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Flow of two-phase oil/water mixtures through sudden expansions and contractions

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Abstract

Pressure loss data in a sudden expansion and a sudden contraction were obtained for two-phase oil/water mixtures, covering a wide range of oil concentration: 0 to 97.3 vol.% oil. The emulsions were of oil-in-water type up to an oil concentration of 64 vol.%. Above this concentration, the emulsions were water-in-oil type. An on-line conductance cell was used to monitor the inversion point and the type of emulsion. The pressure loss was determined from the measured pressure profiles upstream and downstream of the fitting. From the pressure-loss/velocity data, the loss coefficients were obtained. The loss coefficients for the emulsions are found to be independent of the concentration and type of emulsions. Furthermore, there is no observable difference between the loss coefficients for emulsions and single-phase water. © 1997 Elsevier Science S.A.

Keywords: Flow; Two-phase; Emulsion; Oil/water mixture

1. Introduction

Two-phase oil/water emulsions find application in a number of industries, such as petroleum, pharmaceutical, agriculture, and food industries etc. [1]. In many applications, pumping of emulsions through pipes and pipe fittings is required. The determination of friction loss in pipes and fittings is essential in order to specify the size of the pump required to pump the emulsions. Several published papers exist on flow of emulsions through straight pipes [2]. However, little or no work has been reported on flow of emulsions through pipe fittings. In this paper, we report new results on frictional pressure loss in emulsion flow through sudden expansions and contractions.

2. Previous relevant work

In the recent years, several papers have been published on flow of two-phase gas/liquid mixtures through pipe fittings. Sookprasong et al. [3] used the resistance coefficient obtained from single-phase pressure drops for valves and fittings to calculate two-phase pressure drops from a homogeneous flow model. Wadle [4] carried out a theoretical and experimental study on the pressure recovery in an abrupt expansion. He proposed a formula for the pressure recovery based on the superficial velocities of the two phases and verified its predictive accuracy with measured experimental steam–water and air–water data. Several other models available in the literature were also compared with and a good summary of various models is given in this author's work. Schmidt and Friedel [5,6] also studied two-phase pressure drop across sudden contractions and sudden expansions using mixtures of air and liquids, such as water, aqueous glycerol, calcium nitrate solution and refrigerant R12. However, emulsions can generally be treated as pseudo-homogeneous fluids with suitably averaged properties as the dispersed droplets of emulsions are small and are well dispersed [7]. Consequently, the pressure loss for emulsion flow in expansion and contraction should be determinable in the same way as for single-phase fluid flow.

The mechanical energy loss due to friction (i.e., friction loss) in a sudden expansion or a sudden contraction is given as:

$$h_f = \frac{\Delta P}{\rho} = K\frac{V^2}{2} \tag{1}$$

where h_f is the friction loss, ΔP is the pressure loss due to friction, ρ is the mean fluid density, K is the loss coefficient and V is the average velocity in the smaller pipe. If the flow

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is turbulent, K is generally constant independent of the Reynolds number.

3. Experimental work

Fig. 1 shows a schematic diagram of the flow loop developed in the present work. The emulsions were prepared in a large tank equipped with a variable speed mixer and a heating/cooling coil. A centrifugal pump enabled the fluid from the tank to be circulated in the flow loop. The temperature throughout the experiments was maintained constant at 25°C with the help of a temperature controller.

The sudden expansion and sudden contraction used in this work were made from two straight pipes of Schedule 40 stainless steel having inner diameters of 2.037 and 4.124 cm. Six pressure taps were located at distances of 5, 10 and 25 diameters upstream and downstream from the expansion or contraction plane. The pressure differentials were measured with respect to the first pressure tap at 25D upstream position, using Validyne (variable-reluctance) differential pressure transducers. A Coriolis mass flowmeter (supplied by Micro Motion) was used to determine the emulsion flow rate in the flow loop. The Coriolis meter was first calibrated with water by diverting the flow into a weighing tank (see Fig. 1). The output signals from the pressure transducers and the Coriolis meter were recorded by a microcomputer data-acquisition system.

The oil used in the experiments was Bayol-35 supplied by Esso Petroleum Canada. This is a refined white mineral oil with a density of 780 kg/m^3 and a viscosity of 2.72 mPa at 25°C. The emulsions were prepared by mixing/stirring the known amounts of oil and water in a tank.

Oil concentration in the emulsions was increased from 0 to 97.3 vol.%. An on-line conductance cell was used to monitor the type of emulsion (oil-in-water or water-in-oil) flowing through the loop [2]. In Fig. 2, the emulsion conductance versus oil concentration is depicted. The emulsions were oil-in-water (O/W) type up to an oil concentration of 62 vol.%. With further increase in oil concentration, the inversion of phases occurred at 64 vol.% oil; the conductance of emulsion

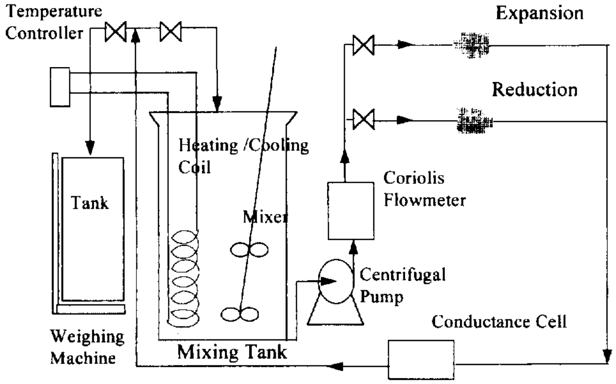

Fig. 1. Schematic diagram of the flow loop.

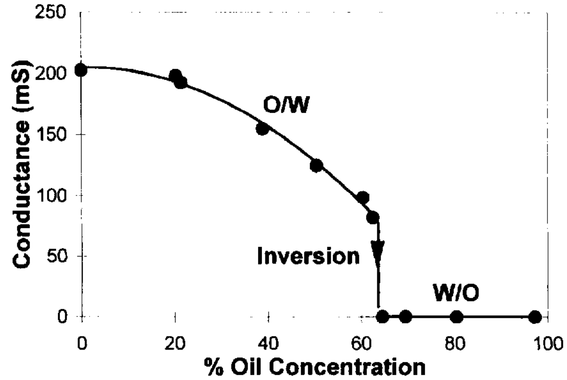

Fig. 2. Conductance versus oil concentration.

dropped sharply to almost zero value. Above 64 vol.% oil, the emulsions were water-in-oil (W/O) type.

4. Results and discussion

4.1. Sudden expansion

A diagram of the pressure profile along the axis of a sudden expansion is shown in Fig. 3. The frictional loss in the inlet section causes the decline in pressure. As the fluid reaches the transitional section, the fluid is decelerated in the enlarged duct area and there occurs a sudden increase in pressure. The friction loss (h_f) due to a pipe expansion can be calculated from the following equation:

$$h_f = \frac{P_1 - P_2}{\rho} + K_1 \frac{V_2}{2} \tag{2}$$

where $P_1 - P_2$ is the pressure change at the expansion plane (ΔP_{exp}), K_1 is equal to $[1-(D_1/D_2)^4]$, and V is the average velocity in a small diameter pipe. The pressure change at the expansion plane (ΔP_{exp}) can be determined from the measured pressure profile downstream of the pipe expansion (in the region of fully developed pipe flow) by extrapolating the pressure profile to the expansion plane.

Experimental pressure profiles for oil-in-water emulsions at various fluid velocities are presented in Fig. 4. Each of the graph differs in the volume fraction of the dispersed phase

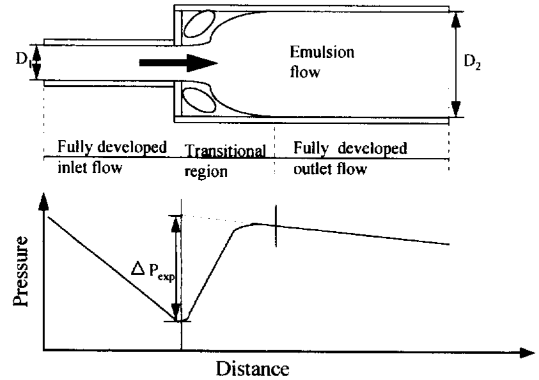

Fig. 3. Pressure profile for a sudden expansion.

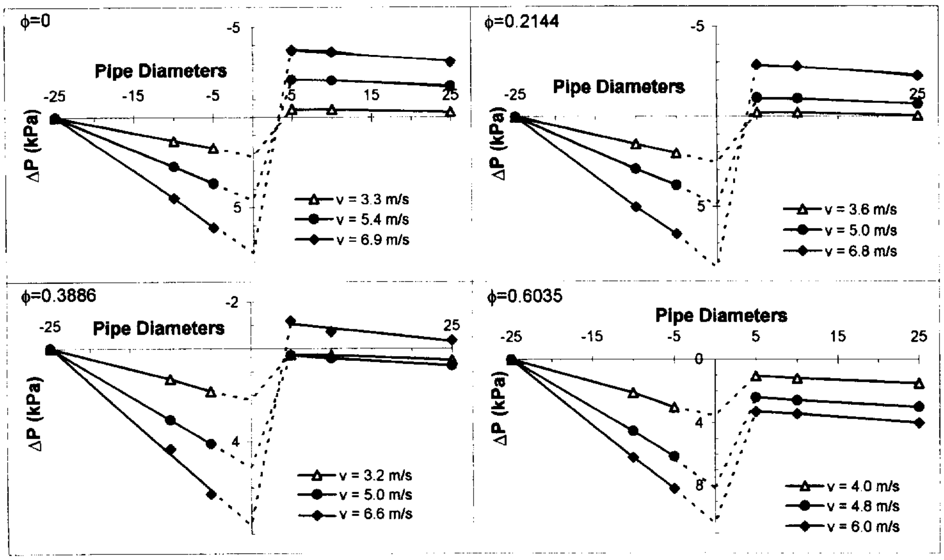

Fig. 4. Pressure profiles for oil-in-water emulsions in a sudden expansion.

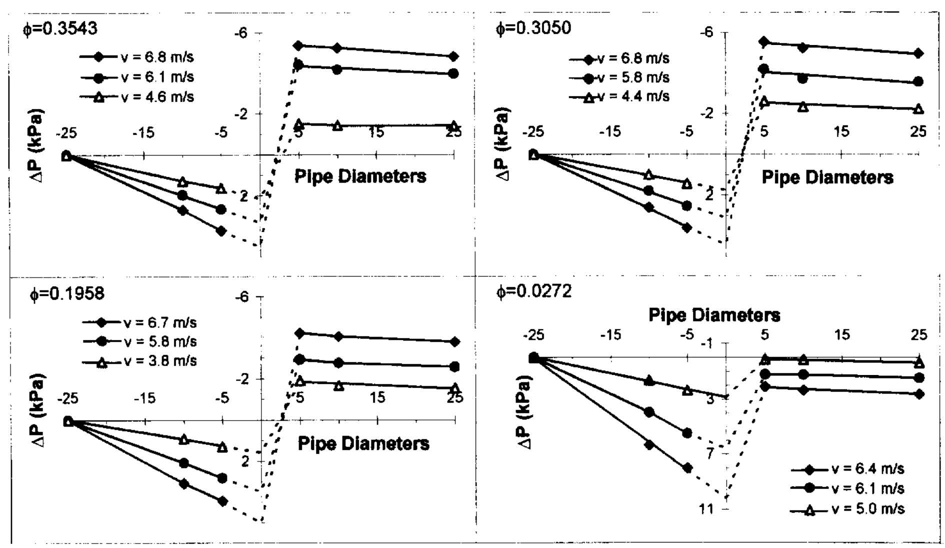

Fig. 5. Pressure profiles for water-in-oil emulsions in a sudden expansion.

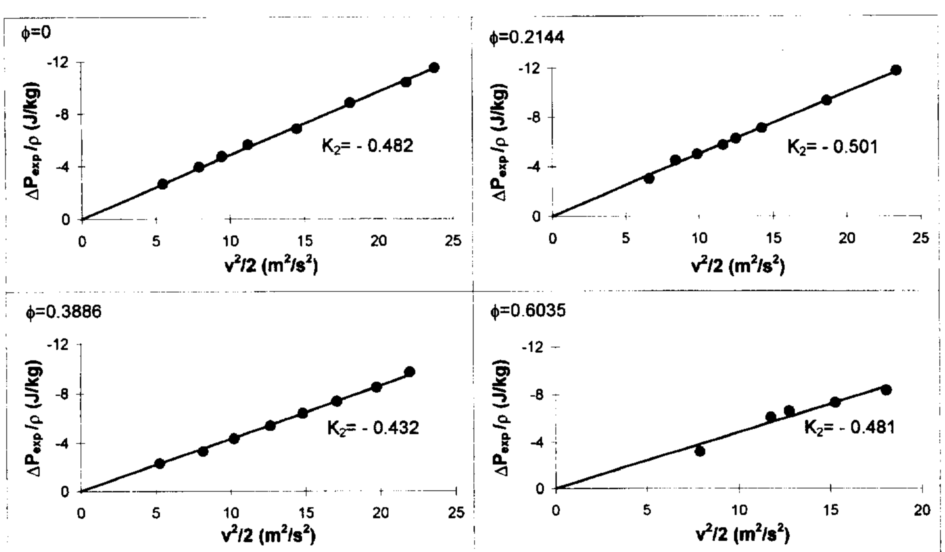

Fig. 6. $\Delta P_{exp}/\rho$ versus $V^2/2$ data for oil-in-water emulsions flowing through a sudden expansion.

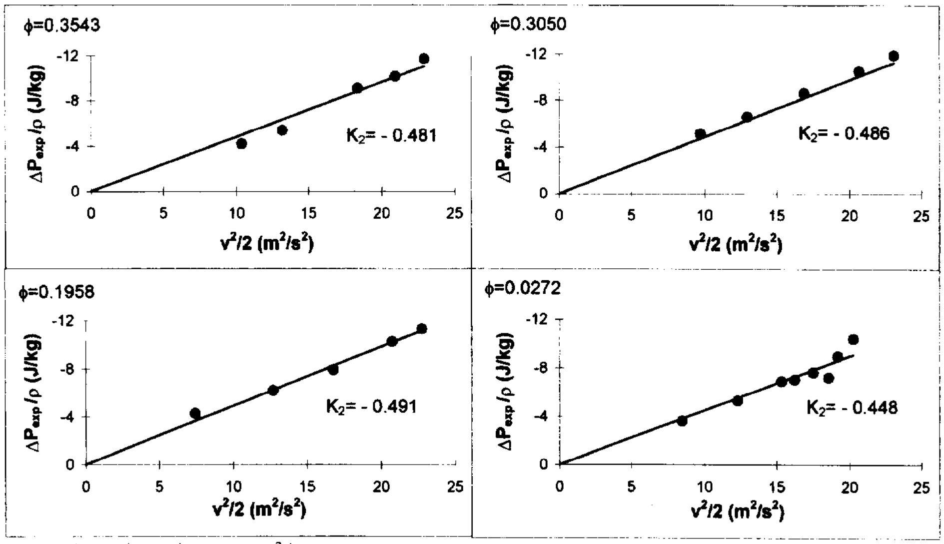

Fig. 7. $\Delta P_{exp}/\rho$ versus $V^2/2$ data for water-in-oil emulsions flowing through a sudden expansion.

(oil) in the emulsion, represented by the symbol ϕ. The pressure profiles are nearly linear up to 5 pipe diameters, both upstream and downstream from the expansion plane. Because there is a change in pipe cross-section and hence a change in mean velocity, the slopes of the pressure profiles before and after the expansion are different. The gradients are greater in the smaller pipe. The pressure profiles for the water-in-oil emulsions are shown in Fig. 5. The water-in-oil emulsions behave in a manner similar to the oil-in-water emulsions.

Figs. 6 and 7 show $\Delta P_{exp}/\rho$ versus velocity head ($V^2/2$) data for various differently concentrated oil-in-water and water-in-oil emulsions, respectively. Since the flow regime is turbulent (see Table 1), $\Delta P_{exp}/\rho$ versus $V^2/2$ data exhibit a linear relationship, that is:

$$\frac{\Delta P_{exp}}{\rho} = K_2 \frac{V^2}{2} \tag{3}$$

Table 1
Range of Reynolds number [a] covered in emulsion flow through a sudden expansion

Emulsion type	Dispersed-phase concentration (ϕ)	Viscosity [b] (mPa)	Reynolds number range
O/W	0	0.90	74828–155784
O/W	0.2144	2.39	30933–58041
O/W	0.3886	5.25	11500–23459
O/W	0.5043	8.87	6861–13228
O/W	0.6035	13.90	5048–7626
W/O	0.3543	6.00	13269–19723
W/O	0.3050	5.37	14149–21819
W/O	0.1958	4.21	15358–26835
W/O	0.0272	2.89	22809–35237

[a] $Re = \rho DV/\mu$, where ρ is mean emulsion density, D is the diameter of smaller pipe, V is the average emulsion velocity, and μ is the emulsion viscosity.

[b] The viscosity data for the emulsions were taken from the work of Pal [2], who measured the viscosity of the same emulsions using pipeline viscometers.

where K_2 is the slope of $\Delta P_{exp}/\rho$ versus $V^2/2$ plots. From Eqs. (2) and (3), the frictional loss in the expansion is given by:

$$h_f = (K_1 + K_2)\frac{V^2}{2} \tag{4}$$

Thus, the loss coefficient for expansion, K_e, is equal to $(K_1 + K_2)$.

The K_e values for different emulsions are plotted as a function of oil concentration in Fig. 8; clearly, the loss coefficient

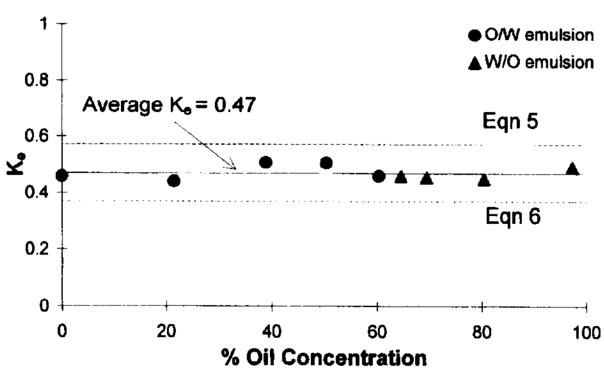

Fig. 8. Expansion loss coefficient as a function of oil concentration.

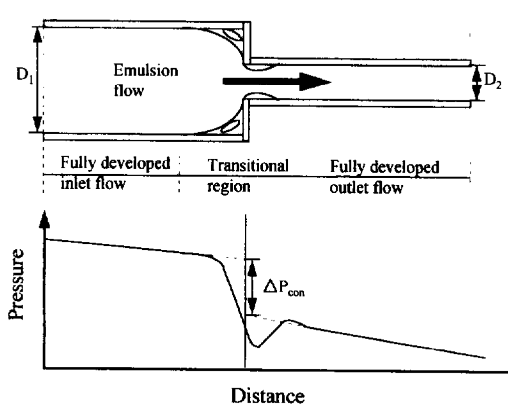

Fig. 9. Pressure profile for a sudden contraction.

is independent of oil concentration and has an average value of 0.47.

The measured K_e values for emulsions are compared with the values obtained from the following equations: (i) Borda–Carnot equation [8]:

$$K_e = (1-\beta)^2 \tag{5}$$

where β is the ratio of the cross-sectional area of a small pipe to the cross-sectional area of a large pipe. (ii) The equation of Wadle [4]:

$$K_e = 2\beta(1-\beta) \tag{6}$$

The β value for the expansion investigated in the present work was 0.244. As shown in Fig. 8, the experimental K_e values for all emulsions lie in between the two values obtained from Eqs. (5) and (6), respectively.

4.2. Sudden contraction

A diagram of the pressure profile for a sudden contraction is shown in Fig. 9. The pressure drop across a pipe contraction, ΔP_{con}, is defined as a local change of pressure ($P_1 - P_2$) in the contraction plane for an assumed fully developed flow in the inlet and the outlet pipes. The pressure change can be determined from the measured axial pressure profiles, in the regions of fully developed pipe flow upstream and downstream of the pipe contraction, by extrapolating these (linear) pressure profiles to the contraction plane.

The measured pressure profiles for a sudden contraction are presented in Figs. 10 and 11 for water-in-oil and oil-in-water emulsions, respectively. Each of the graph differs again in the volume fraction of the dispersed phase (ϕ). Since the pipe cross-section contracts, and hence the mean velocity increases, the slopes of the pressure profiles after the con-

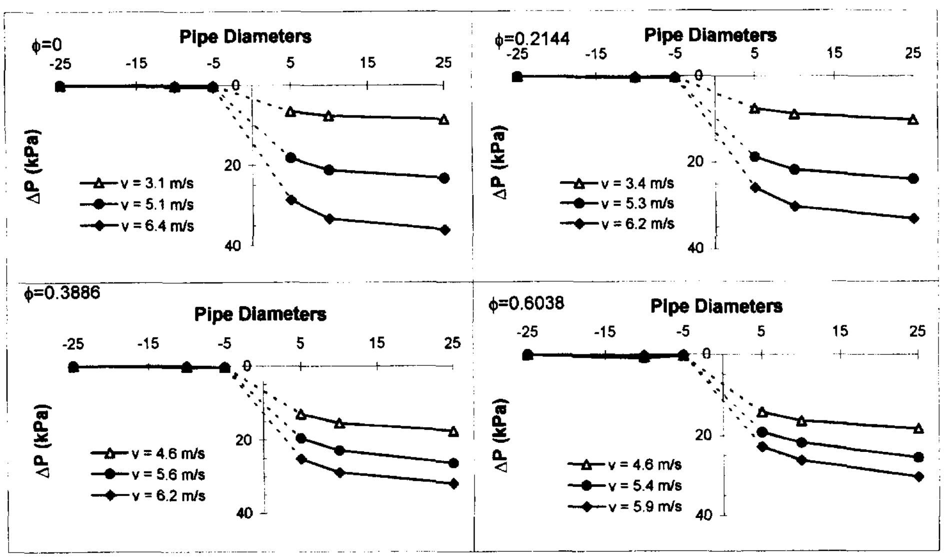

Fig. 10. Pressure profiles for oil-in-water emulsions in a sudden contraction.

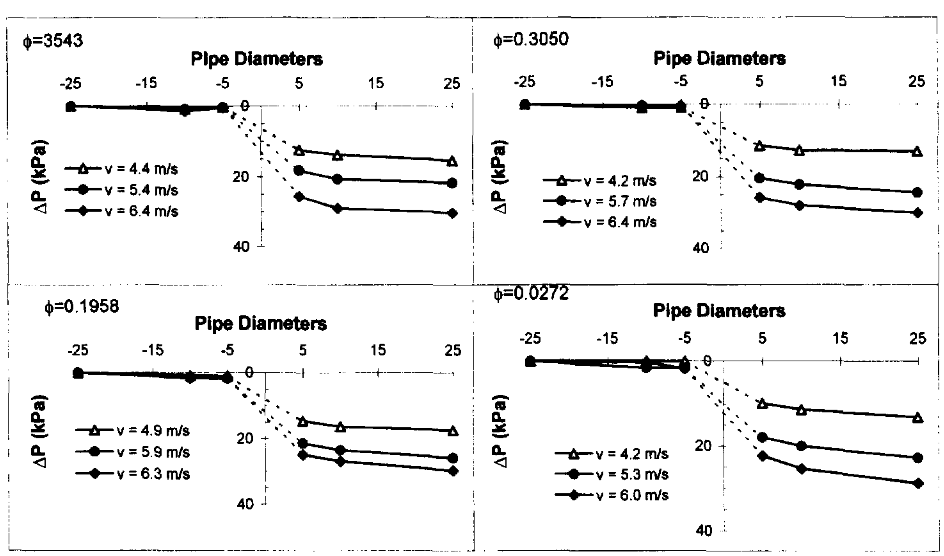

Fig. 11. Pressure profiles for water-in-oil emulsions in a sudden contraction.

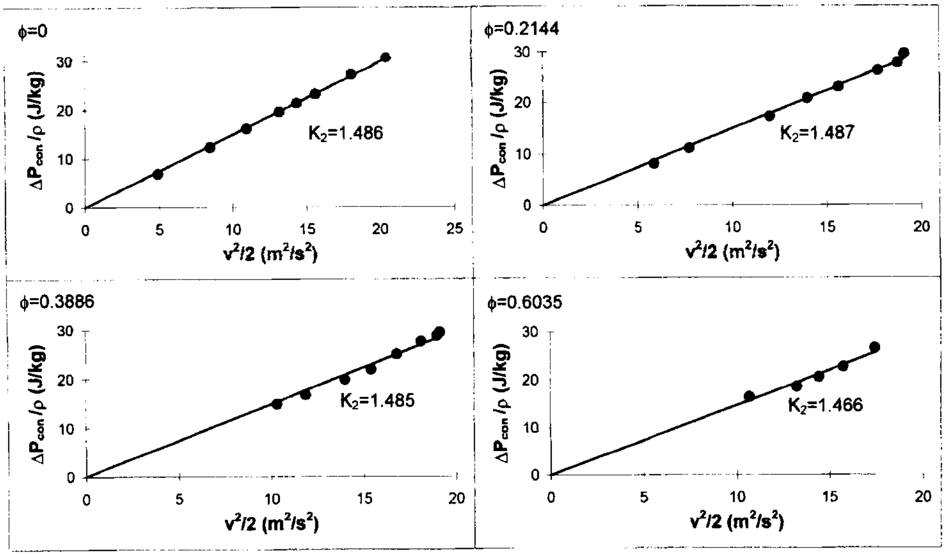

Fig. 12. $\Delta P_{con}/\rho$ versus $V^2/2$ data for oil-in-water emulsions flowing through a sudden contraction.

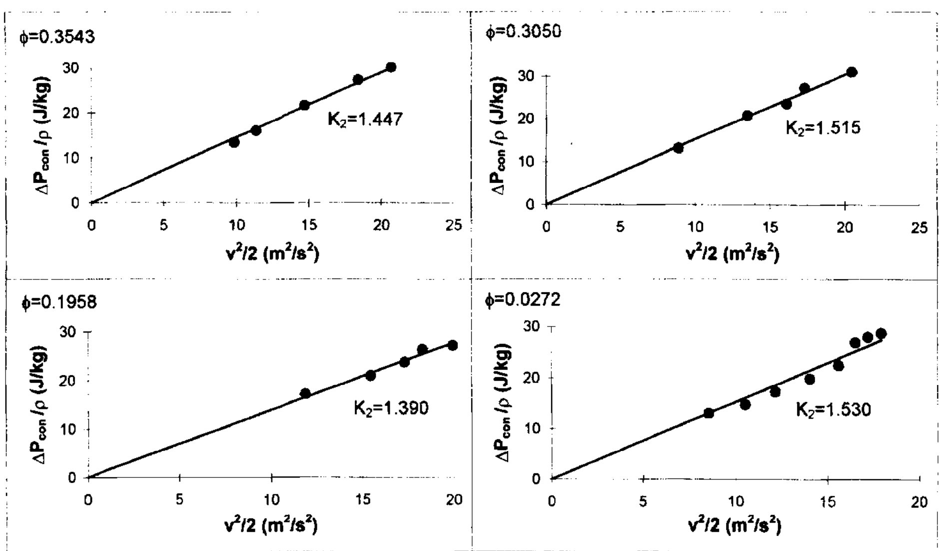

Fig. 13. $\Delta P_{con}/\rho$ versus $V^2/2$ data for water-in-oil emulsions flowing through a sudden contraction.

traction are greater than those before the contraction. The pressure at 5 pipe-diameters downstream from the contraction plane deviates from the linear pressure profile. Therefore, the pressure changes for the contraction were obtained by taking the difference between the linear pressure profiles extrapolated from 25D and 10D to the contraction plane.

Figs. 12 and 13 show $\Delta P_{con}/\rho$ versus the velocity head ($V^2/2$) data for various differently concentrated oil-in-water and water-in-oil emulsions, respectively. Since the flow regime is turbulent (see Table 2), $\Delta P_{con}/\rho$ versus $V^2/2$ data exhibit a linear relationship, that is:

$$\frac{\Delta P_{con}}{\rho} = K_2 \frac{V^2}{2} \tag{7}$$

V is the average velocity in a small-diameter pipe and K_2 is the slope of $\Delta P_{con}/\rho$ versus $V^2/2$ plot. The frictional loss (h_f) due to a pipe contraction can be calculated from the following equation:

$$h_f = (K_2 - K_1)\frac{V^2}{2} \tag{8}$$

where K_1 is equal to $[1-(D_2/D_1)^4]$. Thus, the loss coefficient for contraction, K_c, is equal to $(K_2 - K_1)$.

The plot of contraction loss coefficient (K_c) as a function of oil concentration is shown in Fig. 14 for both emulsion

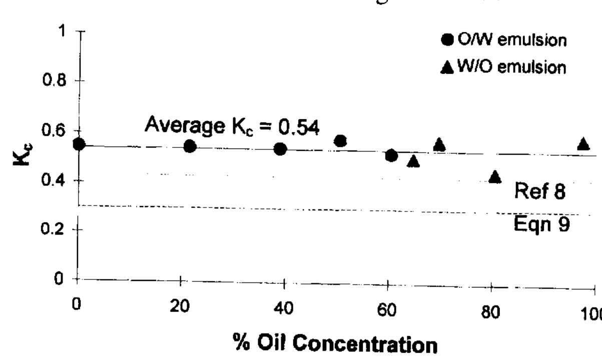

Fig. 14. Contraction loss coefficient as a function of oil concentration.

Table 2
Range of Reynolds number [a] covered in emulsion flow through a sudden contraction

Emulsion type	Dispersed-phase concentration (ϕ)	Viscosity [b] (mPa)	Reynolds number range
O/W	0	0.90	70812–144445
O/W	0.2144	2.39	27532–49663
O/W	0.3886	5.25	16086–21917
O/W	0.5043	8.87	8365–12386
O/W	0.6035	13.90	5866–7496
W/O	0.3543	6.00	12949–18746
W/O	0.3050	5.37	13562–20554
W/O	0.1958	4.21	19411–25127
W/O	0.0272	2.89	22878–33129

[a] $Re = \rho DV/\mu$, where ρ is mean emulsion density, D is the diameter of smaller pipe, V is the average emulsion velocity, and μ is the emulsion viscosity.
[b] The viscosity data for the emulsions were taken from the work of Pal [2], who measured the viscosity of the same emulsions using pipeline viscometers.

types. The loss coefficient is independent of the oil concentration and has an average value of 0.54. The value of K_c calculated from the following empirical equation, given in McCabe et al. [9]:

$$K_c = 0.4(1-\beta) \tag{9}$$

is 0.30 for an area ratio (β) of about 0.244. The value obtained from Perry et al. [8] is 0.43.

5. Conclusions

The main conclusions of this study are as follows: (1) Single-phase Newtonian flow equations can be used to calculate pressure loss in the flow of two-phase oil/water mixtures through a sudden expansion and a sudden contraction. (2) The loss coefficients for a sudden expansion and a sudden contraction are found to be comparable to the values predicted from the published literature. (3) The loss coefficient is not significantly influenced by the type and concentration of emulsions flowing through a sudden expansion and a sudden contraction.

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