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Turbulent flow behavior of surfactant solutions in straight pipes

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ABSTRACT

In this study, the turbulent flow behavior of surfactant test solutions was examined by measuring pressure drop across a straight pipe at various flow rates. The drag reduction character of surfactant solutions was observed to be affected by concentration, pipe diameter, pipe roughness, and solvent type. Higher percent drag reduction occurred at higher concentrations in larger pipes with minimal surface roughness. Surfactant solutions with salt had increased drag reduction due to the presence of longer micelles. In addition, an analytical Fanning friction factor equation was derived for purely viscous power law fluids. Good agreement was observed between predictions and experimental data in the literature with the new equation.

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1. Introduction

Considerable amount of work based on established principles for laminar flow of Newtonian and non-Newtonian is readily available in the literature. Turbulent flow of Newtonian fluids is given by several theoretical equations as well as empirical correlations. These approaches are well-established and can be applied to hydraulic calculations with a high degree of accuracy. The same cannot be stated for turbulent flow of non-Newtonian fluids.

Most fluids used in the oil and gas industry are non-Newtonian. In the case of drilling and hydraulic fracturing applications, these fluids display drag reducing characteristics. As such, solutions to turbulent flow of non-Newtonian fluids can be intractable because of a greater level of complexity. The presence of drag reducing agents adds a dimension of complexity to flow hydrodynamics. Unfortunately, no universal set of flow equations has been reported for non-Newtonian drag reducing fluids. The intractability of solutions has not deterred research into drag reducing flows. Several approaches are available for predicting friction pressure. In deriving equations or correlations, limiting assumptions are imposed to arrive at flow rate–pressure drop relationships.

This paper elucidates hydrodynamics of turbulent flow of non-Newtonian fluids through pipes with emphasis on drag reducing surfactant solutions. A detailed literature review on drag reduction phenomena is presented. The first part of this work deals with drag reduction behavior of the test fluid with respect to the effects of various factors (concentration, pipe diameter, and salinity). The second part presents a Fanning friction factor relationship for purely viscous power law fluids.

2. Literature review: drag reduction fundamentals

Drag reduction can be achieved in two ways—active and passive drag reduction (Singh, 2010). The difference between the two is that energy input is required for passive drag reduction (for example, riblets) and the level of drag reduction is small. Active techniques, on the other hand, involve the use of substances such as high molecular weight polymers and surfactants for drag reduction. Increased drag reduction with additives (as much as 70% with polymers and 80% with surfactants) has been reported.

Two definitions of drag reduction are used in literature and are provided here in chronological order. Savins (1964) defined drag reduction as an increase in the pumpability of a fluid *under turbulent flow* due to the introduction of certain high molecular weight polymers. Similarly, Lumley (1969) defined drag reduction as the reduction of skin friction in *turbulent flow* below that of the solvent. It becomes clear from both definitions that drag reduction is a phenomenon associated with turbulent flow. Mathematically, it is expressed as follows:

$$DR(\%) = \left(\frac{\Delta P_s - \Delta P_a}{\Delta P_s}\right) \times 100 \ \text{(at constant flow rate)} \tag{1a}$$

$$DR(\%) = \left(\frac{f_s - f_a}{f_s}\right) \times 100 \ \text{(at constant Reynolds number)} \tag{1b}$$

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Nomenclature

$\overline{u}_z$	time average velocity
Δp	frictional pressure loss
d	pipe diameter
$\mathrm{d}p/\mathrm{d}l$	pressure gradient
f	Fanning friction factor
h	roughness projection height
K	consistency index
K_p	pipe consistency index
n	flow behavior index
n', N	flow behavior exponent
N_{Re}	Reynolds number
$N_{\mathrm{Re}\ g}$	generalized Reynolds number
q	volumetric flow rate
r	pipe radius
u	average velocity
u^*	friction velocity
u^+	dimensionless velocity
y	distance from wall
y^+	dimensionless distance from wall for Newtonian fluid
y_w^+	dimensionless distance from wall for non-Newtonian fluid

Greek symbols

μ	viscosity
λ	time constant
ρ	fluid density
τ	shear stress
α	area ratio

Subscripts

∞	infinity (high shear rate conditions)
a	additive
o	zero (low shear rate conditions)
s	solvent
w	wall

where, ΔP_s is the pressure loss without additives (i.e., solvent alone), ΔP_a is the pressure loss with additives, f_s is the Fanning friction factor without additives, and f_a is the Fanning friction factor with additives. Eq. (1) is valid based on the assumption of density remaining unchanged with additives in solution.

The Reynolds number, N_{Re} (or generalized Reynolds number, $N_{\mathrm{Re}\ g}$), is used to designate flow regimes—laminar or turbulent. Below a Reynolds number of 2100, laminar flow condition exists and the Hagen–Poiseuille equation (Eq. (2)) is used to calculate the Fanning friction factor for both Newtonian and non-Newtonian fluids. The generalized Reynolds number was proposed by Metzner and Reed (1955) to extend the procedures for determining friction factors for Newtonian fluids to non-Newtonian time-independent fluids.

$$f = \frac{16}{N_{\mathrm{Re}\ g}}$$

$$N_{\mathrm{Re}\ g} = \frac{\rho u d}{\mu_a} \tag{2}$$

where, ρ is the fluid density, u is the fluid velocity, d is the pipe diameter, and μ_a is the fluid viscosity (apparent viscosity for non-Newtonian fluids). The apparent viscosity is used because of the shear rate dependency of non-Newtonian fluids.

Under turbulent flow of Newtonian fluids, several expressions for Fanning friction factor have been reported, the variations depending on whether the flow conduit is smooth or rough. For smooth pipes, the Blasius-type expression (Eq. (3)) and the Drew correlation (Eq. (4)) (Drew et al., 1932) are frequently used. When pipe roughness is considered, the Chen correlation (Eq. (5)) (Chen, 1979) is applicable.

$$f = 0.079 N_{\mathrm{Re}}^{-0.25} \tag{3}$$

$$f = 0.0014 + \frac{0.125}{N_{\mathrm{Re}}^{0.32}} \tag{4}$$

The Drew correlation is valid for 2100 $< N_{\mathrm{Re}} <$ 3×10^6.

$$\frac{1}{\sqrt{f}} = -4 \log\left[\frac{h}{3.7065d} - \frac{5.0452}{N_{\mathrm{Re}}} \log\left\{\frac{1}{2.8257}\left(\frac{h}{d}\right)^{1.1098} + \frac{5.8506}{N_{\mathrm{Re}}^{0.8981}}\right\}\right] \tag{5}$$

where, h/d = relative roughness (dimensionless).

The correlations above are not suitable for non-Newtonian fluids as they overestimate the Fanning friction factor. Several empirical expressions have been reported for non-Newtonian drag reducing fluids with and without pipe roughness (Shah, 1984, 1990).

Fig. 1 is an illustration of the flow behavior of Newtonian, polymeric, and surfactant fluids to explain drag reduction. Curve A represents laminar flow, and the Fanning friction factor is determined using Eq. (2). Curve B represents the path followed by a Newtonian fluid in which the Fanning friction factor is calculated using Eq. (4). Virk's maximum drag reduction asymptote (MDRA) is curve C. This expression was empirically developed for maximum drag reduction attainable by polymeric fluids (Virk, 1975). Typically, Fanning friction factor data for polymers should be contained within the B–C envelope. Surfactants, however, can exhibit drag reduction at higher levels than polymers are able to exhibit. Zakin et al. (1996) empirically determined the corresponding asymptotes for non-polymeric fluids (curve D). The MDRA for polymers and surfactants will be discussed in detail in later sections.

As stated in the introduction, drag reduction additives are not limited to polymers and surfactants; solids, fibers, and other

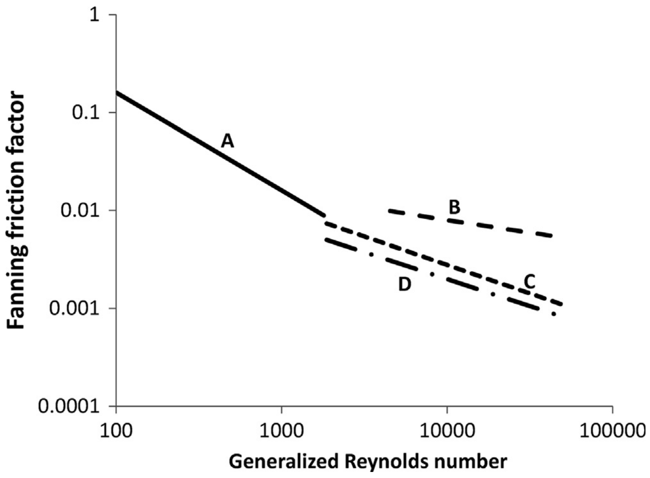

Fig. 1. Maximum drag reduction asymptotes for polymers and surfactants.

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