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Fluid Dynamics and Transport Phenomena

An experimental study of drag reduction by nanofluids in slug two-phase flow of air and water through horizontal pipes[☆]

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ABSTRACT

This study investigates the effect of injecting nanofluids containing nano-SiO_2 as drag reducing agents (DRA) at different concentrations on the pressure drop of air–water flow through horizontal pipe. The test fluid used in this study was air–water with nano-SiO_2 particles at 0.1%–1% mass concentration. The test sections of the experimental set-up were five pipes of the same length of 9 m with ID from 0.0127m–0.03175m (0.5 to 1.25 in). Air–water flow was run in slug flow regime under different volumetric flow rates. The results of drag reduction (η%) indicated that the addition of DRA could be efficient up to some dosage. Drag reduction performed much better for smaller pipe diameters than it did for larger ones. For various nanosilica concentrations, the maximum drag reduction was about 66.8% for 0.75% mass concentration of nanosilica.

1. Introduction

The phenomenon of drag reduction in pipeline flows was reported at first by a British chemist, Toms, in 1948 [1]. Drag reduction is beneficial to pipeline systems in several ways; it can save pumping power, increase the flow rate or decrease the size of pumps in turbulent pipe flow systems. Several studies have been conducted on drag reduction by polymeric additives [2–8], but some studies have been conducted on drag reduction in the pipe flows by nanofluids [9–18]. Nanofluids are suspensions including a base liquid such as oil, water, ethylene glycol and nanoparticles that have been dispersed into liquid phase by surfactants and ultrasonication. Few studies have been conducted on different properties of nanofluids such as tribological properties. In addition, nanofluids can modify the surface tension for two-phase systems. Until now, there has been just one experiment conducted on pressure drop in two-phase pipe flows. Wang and Bao [19] studied the two-phase flow of nitrogen and water-based CuO nanofluids into vertical capillary tubes and concluded that the effect of nanofluids on the two-phase flow patterns resulted from the change of the gas–liquid surface tension.

In our study, SiO_2 nanoparticles, which were non-expensive, effective and easily accessible, were used as drag reducing agents. The nanofluids and air in different turbulent flow conditions were injected into the horizontal smooth and rough pipes under slug flow regime. Slug flow was preferred, because it was a significant flow regime as far as transport processes were concerned. The unusual nature of slug flow, *i.e.* alternating sections of gas and liquid, was able to apply single-phase drag reduction information combined with two-phase flow data for analyzing the physical structure of slug flow. The extent of drag reduction under different flow conditions was measured and the results were extended to be used in large scales.

2. Definition of Drag Reduction

Drag reduction is defined as a flow phenomenon in which a small amount of additives decreases significantly the friction factor of a fluid. Here, the purpose of drag reduction is to improve capacity, reduce pumping power and improve mechanical efficiency using active agents, known as Drag Reduction Agents (DRA). In single and multi-phase flows, drag reduction percentage (η) can be defined as the fraction of drag reduction in the frictional pressure drop under the same flow rate:

$$\eta=\frac{\Delta P-\Delta P_{\mathrm{DRA}}}{\Delta P}\times 100. \quad (1)$$

In this equation, ΔP is the pressure drop in the absence of DRA and ΔP_{DRA} is the pressure drop in the presence of DRA.

3. Experimental Methods

3.1. Nanofluids preparation

In this study, distilled water (DW) and nanosilica particles were used to make nanofluids. Nanosilica-particles (nano-SiO_2) were provided by Merck Company. As specified by the vendor, the particle sizes were 20–30 nm, and the true material density was 2.4 $g\cdot cm^{-3}$ with

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180–600 $\mathrm{m^2 \cdot g^{-1}}$ specific surface area (SSA). There are two different methods for producing stable nanofluids. The first is to use a surfactant. In this method, surfactant is dissolved in base liquid at the mass concentration of 0.5% and then solid nanoparticles and surfactant solution are mixed to make well-dispersed and homogenous suspensions. The other method is to attach hydrophilic functional group of base liquid onto the surface of nanoparticles, and acidic mixtures are used to modify the surfaces of solid [19]. In this study, the first method was used to produce the nanofluid suspensions, and sodium dodecyl sulfate (SDS, Sigma-Aldrich Co.) was used as surfactant. At first, SDS was dissolved in DW at 0.5% (by mass) as base fluid under magnetic stirring. After that the mixture was stirred by a magnetic stirrer and was sonicated with a 400 W, 40 kHz ultrasonic processor to produce well-dispersed and homogenous suspensions. Nanofluid suspensions were prepared in the range of 0.1%–1% (by mass). All nanofluids were appropriately dispersed and were kept stable even after a two-week period, that was suitable for experimentation. The viscosities and densities of prepared nanofluid suspensions for the experimental conditions at a temperature of 25 °C are given in Table 1.

Table 1
Viscosities and densities of prepared nanofluids at 25 °C

C/% (by mass)	$\rho_{\mathrm{nf}}/\mathrm{kg \cdot m^{-3}}$	$\mu_{\mathrm{nf}}/\mathrm{mPa \cdot s}$
0.1	1.0006	0.901
0.25	1.0014	0.902
0.5	1.0029	0.905
0.75	1.0043	0.907
1	1.0059	0.910

3.2. Experimental procedure

The main purpose of this study was to investigate the drag reduction by nanofluid on two-phase slug flow of air–water through horizontal pipes. The test section of the experimental set-up consisted of a smooth Unique pipe (five-layer composite pipe of poly ethylene and aluminum, produced by Foshan Rifeng Enterprise Co., Tehran, Iran) with 9 m length and 1.27 cm ID, four parallel horizontal galvanized rough pipes with 9 m length and 1.27, 1.905, 2.54, 3.175 cm IDs. In the first set of experiments, the pressure drop in horizontal slug flow of air–water through each pipe was determined in the range of 250–1500 $\mathrm{L \cdot h^{-1}}$ of water and 300–2400 $\mathrm{L \cdot h^{-1}}$ of air flow. Then, nanofluid suspensions at 0.1%–1% mass concentration in the range of 250–1500 $\mathrm{L \cdot h^{-1}}$ flow rate of liquid were injected through pipes and the pressure drop values were also recorded. Due to the importance of drag reduction in turbulent flow conditions, this study focused on the turbulent flow through horizontal pipes.

Air and water properties for the experimental conditions at 25 °C temperature are given in Table 2.

Table 2
Air and water properties at 25 °C

$\rho_{\mathrm{air}}/\mathrm{kg \cdot m^{-3}}$	$\mu_{\mathrm{air}}/\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$	$\rho_{\mathrm{water}}/\mathrm{kg \cdot m^{-3}}$	$\mu_{\mathrm{water}}/\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
1.185	1.85×10^{-5}	1000	9×10^{-4}

The axial pressure drop through pipes was determined by a differential pressure transmitter, model KH3351 (Rosemount Co., U.S.A.), with 0.1 Pa precision. To eliminate the entrance and exit effects, the differential pressure taps were installed at 1.5 m away from the entrance and end of the pipes. Each nanofluid solution was prepared as the master solution and then injected in the pipes by a gear pump at the entrance of the pipes. Flow diagram of the experimental apparatus is shown in Fig. 1, schematically.

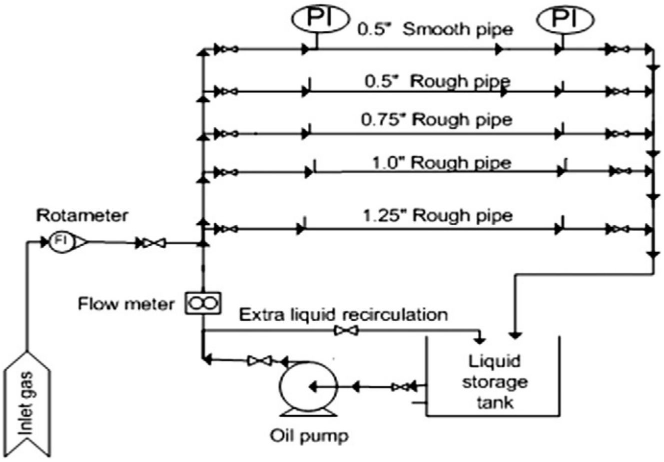

Fig. 1. Schematic diagram of experimental apparatus.

To investigate the precision of the experimental data, the obtained experimental friction factors were compared with Blausius equation for single-phase flow (Fig. 2). The friction factors obtained from experimentations were calculated by

$$f = \frac{\Delta P}{\frac{\rho v^2}{2}\frac{L}{D}}. \tag{2}$$

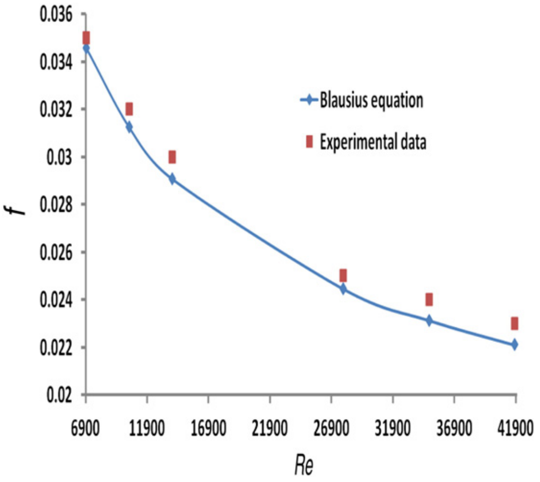

Fig. 2. Experimental data in comparison with the theoretical data.

The Blausius equation is

$$f = \frac{0.316}{Re^{0.25}} \tag{3}$$

with

$$Re = \frac{\rho v D}{\mu}. \tag{4}$$