Drag Reduction Characteristics of Micro-Fibrillated Cellulose Suspensions

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Abstract

Drag reduction characteristics of micro-fibrillated cellulose (MFC) suspensions are evaluated in a fully developed turbulent pipe flow. Drag reduction is estimated from pressure drop measurements obtained with a differential pressure sensor mounted on the up- and down-stream ends of a 3.0 m long pipe, part of the 1000 liter, pilot-scale flow loop. Two pipe diameters are considered, namely 45mm and 57mm, with flow rates ranging from 300 – 1000 l/min. MFC concentration has been chosen in the range 0.02 – 0.2% by mass and is compared with the flow of water under identical conditions at room temperature.

In the fully turbulent regime, the rheology of the suspensions is shown to be identical to that of water. Drag reduction is found to increase with flow rate and with MFC concentration up to 0.15%, after which it was found to decrease. A maximum drag reduction of approximately 9% was observed in each pipe. Further, the flow 0.02% MFC suspension increased the drag in the 57mm pipe at lower flow rates. Results from this study may have implications on turbulence damping during forming, energy reduction during paper-making processes and in the design and operation of MFC production.

Introduction

Micro-fibrillated cellulose (MFC) is a novel form of cellulose produced by delamination of cellulosic fibres [1]. One particular method for producing MFC, is by exposing the cellulose fibres to high shear levels by flow through a high-pressure homogenizer [2]. Fully delaminated MFC consists of long (in the micrometer range) microfibrills (diameter =10-20 nm) and has the appearance of a highly viscous, shear-thinning transparent gel. MFC exhibits many of the attractive mechanical properties which are observed only at the nano-scale. Further, MFC represents an attractive alternative to other nano-materials since it is derived from a renewable, green source. The list of applications for MFC is seemingly endless. Immediate foreseeable applications in the paper industry include use as a strength additive for paper and board products, coating additives, security papers, food packaging, gas barriers and as a part of novel nano-composites. Other potential applications include food and emulsion/dispersion applications, medical, cosmetic, pharmaceutical and hygiene/absorbent applications [2].

Until only recently, commercialization and large scale production of MFC has failed due to the high energy input required to delaminate the fibres. However, recent developments in this field, specifically through chemical pre-treatment of the raw cellulose fibres, have led to the production of MFC with as much as 98% lower energy requirement [3]. In light of this development, significant interest has been made with respect to the characterization of MFC, in particular its rheological and large-scale flow properties.

Two general methods exist for characterizing the rheology of a complex fluid. These are the *dynamic* and *flow based* measurements[1]. With dynamic measurements, the higher order rheological properties of a fluid, for example, the internal storage and loss modulus are obtained. This includes the highly academic discussion of the existence yield stress. With flow based measurements, fluid properties such as viscosity - shear or extensional - can be obtained. Both of these methods are traditionally off-line methods, i.e. a fluid sample must be removed the system or process for analysis, for example in a laboratory with a commercial device. A laboratory-based rheological study of MFC suspensions (cellulose I) was used by [3] to determine the visco-elastic and visco-plastic properties of concentrated MFC suspensions at mass concentrations ranging from 0.125% - 5.9%. Using an oscillatory shear rheometer, it was shown that the storage modulus, *G*, of the suspensions, i.e. the frequency dependent ratio of applied stress over strain of the fluid, is essentially independent of frequency, i.e. it is a constant for a given concentration of MFC. It was further shown that *G* increases exponentially from the lowest to highest concentrations – specifically by 5 orders of magnitude from approximately 10 Pa – 10^5 Pa. Measurements of the shear rate-shear stress dependence of the different concentrations showed the MFC suspensions to be highly shear-thinning, i.e. the viscosity was found to decrease with increasing shear. This finding agreed with previous studies based on MFC prepared purely from mechanical disintegration [4]. In addition to exhibiting a highly shear thinning character, a significant yield stress was observed – one which increased by approximately 4 orders of magnitude, from approximately 10 Pa·s- 10^4 Pa·s, over the concentration range 0.25% to 5.9% by mass. Unfortunately, viscosity measurements were not made for the 0.125% suspensions.

A more general, on-line approach for characterizing the rheology of a fluid is performed by forcing a fluid linearly through a pipe of constant diameter. This approach is well suited for measurement of viscous and visco-plastic properties of suspensions which appear in numerous industrial applications. In particular, the steady state behavior in the laminar region, depending on the solid contents in the suspension, leads to the classical rheological models, like Bingham, Ostwald and Herschel-Buckley models. In practice, these models involve fitting two or three parameters to a set of rheological measurements. With the focus on production, pipe viscometers are preferable for suspension flow, since they do not violate the assumption of small gap flow, as used in most commercial off-line devices. The characteristic length scale of the pipe diameter and time scale related to flow velocity in laminar flow conditions are secured and consequently the rheological properties of the suspension are obtained. One major advantage of this approach is ease of up-scaling. Pipe viscometer measurements, which are essentially based on measurements of the pressure drop along a length of pipe, can be arranged in a flow loop design thus enabling turbulent flow conditions. Further, this approach lends itself well to industrial-type applications. To the best knowledge of the authors, flow based rheological measurements of MFC suspensions, spanning the laminar-turbulent spectrum, are currently unavailable in the literature (at least not officially).

In addition to its laminar-turbulent fluid behavior, the effect of MFC on local turbulence is also of interest from both a practical and fundamental point of view. For example, large reductions in turbulent drag resulting from the addition of long-chain polymers and/or small, non-Brownian particles to a turbulent flow have been observed by a number of researchers (e.g. [5-20]). Numerous industries already take advantage of this phenomenon for the purpose of reducing pumping and process costs, for example, oil pipelines, flood water disposal, airplane fuel tank filling, and in the transport of suspensions and slurries, just to name a few. Early experimental studies on pipe flows have shown that turbulent drag reductions (TDR) are possible in suspensions involving different additives under different flow conditions (e.g. [5,6, 20]). The theoretical mechanisms attributing to TDR have been studied in detail using both numerical and experimental techniques (e.g. [8-16,18,19]). However, the general conclusion is that the mechanisms behind polymer-based drag reductions are

[1] In fact, there are a wide range of different techniques for measuring the rheology of a fluid. The two mentioned here are, in the authors opinion, the most commonly used in both research and industry.

fundamentally different from those responsible for non-Brownian fibre-based drag reduction. While the exact details of this phenomenon are still under investigation, it is generally agreed that the mechanism for polymer based drag reduction is based on the ability of polymers to stretch and relax. Specifically, the polymers are believed to absorb turbulence while in a stretched state, and then subsequently dissipate that energy through polymer relaxation [20]. On the other hand, turbulent drag reduction with non-Brownian fibres is believed to be inertia based, whereby the fibres redirect the turbulent momentum in the near wall region toward the flow direction [6, 16]. These differences suggest synergies in TDR between polymers and fibres, an argument that was supported by the early experimental findings of [21]. The interactions between MFC fibres and local turbulence poses an interesting question from a fundamental standpoint in the sense that the length scale of MFC fibres lie intermediate to that of a polymer and that of a conventional cellulose fibre. From a production point of view, little is known on the optimality of process conditions involving MFC, i.e. optimal flow rate, pipe diameter, and concentration, such that energy consumption is minimum during processing. From a papermaking perspective, the MFC-turbulence interactions are of practical interest in relation to transport, mixing and separation mechanisms.

The goal of this study is to investigate the turbulent drag reduction characteristics of MFC suspensions at pilot scale under large-scale process flow conditions. We do so by measuring turbulent drag reduction, indicated as pressure differentials of MFC suspensions relative to that of water under identical flow conditions. Turbulent drag reduction is measured as a function of flow rate, for a range of MFC concentrations and in two different pipe sizes.

Experimental Methods

System overview

The pilot-scale experiments were performed in the re-circulatory pipe flow facility of Innventia AB. A schematic diagram of this facility is shown in Figure 1. The main part of this facility consists of two long sections of cylindrical PVC pipe, with length 3.0 m. The flow loop is constructed in a modular manner such that different piping and experimental set-ups can be easily interchanged and studied. In this work, we considered two different pipe diameters, namely 45mm and 57mm inside diameters. The fluid is re-circulated from an open reservoir, approximately 1 m^3 in volume, which is continuously mixed with a 40cm diameter impeller. The bulk suspension flow is controlled by a 4.2 kW variable frequency drive centrifugal pump (ITT Flygt pump 3102- 152 mm impeller and ITT/ABB PS 200 VFD). Flow is measured through the device with a magnetic flow meter (Bailer, Fisher & Porter, model no. 10DS3111). Pressure sensors are mounted on either end of the pipe (Fuji FKCX22, 6 kPa and FKCX35, 130 kPa), specifically positioned at 0.25m and 2.8m. The facility is also fitted with a MetFlo DUO ultrasonic Doppler velocimetry profiler (UVP). Average temperature and conductivity is measured in the reservoir and at the end of the test section using a Hach, HQ40D mutli-parameter measurement probe. A high resolution conductivity probe, used for local turbulence measurements, is also mounted in this system, however was not during these experiments. All data is logged continuously while the facility is in operation using LABVIEW.

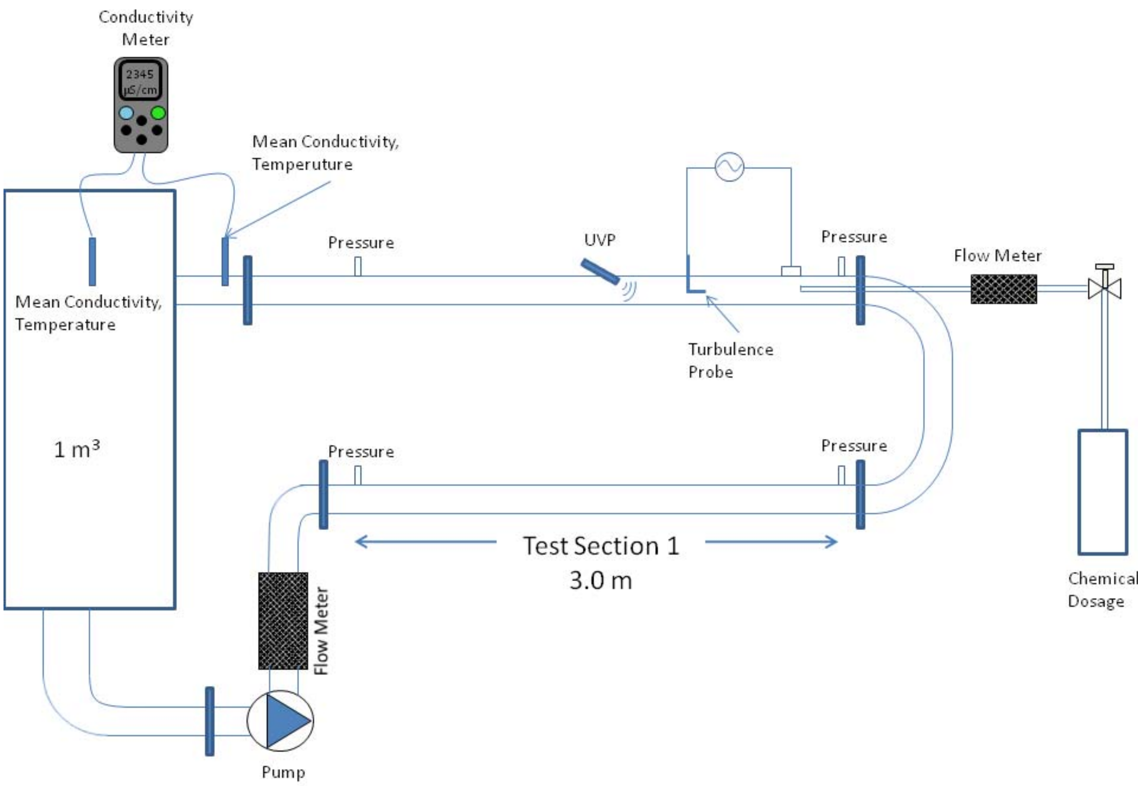

Figure 1: Overview of the Innventia flow loop facility.

MFC Suspensions

The suspensions considered were composed of micro-fibrillated cellulose (MFC), (cellulose I), produced at the Innventia MFC production plant in Stockholm, Sweden. The MFC fibres originated from bleached sulphite cellulose pulp, consisting of 40% pine and 60% spruce with a hemi-cellulose content of 13.8% and lignin content of 1%. The pulp was used in its never dried form. Cell wall delamination was carried out in four steps. The pulp was first past through a refiner, followed by enzymatic pre-treatment. The pulp was then passed through a refiner a second time, after which it was passed through a high-pressure homogenizer. For complete details on this process, see reference [3]. After the homogenization, a 0.2% mass fraction suspension of MFC in water was produced with which drag reduction trials were run directly. Subsequent trials at lower concentrations were carried out by dilution of the 0.2% suspension with tap water, followed by rigorous mixing and recirculation through the flow loop at high speed.

Drag Reduction Characterization

We assume fully developed turbulent flow through a straight pipe with diameter d. Pressure drop measurements, ΔP, were collected by varying the flow rate manually with the pump speed and sampling the differential pressure at a set of fixed flow rates. A total of 8, equally spaced measurement points were gathered for flow between 300 l/min and 1000 l/min, i.e. at 300, 400, 500,…,900, 1000 l/min. At each flow condition, 5 measurements of the pressure differential were collected, each of which contains 900 samples, sampled at a rate of 300 Hz, and subsequently averaged. With this data, the wall shear-rate-shear stress, Fanning friction factor and turbulent drag reduction, were computed. For Newtonian and non-Newtonian fluids, at all flow regimes, the wall shear stress, τ_w, and pseudo-strain rate, $\dot{\gamma}$, based on measurements of the pressure differential along the pipe are given by

$$\tau_w = \frac{d\Delta P}{4L_p} \tag{1}$$

$$\dot{\gamma} = \frac{8V}{d} \tag{2}$$

where V is the average velocity of the fluid in the pipe and the pipe length, $L_p = 2.55m$. The wall shear stress is often expressed in terms of the Fanning friction factor, f, which is given by

$$f = \frac{\tau_W}{\frac{1}{2}\rho V^2} \tag{3}$$

It should be mentioned that, when using the Fanning friction factor, it is customary to plot in terms of the Reynolds number, Re, which is define as

$$\mathrm{Re} = \frac{\rho V d}{\mu} \tag{4}$$

where ρ and μ are the density and dynamic viscosity respectively of the fluid. The amount of drag reduction, defined as the percentage of pressure drop due to the addition of MFC fibres, relative to that of water, is

$$\%DR = \frac{\Delta P_{H_2 0} - \Delta P_{suspension}}{\Delta P_{H_2 0}} \times 100\% \tag{5}$$

These measurements are often linked directly to the turbulence spectra (e.g. Lee et al. 1974, Ptaskinski et al. 2001), thus can provide an indication of turbulence damping.

Results

Turbulent rheological data for the MFC suspensions in each pipe size are presented in Figure 2. These curves enable calculation of the generalized Reynolds number for the non-linear MFC suspensions. However, it is easy to see that, for all flow rates considered here, the suspensions are essentially Newtonian, and behave rheologically similar to water. Hence the distinction in Reynolds number is only a minor one.

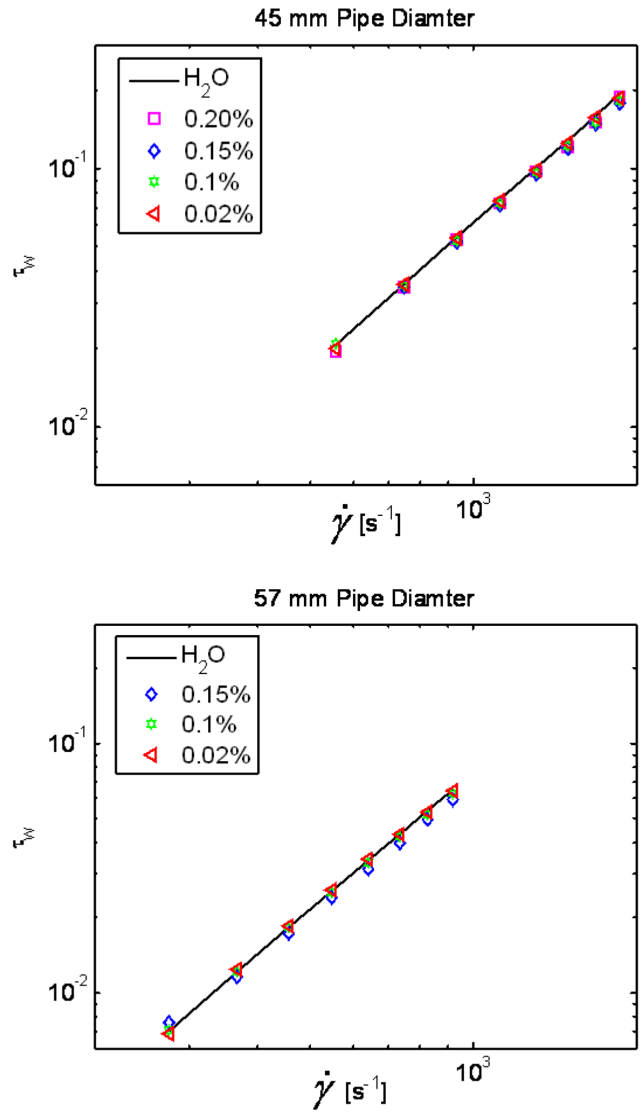

Figure 2. Rheological properties of the MFC suspensions in the turbulent regime.
Top: 45mm pipe, Bottom: 57mm pipe.

Figure 3 shows friction factor-Reynolds number data for the MFC suspensions compared with water in the two pipes. These plots show that the MFC fibres tend to reduce the overall friction factor in the pipe flow at all concentrations and at sufficiently high Re number, i.e. they act as drag reducers. The friction is always found to decrease with increasing Re. The friction factor is generally found to decrease as the concentration of MFC is increased. This trend was noted up to a maximum concentration of 0.15%. It should be pointed out that measurements were not made at higher concentrations in the 57mm pipe. The friction factor behavior is somewhat different in each pipe. Specifically, in the 45mm pipe, we generally measured reductions in *f* for all flows. However the reductions are found to be quite small in many cases. In the 57mm pipe, greater reductions in *f* are observed at higher concentration of MFC, however increases in *f* are observed for lower concentrations at lower velocities.

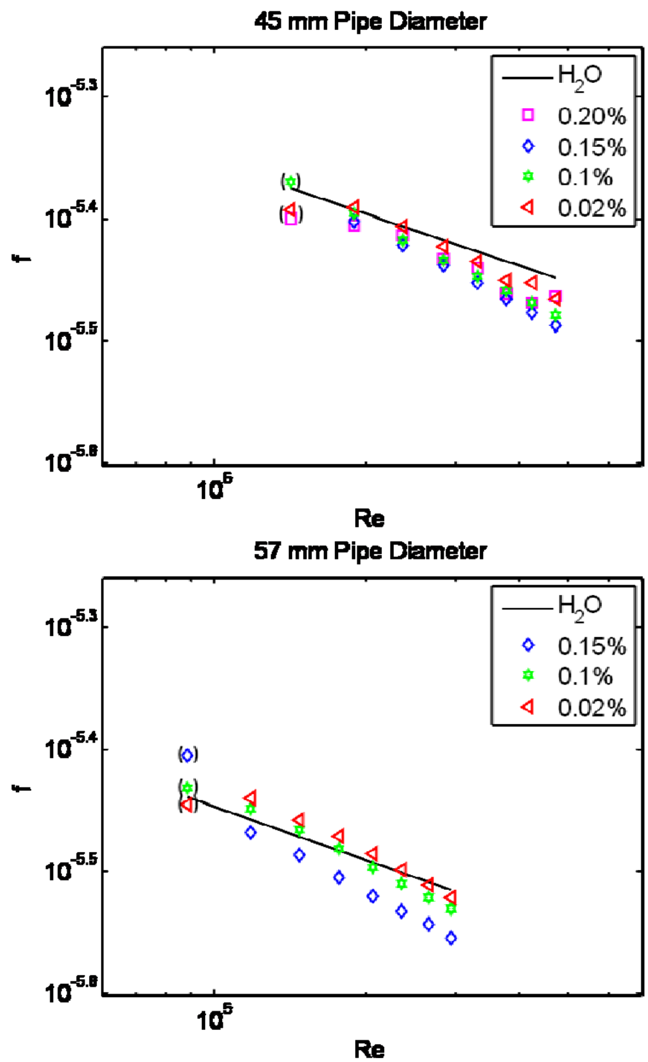

Figure 3. Friction factor-Reynolds number results for the MFC suspensions.
Top: 45mm pipe, Bottom: 57mm pipe (change to identical scales).

Figure 4 shows the percent turbulent drag reduction in both pipes. These plots essentially re-iterate what was observed in the friction factor-Reynolds number plots. In both pipes, the greatest drag reduction, approximately 9%, is observed with the 0.15% suspensions at 1000 l/min flow rate. In the 45mm pipe, a similar drag reduction-flow rate trend is observed with the intermediate concentrations, i.e. 0.15% and 0.1 %. Drag reduction measurements at concentrations above or below these values, show non-monotonic trends. In the 57mm pipe, the flow rate dependence is similar for all concentrations. At MFC concentrations below 0.15%, the suspensions do not reduce turbulent drag, rather increase it, unless the flow rate is sufficiently high. This is an interesting result from a processing point of view. It should be pointed out that, although the flow rates are identical in each pipe, the velocity in the 45mm pipe is significantly larger than in the 57mm pipe. This is possibly one fundamental reason for this observation. Nonetheless, these results should provide some insight when designing an MFC process flow system.

It should also be mentioned that, at flow rates below 350 l/min, the pump RPM control is poor. This believed to be the cause for the deviations in the trends of drag reduction measurements in this flow range, as indicated in Figures 3 and 4 with brackets.

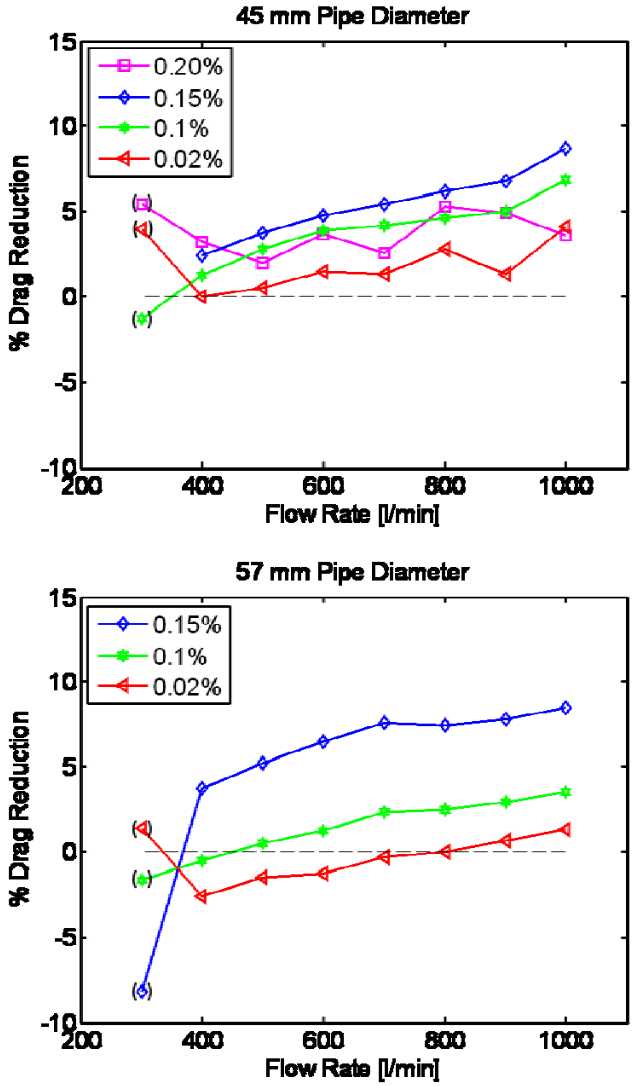

Figure 4: Percent turbulent drag reduction for the MFC suspensions. The dashed lines indication the zero- level. Shown are the 45mm pipe (TOP), and the 57mm pipe (BOTTOM).

Conclusions

Turbulent drag reduction characteristics of micro-fibrillated cellulose suspensions were evaluated in a fully developed turbulent pipe flow from pressure drop measurements of flow through a 3.0 m long pipe. The effect of MFC mass concentration, 0.02% - 0.2%, and flow rate, 300 l/min – 1000 l/min, on turbulent drag reduction was evaluated in two different pipe sizes, 45mm and 57mm, inside diameter. It was shown that, in the fully turbulent regime, the rheology of the MFC suspensions is identical to that of water. In both pipes, turbulent drag reduction was found to increase with flow rate and with MFC concentration up to a maximum at 0.15% concentration by mass, after which it was found to decrease. A maximum drag reduction of approximately 9% was observed in each pipe. However, in the 57mm, the flow of 0.02% MFC suspension was found to increase the turbulent drag at lower flow rates.

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