and a rough pipe of galvanized iron with 8.8 m long and 1.27 cm ID. In the first sets of experiments, it was observed that there is no any different between using natural gas or air as the gas phase. Therefore for increasing security and safety measurements, air was used as the gas phase in all experiments. As liquid phase, crude oil prepared from Shiraz oil refinery situated at the Fars province in the south west of Iran was used. A polyalphaolefin (polyisobutylene) was selected as DRA. This polymer is oil soluble, and its required concentration is such that the properties of the solution could be considered the same as the crude oil. Each solution was prepared as master solution and then injected in the pipes by a JMS syringe pump (model SP-500) at the entrance of the pipes. The liquid flow rate was measured by a liquid flowmeter, and the gas flow rate by a rotameter. The axial pressure drop was determined by using inverted manometers installed at several points along the tubes. For elimination of the entrance and end effects, the manometers were installed at 1.5 m from the entrance and the exit of the pipes. The oil was fed through the system by a Moyno-progressive cavity pump and air was fed by a compressor of Tehran Compressor Company. The slug flow regimes were investigated in this work. A schematic flow diagram of the experimental apparatus is shown in Fig. 1.

It should be noted that for crude oil as a power law fluid, k and n are the two important parameters which will affect the frictional pressure gradient calculation for the system. These two parameters are determined experimentally by studying the laminar flow of crude oil and air through the smooth Polycarbonate pipe. Using the results of these experiments a logarithmic plot of τ_w versus $(8v_{ns}/D)$ was obtained and shown in Fig. 2. As it is seen this plot is linear, indicating that the mixture of crude oil and air is a power law fluid. Then n is evaluated as the slop and k as the intersection of this curve according to Eq. (2).

$$\tau_w = k(8v_{ns}/D)^n. \tag{2}$$

In this equation v_{ns} is defined as

$$v_{ns} = v_{sl} + v_{sg}, \tag{3}$$

where

$$v_{sl} = Q_l/A \tag{4}$$

and

$$v_{sg} = Q_g/A. \tag{5}$$

Air and oil specifications for the experimental conditions are given in Table 1.

In this study Re, slip Reynolds number, is defined as follows:

$$Re = \rho_s v_s^{(2-n)} D^n/(8^{(n-1)}k), \tag{6}$$

where

$$v_l = Q_l/(H_L A), \tag{7}$$

$$v_g = Q_g/(H_G A), \tag{8}$$

$$v_s = v_g - v_l, \tag{9}$$

$$\rho_s = H_L\rho_l + H_G\rho_g, \tag{10}$$

H_L, liquid holdup and H_G, gas void fraction, were calculated from Beggs and Brill correlations [21].

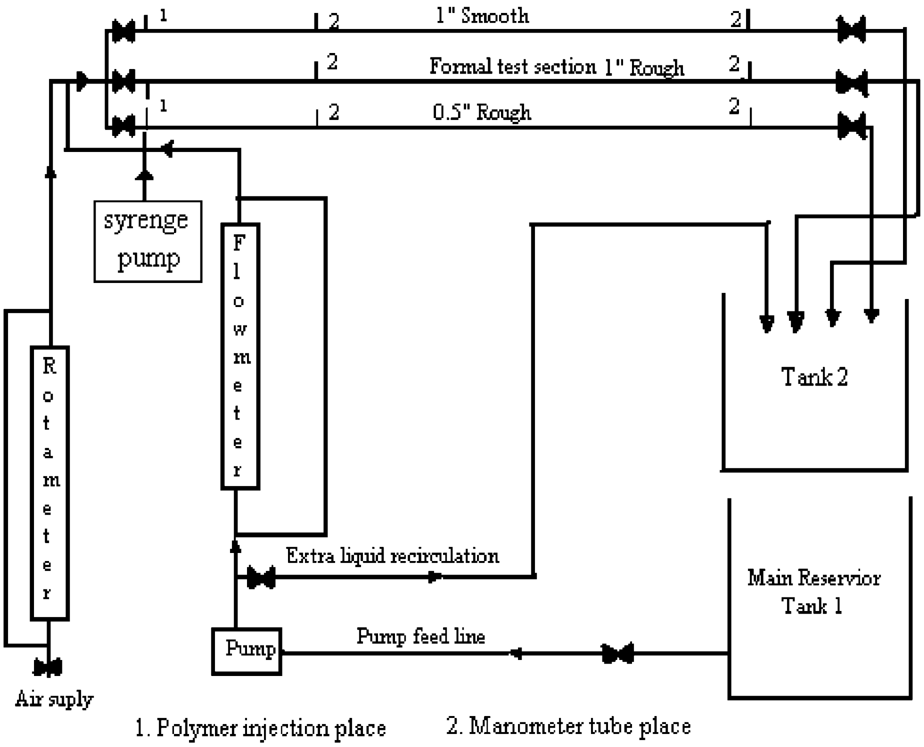

Fig. 1. A schematic diagram of the experimental apparatus.

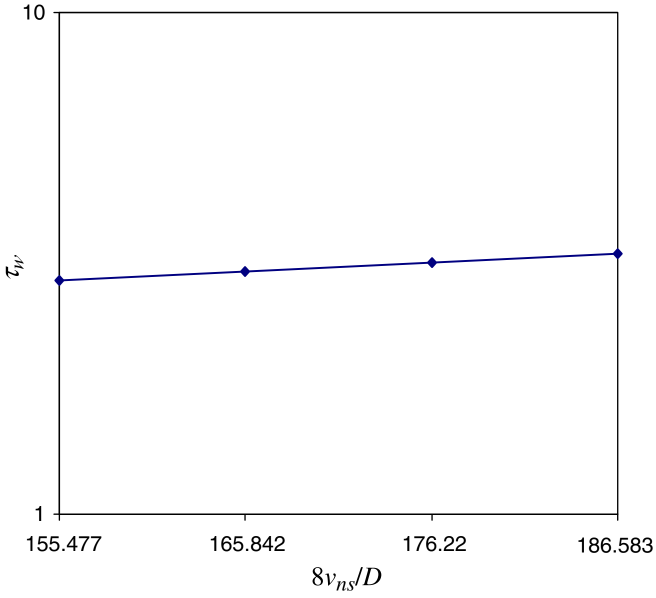

Fig. 2. Logarithmic plot of τ_w versus $(8v_{ns}/D)$.

Table 1
Oil and air specifications

ρ_{oil} (kg/m^3)	ρ_{air} (kg/m^3)	API	n	k (kg/m s^{2-n})
886	1.2	28.2	0.65	0.011

5. Results and discussion

In Figs. 3–5 the percent drag reduction is plotted versus polymer concentration in different pipes for slug flow regime. It is observed that, by adding of a low concentration of the polymer, one can find a reduced pressure drop per unit length at the same flow conditions. Also the percent of drag reduction increases with increasing of the polymer concentration, but there is a critical concentration above which no more reduction

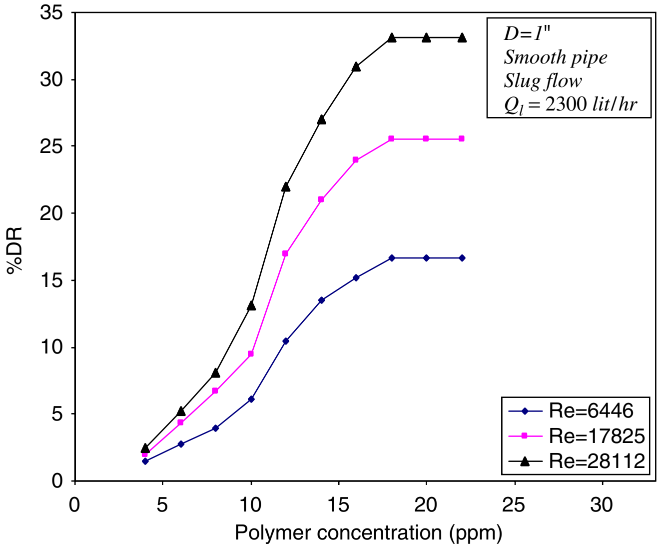

Fig. 3. Variation of %DR versus DRA concentration for smooth pipe.

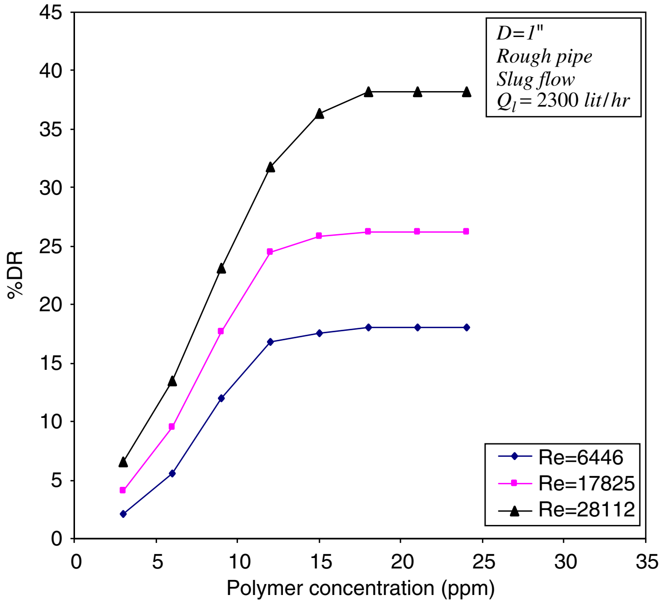

Fig. 4. Variation of %DR versus DRA concentration for rough pipe.

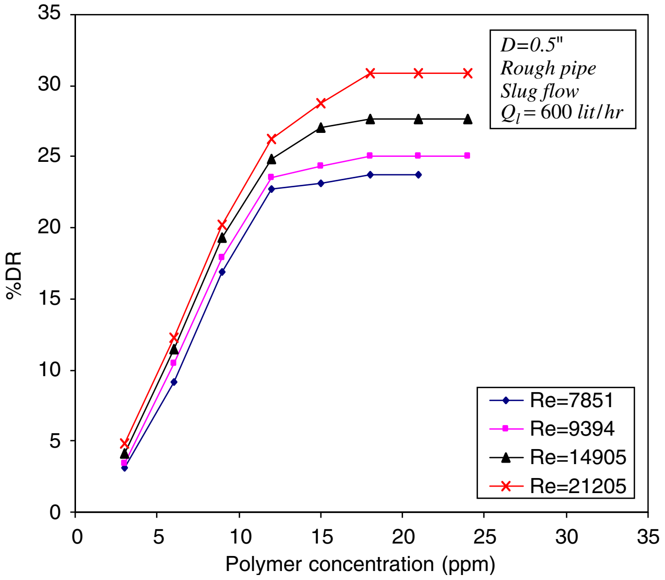

Fig. 5. Variation of %DR versus DRA concentration for rough pipe.

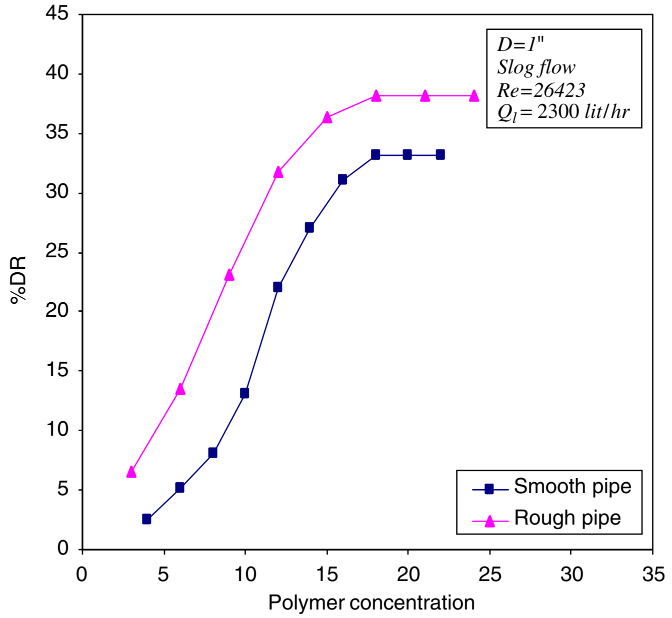

Fig. 6. Comparison of %DR versus DRA concentration for smooth and rough pipes.

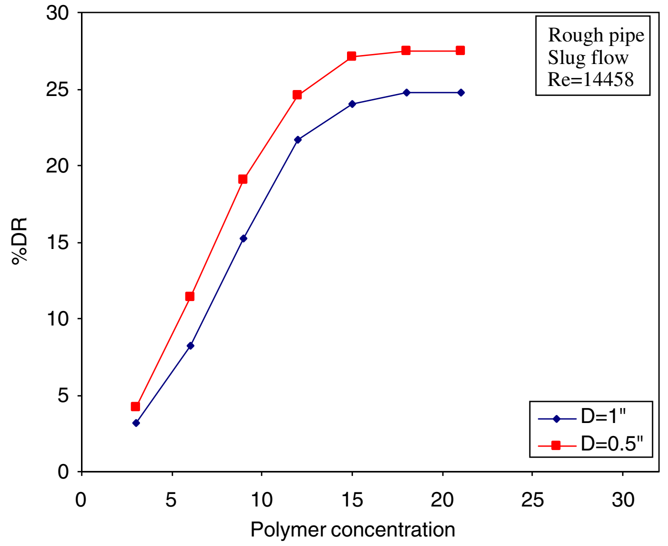

Fig. 7. Variation of %DR versus DRA concentration for different pipe diameters.

can be obtained. It should be mentioned that, the optimum concentration of polyisobutylene in crude oil is 18 ppm, independent of the type or diameter of the pipe for this system.

In Fig. 6 the percent drag reduction is plotted versus polymer concentration for 1″ smooth and rough pipes at the same flow conditions. It is observed that in rough pipe the drag reduction is more than smooth pipe. The reason for this phenomenon is that as it is known the DRAs are effective only in turbulent flow and their effects are enhanced by the degree of turbulency. So since the roughness of the pipe increases the turbulency of the flow, the drag reduction is more pronounced for this case.

In Fig. 7 the percent drag reduction is plotted versus polymer concentration for slug flow regime in rough pipes of 1″ and 0.5″ diameters. It is observed that in 0.5″ pipe the drag reduction is more. Indeed with decreasing of pipe diameter, the relative roughness ε/D is increased, this would result in higher degree of turbulency, what represents better the effect of the DRA.

During the experiments, it was observed that, in some cases the magnitude of drag reduction is decreased and in other cases it is increased with increasing liquid superficial velocity. These variations are shown in Figs. 8 and 9.

This contradiction could also be observed in the works of Kang and Jepson (1999, 2000) and Sylvester and Brill (1976)

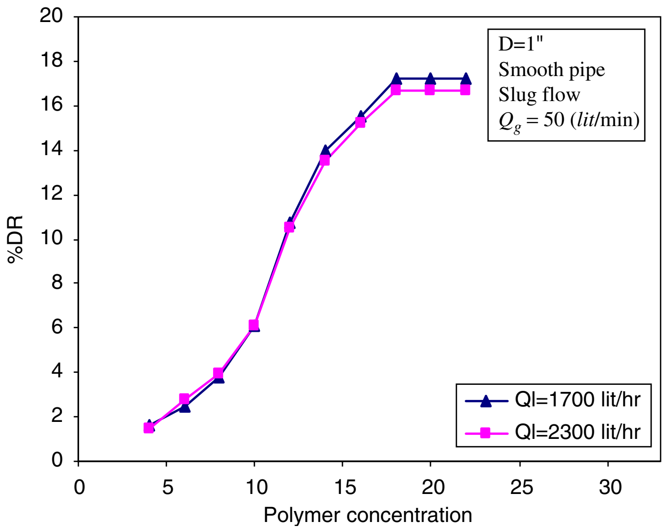

Fig. 8. Comparison of %DR versus polymer concentration for different liquid flow rate.

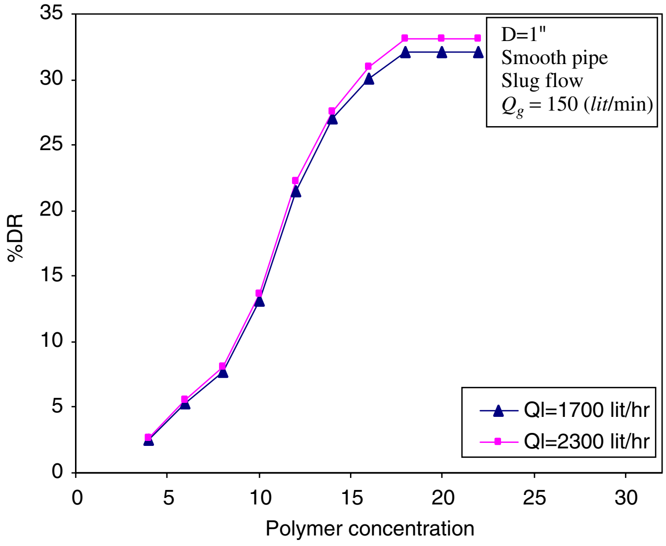

Fig. 9. Comparison of %DR versus polymer concentration for different liquid flow rate.

from one side and Al-Sarkhi and Hanratty (2001a,b) from the other side. The two first groups mentioned the decreasing of drag reduction with increasing superficial liquid velocity, while the second group mentioned the increase of drag reduction with increasing superficial liquid velocity.

In order to justify this contradiction, the results given in Figs. 8 and 9 are considered more precisely. It is noted that in these figures the amount of Q_g in completely different and so it could be concluded that this is the gas slip velocity and as a result the slip Reynolds number which affect the amount of drag reduction for a given polymer concentration.

In order to explain the obtained results with a more realistic mechanisms, it should be noted that according to our observations the presence of DRA was not effective while the flow was laminar and it's role came into play with appearance of tunbulency in the system and became more pronounced with increase of Reynold's number, with increase of pipe roughness and with decrease of pipe diameter. Indeed all of these three parameters in some way could affect the height of turbulence fluctuations. So it can be said that the main role of a DRA is to reduce the height of fluctuations and in this way to decrease the rate of power loss or pressure loss in the direction of flow. For a special case of slug flow, Soleimani et al. (2002) suggested a nearly similar approach according to that the damping of turbulence by DRA could affect the initiation of slugging.

Notation

A	inside pipe area, m^2
D	inside pipe diameter, m^2
DR	drag reduction, dimensionless
DRA	drag reducing agent
H_G	gas void fraction
H_L	liquid holdup
k	fluid consistency index in the power law fluids, $kg/m\,s^{2-n}$
n	flow behavior index in the power law, dimensionless
ppm	parts per million
Q_g	gas flow rate, m^3/s
Q_l	liquid flow rate, m^3/s
Re	slip Reynolds number, dimensionless
v_g	gas slip velocity, m/s
v_l	liquid slip velocity, m/s
v_{ns}	mixture no-slip velocity, m/s
v_s	slip velocity, m/s
v_{sg}	superficial gas velocity, m/s
v_{sl}	superficial liquid velocity, m/s

Greek letters

Δp_f	frictional pressure drop without DRA, N/m^2
Δp_{fdra}	frictional pressure drop with DRA, N/m^2
λ_g	gas no-slip holdup, dimensionless
λ_l	liquid no-slip holdup, dimensionless
ρ_g	gas density, kg/m^3
ρ_l	liquid density, kg/m^3
ρ_s	slip mixture density, kg/m^3
τ_w	wall shear stress, N/m^2

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