Journal of Petroleum Science and Engineering 111 (2013) 78–86

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

A general model for predicting drag reduction in crude oil pipelines

H.R. Karami, D. Mowla *

School of Chemical and Petroleum Engineering, Shiraz University, Shiraz, Iran

ARTICLE INFO

Article history:
Received 27 January 2012
Accepted 25 August 2013
Available online 7 October 2013

Keywords:
fluid mechanics
mathematical modeling
non-Newtonian fluids
turbulence
drag reduction
friction factor

ABSTRACT

In this study, by investigating various experimental parameters, a general model is proposed for predicting the phenomenon of drag reduction in crude oil pipelines. The proposed model employs a comprehensive analysis of various operation parameters such as oil flow rate and temperature, pipe diameter and roughness, various types of drag reducing agents (DRA) and concentration. The friction factor has been calculated using experimental data and the relevant model has been developed by considering the changes of $f^{-1/2}$ by $Re\, f^{(1-n/2)}$. The proposed model shows a good agreement with the experimental data.

1. Introduction

Negative consequences of pipeline pressure losses can be avoided through several ways. One of the best alternatives is using additives called drag reducing agents (DRA). Practically, adding a small concentration of such additives to the fluid reduces the friction of the fluid and increases the capacity of the pipeline without changing the pipeline conditions. In other words, most operating systems require pumping fluids at high flow rates, which in turn, generates high frictional pressure losses. By reducing skin friction of the flow, drag reducing agents can reduce the energy consumption of pumping.

Primary studies were conducted by Toms (1948) and Mysles (1949) on drag reduction. They investigated the effect of adding some polymers for reducing skin friction and pressure drop in pipelines in their individual studies. The experimental work done by Toms (1948) led to the drag reduction effect being known as Toms' effect.

Due to the vital importance of this subject, numerous studies have focused on various parameters affecting drag reduction. Among them Debrule and Sabersky (1974), Mansour and Aswad (1989), Mowla et al. (1991, 1995), Kang and Jepson (2000), Al-Sarkhi and Hanratty (2001), Al-Sarkhi and Soleimani (2004), Mowla and Naderi (2006), Gallego and Shah (2009), and Karami and Mowla (2012) are considerable.

Despite the great number of studies in this regard, the underlying mechanisms of drag reduction are not clearly defined yet; this problem is related to understanding the turbulent flow and dynamics of polymer. Among the existing mechanisms of drag reduction by dilute polymer solutions, there are two acceptable explanations. One was proposed by Lumley (1969) and the other one by Joseph et al. (1986) and also De Gennes (1986).

The mechanism proposed by Lumley (1969) is based on the elongation of coiled polymer molecules and hence increasing the thickness of viscous sublayer. Joseph et al. (1986) and De Gennes (1986) introduced the elastic properties of polymers as the reason for drag reduction.

Accurate determination of the friction pressure losses of dilute drag reducing polymer solutions has remained a challenge in many practical applications. Virk (1975) conducted a comprehensive study on drag reduction for water flow and proposed relationships for the Fanning friction factor, which helps other researchers to analyze their results. He investigated the performance of different polymer solutions and found a trend to a maximum drag reduction (MDR) asymptote in all cases.

Sher and Hetsroni (2008) proposed a mechanistic model for the turbulent drag reduction by additives, in accordance with the elastic properties of polymer, and compared their results with Virk's experiments (1975).

Based on the experimental data obtained for different operating conditions, Mowla and Naderi (2004) proposed a mathematical model for predicting the drag reduction by a given polymer at two phase flow. Their proposed model could also be used for calculating friction and maximum drag reduction as a function of DRA concentration.

Gallego and Shah (2009) developed a generalized friction pressure correlation for the phenomenon in coiled and straight

* Correspondence to: Chemical Engineering Department, School of Chemical and Petroleum Engineering, Shiraz University, Shiraz 71345-1789, Iran.
Tel.: +98 711 2303071; fax: +98 711 6474619.
E-mail address: dmowla@shirazu.ac.ir (D. Mowla).

0920-4105/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.petrol.2013.08.041

Nomenclature

A_n	dimensional function of flow behavior index
A_{1n}	dimensional function of flow behavior index
B_n	dimensional function of flow behavior index
C	concentration of DRA, ppm
C_n	dimensional function of flow behavior index
C'_n	dimensional function of flow behavior index
D	inside pipe diameter, m
$DR\%$	percent drag reduction, dimensionless
DRA	drag reducing agent
f_f	Fanning friction factor without DRA, dimensionless
$f_{f\ drag}$	Fanning friction factor with DRA, dimensionless
k	fluid consistency index in the power law fluids, kg/m s^{2-n}
l	distance between two points that measures the pressure drop
n	flow behavior index in the power law, dimensionless
P_n	dimensional function of flow behavior index
Re_{MR}	Metzner and Reed Reynolds number, dimensionless
$(Re\, f^{(1-n/2)})^*$	value of $Re\, f^{(1-n/2)}$ at the critical wall shear stress (τ_w^*), dimensionless
R	radius of pipe, *m*
R_G	radius of gyration, nm
T	employed experimental temperature, °C
T_b	boiling point of DRA, °C
T_0	reference temperature, 100 °C
u^*	friction or shear velocity, m/s
V	crude oil velocity, m/s

Greek letters

α	dimensionless parameter in Eq. (14)
β	dimensionless parameter in Eq. (14)
γ	dimensionless parameter in Eq. (14)
φ	dimensionless parameter in Eq. (14)
θ	dimensionless temperature defined by Eq. (15)
ε	absolute roughness of pipe, *m*
ξ	slope increment of the Dodge–Metzner equation by the addition of DRA, dimensionless
Δ	slope increment of the Prandtl–Karman equation by the addition of DRA, dimensionless
ΔP	pressure drop of the flow, N/m^2
ρ	crude oil density, kg/m^3
μ	viscosity of the fluid, kg/m s
τ_w	wall shear stress, N/m^2
$\tau_w{}^*$	critical wall shear stress, N/m^2

tubing on the basis of the energy dissipation of eddies in turbulent flow fields and shear rate dependent relaxation time. They found that their model in straight tubing correlated better than the previously developed models.

Also, Shah et al. (2006) developed new correlations for predicting the friction factor values as a function of the solvent's Reynolds number for both straight and coiled tubing using the data of an optimum concentration of polymeric fluid.

Due to the significance of the issue, the present study involves proposing a generalized mathematical model for relating the Fanning friction factor with various parameters. The outcome correlation predicts the drag reduction in crude oil pipelines under different operating conditions such as temperature, flow rates, pipe diameter and roughness and also for different types and concentrations of various DRAs through 648 experimental data. Comparisons showed a good agreement between the model and experiments at various conditions. It is notable that the mean value of the absolute percentage error of the final model is about 3.5%.

2. Drag reduction effects

Percentage of drag reduction (DR%) is defined as the ratio of reduction in the frictional pressure drop using DRA to the frictional pressure drop without DRA at the same operating conditions as

$$DR\% = 1-(f_{f\ drag}/f_f)100 \quad (1)$$

Here, f_f and $f_{f\ drag}$ are the friction factors in the absence and presence of DRA, respectively. The Fanning friction factor of the pipe is related to the pressure drop by

$$f = \frac{4\tau_w}{2\rho V^2} = \frac{D\Delta P}{2l\rho V^2} \quad (2)$$

where τ_w is the wall shear stress, ρ is the crude oil density, V is the crude oil velocity, D is the inside pipe diameter, ΔP is the pressure drop of the flow and l is the distance between two points that measures the pressure drop.

Adding small amounts of *DRA*, e.g. a few parts per million (ppm), can greatly reduce the turbulent friction factor of a fluid; so *DR%* increases, which means lower energy consumption by the pump.

It is notable that drag reduction is considerably higher in turbulent flow. In pipelines, the turbulent flow occurs when Reynolds number exceeds 2300. Since crude oil is a non-Newtonian fluid of power-law type, its Reynolds number would be defined by the generalized Reynolds number of Metzner and Reed (1955) as given by

$$Re_{MR} = \frac{D^n V^{2-n}\rho}{8^{n-1}k((3n+1)/4n)^n} \quad (3)$$

where its rheological properties could be determined by two indexes n and k, indicating flow behavior and consistency index of the crude oil, respectively. In the case $n=1$ and $k=\mu$, Eq. (3) reduces to the conventional Reynolds number ($DV\rho/\mu$) for a Newtonian fluid.

3. Experimental procedures

In order to propose a general model involving oil flow rate and temperature, pipe diameter and roughness and the type of DRA and concentration, an experimental apparatus, as shown in Fig. 1, was constructed to carry out the experiments.

Various concentrations of three types of dilute polymeric solutions as drag reducing agents have been tested at four temperatures and flow rates in the apparatus installed with three pipes, each with a different value for diameter and roughness. Pipe no. 1 is 1 in. in diameter, a rough pipe of galvanized iron (relative roughness $(\varepsilon/D)_1 = 0.0059$); pipe no. 2 is 1 in. in diameter, a smoother pipe of carbon steel ($(\varepsilon/D)_2 = 0.0018$) and pipe no. 3 is 0.5 in. in diameter of the galvanized iron ($(\varepsilon/D)_3 = 0.0118$). All pipes are 8.8 m long. The pipes were marked as P_1, P_2 and P_3 in Fig. 1. Another pipe is also used to recycle the extra fluid to the tank which is used as a holding tank for crude oil.

Circulation of the fluid has been done by a Moyno cavity progressive pump through each pipe. Flow rates of the circulating