Effect of drag reducing polymer on horizontal liquid–liquid flows

L.C. Edomwonyi-Otu, M. Chinaud, P. Angeli *

Department of Chemical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

A B S T R A C T

The effect of adding a drag reducing polymer in the water phase during horizontal oil–water flows was studied experimentally. Experiments were carried out in a 14 mm ID acrylic pipe using tap water and kerosene oil (Exxsol D140: density 828 kg/m^3; viscosity 5.5 mPa s at 23 °C) as test fluids. An initial master solution of the polymer (Magnafloc 1011, a copolymer of polyacrylamide and sodium acrylate) at 1000 ppm concentration was added at different flowrates into the water phase to give polymer concentrations in the test section between 2.5 and 50 ppm. Flow patterns were investigated with high speed imaging while conductivity probes were used to obtain interface properties in separated flows. It was found that as little as 20 ppm polymer in the water phase could give maximum drag reduction of about 45% during two-phase flow. When polymer was added, the region of stratified oil–water flow extended to higher superficial oil and water velocities. In separated flows, the polymer addition resulted in a decrease in the interface height and increase in average water velocity. In addition, interfacial wave amplitudes decreased while wave lengths and celerities increased. Velocity measurements in single phase water flows with particle image velocimetry showed that the addition of polymer changed the axial velocity profile and decreased the Reynolds stresses to almost zero values.

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1. Introduction

Drag reduction (reduction of the frictional pressure drop) during fluid flow [1,2], is an engineering intervention to decrease the cost of pumping for fluid transportation over long distances. This reduction is accomplished by the addition of small amounts of certain materials such as polymers, fibres or surfactants known as drag reducing agents (DRA) to the flow system. Since it was first observed by Toms [3] there have been numerous papers published on the drag reduction phenomenon in single phase flows, summarised in a number of reviews [4–8]. A notable application is the addition of 10 ppm of an oil-soluble polymeric additive to the 1.25 m diameter and 1300 km long Trans-Alaskan pipeline in 1979, which led to 50% reduction in pressure drop and eliminated the need for 2 additional pumping stations. Since then, drag reducing polymers have found applications in the Iraq–Turkey oil pipeline and in the Oseberg Field in the North Sea [9] amongst others. These polymeric solutions are injected downstream of a pumping station to avoid degradation and have been found to be environmentally friendly because of their biodegradability [2,4]. DRAs have also found applications in oil well fracturing operations [10], district heating and cooling [7,9,11], petroleum loading and

offloading as well as in refineries [1], in pipeline corrosion inhibition [12], in firefighting, as anti-misting agents in jet fuels, in irrigation and hydropower systems [7], and in sewage systems to prevent overflow during heavy rain [13].

More recently the effects of drag reducing polymers on multiphase flows and particularly gas–liquid ones, were investigated where it was found that in addition to pressure drop reduction, the polymers had a significant effect on the flow patterns and their transition boundaries [14–19]. With the addition of polymer in the water phase, maximum drag reduction was obtained when the slug and annular flow patterns changed to stratified flow. Waves were dampened in stratified-wavy flows and slug frequencies reduced in slug flow. The liquid hold-up and interface height increased for slug and annular flows; this was attributed to the dampening of the waves which reduced atomization as well as addition from the liquid film that covered the pipe wall in annular flow before the polymer was added.

However in a recent study, Liu [20] did not find any changes to flow patterns when polymer was added to gas–liquid flows in a 40 mm pipe even at concentrations as high as 300 ppm, irrespective of pipe inclination. The author did not discuss these findings, but they can possibly be attributed to the lower superficial gas velocities (Usg < 8.3 m/s) and higher superficial liquid velocities (Usl = 0.5, 1 m/s; Re_L = 14,000 and 28,000) in this study compared to previous ones.

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* Corresponding author. Tel.: +44 2076793832.
  E-mail address: p.angeli@ucl.ac.uk (P. Angeli).

The literature on drag reducing agents in liquid–liquid flows is limited, with previous studies showing that small amounts of polymer added in the water phase reduce the pressure drop by about 65% and extend the region of stratified flow significantly. Polymer addition was also found to cause dampening of interfacial waves and changes in the flow patterns, liquid hold-up and interface height [1,21–25].

Despite the many studies available, the mechanism of drag reduction is still not entirely understood while different theories have been suggested [1,2,8,26]. The proposed mechanisms involve thickening of the buffer layer, turbulence suppression, vortex dissipation, reduction in Reynolds stresses, and interference of the DRA with the momentum and vorticity transport in the radial flow direction and re-distribution of the turbulent kinetic energy in the axial direction. These result in the modification of the logarithmic velocity profile. The changes in the velocity field with polymer addition have been studied both experimentally [5,6,11,27–30], including the use of laser doppler velocimetry (LDV) and particle image velocimetry (PIV) [27,30–33], and numerically [11,30]. Mechanistic models have also been suggested [34,35]. The mechanistic model of Sher and Hestroni [35] suggested a turbulent kinetic energy dissipation mechanism in polymeric fibre suspensions. They postulated that rotational flow kinetic energy is converted to polymer elastic energy when the initially coiled polymer is rotated and stretched in the turbulent eddies which in turn is dampened when the polymer relaxes in the surrounding viscous fluid. The authors argued that in a turbulent flow field, the dominant forces on a polymeric fibre are elastic and centrifugal, and adopted the dumb-bell model which simplifies polymers as springs with masses at their ends. The polymer alignment, extent of stretching and subsequent relaxation in the surrounding fluid determines its drag reduction effectiveness.

One of the main patterns in liquid–liquid flows is the stratified one. The waves that develop at the interface have been linked to drop formation and transition to dispersed patterns [36,37]. However, there is very limited information available on how the added polymer influences the interfacial waves in stratified flows. The aim of the current work is to investigate experimentally the effect of polymer addition in horizontal stratified oil–water flows with emphasis on the interfacial wave characteristics.

2. Experimental set up

The experimental studies were carried out in an acrylic test section 4 m long with 14 mm ID, using tap water and middle distillate oil, Exxsol D140 as test fluids (fluid properties are shown in Table 1). A schematic of the experimental flow facility can be seen in Fig. 1.

The two fluids are stored in separate tanks and are pumped into the test section through centrifugal pumps. The flow rates of the water and oil phases are controlled by two variable area flowmeters with maximum flowrate of 7.5 l/min and an uncertainty of 0.013 l/min (±0.2%). A 35 l/min flowmeter with an uncertainty of 0.06 l/min (±0.2%) was used for flowrates higher than 8 l/min during single phase water flow measurements. The fluids join at the test section inlet through a Y-junction that minimises mixing. A photograph of the inlet section can be seen in Fig. 1b. The section

Table 1
Properties of the test fluids.

Properties	Oil	Water
Density, kg/m^3	828	1000
Viscosity, mPa s	5.5 @ 23 °C	1.0 @ 23 °C
Interfacial tension, mN/m	39.6 @ 23 °C	

was engraved on two sides of an acrylic block joined together. It consists of two side inlets with 14 mm ID each, one for each fluid. Within each of the inlets there was an acrylic mesh (plate with holes) to eliminate any large flow structures in the fluids resulting from changes in flow directions before the test section. The two side channels joined at a very small angle (equal to 30°) which ensured minimum disturbance at the interface as the two fluids joined. After the test section, the two fluids flow into a separator tank from where the oil is returned to its storage tank after separation. The water phase was not recycled but fresh water with new polymer solution was used in each run to avoid degradation effects when the solution is passing through the pump.

Pressure gradient was measured using a differential pressure transducer (ABB 266MST; max pressure 6 kPa, 0.04% base accuracy) connected to two pressure ports (0.5 m apart) located at 3.25 m and 3.75 m respectively from the point where the two fluids join. An acrylic box filled with glycerol was placed between the pressure taps at 250D (D is the pipe diameter) to improve visualization of the flow patterns. A ruler was inserted in the viewing box for scaling. The flow patterns and their boundaries were identified with a high speed camera (Photron Ultima APX, monochrome) operating at 1200 fps which was placed opposite the viewing box. Two conductance probes, a wire and a ring one, placed 0.1 m after the viewing box were used to record over time the oil–water interface height at a frequency of 512 Hz. The wire probe consists of two parallel, stainless-steel wires, 4 mm apart and 0.5 mm in diameter and records the interface height at the pipe centre. The ring probe has two stainless steel rings, 3 mm wide and 10 mm apart placed at the pipe periphery in contact with the fluid and flush at the pipe wall. This probe measures interface height at the wall. The data obtained from the probes was treated following the methodology developed by [38].

The polymer used in this study was Magnafloc 1011 (co-polymer of polyacrylamide and sodium acrylate). A master solution of 1000 ppm polymer in water was initially prepared by slowly dissolving 10 g of the polymer powder into 10 l of deionized water which was gently stirred with a 3-bladed mechanical stirrer (Heildolph, D-91126) for about four hours. The solution was then left overnight to allow for proper hydration of the polymer molecules. For the experimental runs, the master solution was injected into the water phase in the test section using an air-pressurized system (see inset in Fig. 1) at flowrates suitable for achieving the concentrations required in the experiments. The air-pressurized polymer injection system is similar to that described by [14,24]. The polymer master solution is put in a pressurized vessel at 2 bar. Air is supplied to the vessel and pushes the polymer out and into the test section. The calibration of the polymer flowrate was carried out when the polymer line was not connected to the main test section but was at the same vertical position where the online injection point is situated.

The injection point was a single hole, 1.5 mm diameter, located at the lower part of the water inlet pipe, 0.5 m upstream of the mixing point of the two fluids. The polymer joined the water pipe 0.5 m before the Y-inlet junction at the concentration of the master solution. The water phase then passed through the acrylic mesh in the water inlet of the Y-junction which enhanced mixing. The position of the measurements (at 250D) and the turbulent nature of the flows further enhanced mixing of the polymer with the water phase.

In the experiments, water superficial velocities, Usw, varied from 0.052 m/s to 0.8 m/s, and oil superficial velocities, Uso, varied from 0.008 m/s to 0.7 m/s, while the polymer concentration in the water phase was between 2 ppm and 50 ppm. For every condition, once the flowrates of the two phases and of the injected polymer solution were set, data was obtained after about 5 min to allow a stable flow. Experiments were repeated 3 times with an average