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Empirical correlation for predicting pressure gradients of oil-water flow with drag-reducing polymer

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ABSTRACT

This study deals with development and evaluation of empirical correlation for predicting pressure gradients of oil-water flow after the addition of drag-reducing polymer. The experimental pressure gradient data used for the correlation were obtained from three different acrylic pipe diameters (30.6, 55.7 and 74.7 mm) at different inclination angles. The drag-reducing polymer (DRP) which was a water-soluble copolymer of polyacrylamide and 2-acryamido-2-methylpropane sulfonic acid, was injected at 40 ppm concentration into the water phase of the oil-water flow. The flow conditions of 0.4–1.6 m/s mixture velocities and 0.05–0.9 input oil volume fractions were imposed. The measured pressure gradient data after the addition of the DRP were used to develop a friction factor correlation as a function of mixture Reynolds number. The developed correlation when tested against the current and previously published experimental data showed a good performance. It also showed the best performance when compared with similar existing correlation and homogeneous model.

1. Introduction

Pressure gradient and holdup of oil-water flow are the most important parameters in the design of directional wells or pipelines through which the oil-water mixture flows. Therefore, the proper design depends strongly on the accurate predictions of these two parameters. Two modelling approaches such as mechanistic and empirical models can reliably predict these parameters, especially the pressure gradients. Mechanistic models are classified as two-fluid model which is used to predict the pressure gradients of separated oil-water flow and homogeneous model which is used to predict the pressure gradients of dispersed oil-water flow. On the other hand, the empirical models or correlations are usually developed from available experimental data.

Modified mechanistic models are more frequently used to predict the pressure gradients of oil-water flow by researchers than the empirical correlations. However, the main challenge in using two-fluid model is the determination of the correct shape of the interphase between the oil and the water. In ordinary two-fluid model, the interface separating the two phases of the separated flow is often assumed to be planar but extensive and careful observations of the interfacial behaviour confirm that the interfacial shape in segregated flow is usually not flat [1]. The interfacial shape can approach a plane or lunar configuration depending on the factors such as the physical properties of the fluids, fluid-wall wettability, pipe geometry (i.e. diameter and inclination angle) and holdup of each phase. The wall-wetting properties of liquids and interfacial tension are particularly important in determining the flow pattern of oil-water flow because of the relatively low density differential between the two fluids which weakened the effect of gravity. For homogeneous model, the challenge is to know the suitable mixture viscosity correlation, which depends on the knowledge of phase inversion point, to be used for a particular oil-water flow system.

As stated earlier, empirical correlations are based on known experimental data. Early predictions of pressure gradients using empirical correlations were carried out on gas-liquid flows [2,3]. Garcia et al. [4] also developed composite power law friction factor correlations for gas-liquid flow in horizontal pipes for each flow pattern and combined flow patterns. They used 2435 experimental data in horizontal pipelines which were taken from different sources, including new data for heavy oil. The predicted pressure gradients by the correlations were compared with the data from which the correlations were developed and with those obtained from many reported correlations in the literature. Also, they conducted a comprehensive performance comparison between different models and correlations by means of their proposed modified relative performance factor (PF), which is a statistical measure that allows models and correlations to be ranked for accuracy. The

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Nomenclature

Roman letters	Description (Unit)
AAE, E_5	absolute average error (Pa/m)
$AAPE$, E_2	average absolute percent error (%)
AE, E_4	average error (Pa/m)
$AFFC$	friction factor correlation of [8] (–)
APE, E_1	average percent error (%)
$CFFC$	current friction factor correlation (–)
DRP	drag-reducing polymer (–)
EXP	experimental (–)
f_m	mixture friction factor (–)
$f_{m\text{-}DRP}$	mixture friction factor at maximum drag reduction (–)
HM	homogeneous model (–)
D or ID	pipe internal diameter (m)
L	pipe length or distance between two pressure impulse lines (m)
PF	relative performance of a model or correlation (–)
PSD, E_3	percent standard deviation (%)
Re_m	mixture Reynolds number (–)
Re_o	Reynolds number of oil (–)
Re_w	Reynolds number of water (–)
SD, E_6	standard deviation (Pa/m)
U_m	mixture velocity (m/s)
U_{so}	superficial velocity of oil (m/s)
U_{sw}	superficial velocity of water (m/s)
dP/dL	pressure gradient (Pa/m)
$(\Delta P/L)_{DRP}$	pressure gradient at maximum drag reduction (Pa/m)
$(\Delta P/L)_{\text{-}Exp}$	experimental pressure gradient (Pa/m)
$(\Delta P/L)_{\text{-}Pred}$	predicted pressure gradient (Pa/m)
$\Delta P_F/L$	frictional pressure gradient (Pa/m)

Greek symbols	Description (Unit)
ρ	fluid density (kg/m^3)
ρ_m	mixture density (kg/m^3)
ρ_o	density of oil (kg/m^3)
ρ_w	density of water (kg/m^3)
μ_m	mixture viscosity (cP)
μ_o	viscosity of oil (cP)
μ_w	viscosity of water (cP)
α_o	oil fraction or oil cut (–)
α_w	water fraction or water cut (–)

Subscripts	
m	mixture
o	oil phase
s	superficial
w	water phase

developed correlations performed the best among all the other ones with which it was compared.

Meanwhile, there are very few works in recent times in which the empirical correlations were used in predicting the pressure gradients of oil-water flow. One of such was done by [5]. He achieved this by using the fanning friction factors obtained from pressure gradient data of [6] for oil-water separated flow (stratified, dual continuous and annular flows) in horizontal acrylic and steel pipes to come up with a power law pressure gradient correlation. The correlation was validated against eleven published experimental data set of oil-water separated flow which covered a wide range of flow conditions involving different oils, pipe diameters and materials. The predicted pressure gradients were in good agreement with some published experimental data. The prediction of the correlation was also tested against the two-fluid model and it was found that the correlation performed better in predicting the pressure gradients in all the different sources except those of [1,7].

It is should be emphasized that all the above models and correlations were developed from two-phase flows without DRP. The only work found in the literature which developed empirical correlations for two-phase horizontal flows with DRP was carried out by [8]. Although they developed power law correlations for friction factor prediction of both gas-liquid and oil-water flows at maximum drag reductions by DRPs, the data used for the correlations were very limited, especially those of oil-water flow. Also, they only compared the pressure gradients obtained from the predicted friction factors with the experimental pressure gradients from which the correlations were developed. Therefore, the present work is to provide a more representative friction factor correlation as it is developed using experimental data obtained from oil-water flow with DRP in different pipe inclinations and diameters. This will better predict pressure gradients of oil-water flow at maximum drag reductions by DRPs. The used experimental pressure gradients for the correlation are considered to be at maximum drag reductions because the concentration of the DRP (40 ppm) injected into the oil-water flow was enough to achieve the maximum drag reductions as preliminary results at different flow conditions presented in our previous published work had shown [9].

2. Correlation development

The motivation for this correlation development is the fact that the well-established models cannot predict the pressure gradients of oil-water with DRP. This is because of the change in the effective (or elongational) mixture viscosity of the oil-water flow by the DRP which caused significant decrease in the friction factor and in turn decrease in the pressure gradients (i.e. drag reduction) [10]. As an illustration, the measured pressure gradients of dispersed oil-water flow after the addition of DRP in the 30.6-mm horizontal pipe are compared with the pressure gradients obtained using homogeneous model at the same flow conditions as shown in Fig. 1. It can be seen that there is a huge difference between the magnitudes of the two sets of the pressure gradients. The inability of the homogeneous model and indeed all other existing models to adequately predict the pressure gradients is because the effect of the drag reduction by DRPs is not incorporated into the development of the models.

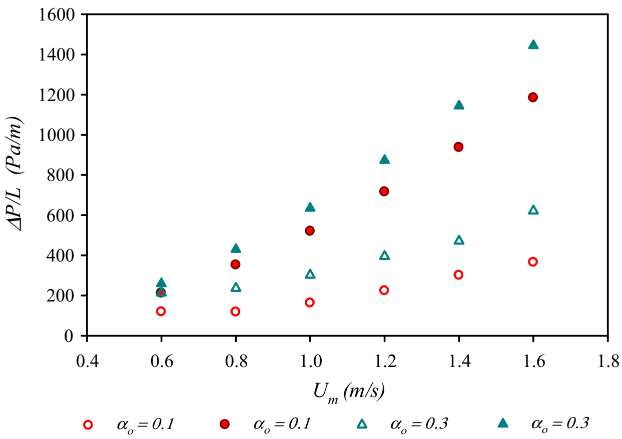

Fig. 1. Experimental pressure gradients of oil-water flow with DRP (hollow symbols) and pressure gradients from homogeneous model (filled symbols).