Two-Phase, Gas-Liquid Flows in Static Mixers

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Static mixers are used for many gas-liquid two-phase operations. Some of the typical applications are processing of natural gas to remove hydrogen sulfide or carbon dioxide, waste water treatment, dissolution of gases, hydrogenation, chlorination, and so on (Grosz-Roll et al., 1972; Rader et al., 1989).

Fan et al. (1975) have experimentally studied the pressure drop for oxygen-water system in a bubble column packed with Sulzer-Koch-type mixing elements. They observed that the ratio of pressure drop through the packed bubble column to that through the unpacked one was slightly greater than one.

The suitability of static mixers to mix fluids of very widely different viscosities has been demonstrated by Sir and Lecjaks (1982). Two-phase operations in polymer industry involve very viscous fluids. Due to the high viscosity of these fluids, the flow will be predominantly in laminar region for both fluids. There are no data on gas-liquid two-phase systems incorporating viscous Newtonian and non-Newtonian fluids where flows are predominantly in laminar region.

Experimental Studies

Experimental arrangement of the system is shown in Figure 1. A 26-mm-id vertical pipe was stacked with 24 numbers of static mixer elements. Three different types of static mixers were used: Kenics, Sulzer, and Komax. The elements were supplied by a local fabricator, MAMKO. The Kenics mixer consisted of alternating left- and right-handed helices with an angle of twist of 180°. The edges of the helices adjacent to each other formed an angle of 90°. The Sulzer mixer consisted of a framework of strips inclined relative to one another, whose main axis was perpendicular simultaneously and at an angle to the pipe axis. Numerous elements, rotated through 90° and arranged successively in the pipe, formed the mixer. The Komax mixer was constructed from slotted sheet metal pieces with bent ends. Triangular-shaped flow channels were formed by pushing the elements together in a pipe.

The total number of elements used in each case was 24 with the l/D ratio of 1.5 for a single element of each type. Pressure drop was measured using manometer. Test liquid was circulated through the assembly using a gear pump (0.75 hp, 0.56 kW). The liquid flow rate was measured by noting the time for collecting a fixed volume of liquid. The flow rate was changed from 0.15×10^{-4} m^3/s to 1×10^{-4} m^3/s. Initially the pressure drop data were collected for the single-phase flow of liquid alone. For the two-phase flow study, air was supplied to the flowing liquid cocurrently. Air was introduced through a "Tee" joint of inside diameter of 26 mm. The air flow rate was varied from 6×10^{-6} m^3/s to 1×10^{-4} m^3/s. Air was separated from liquid at the end of pipe line, and the liquid was recirculated. A sight glass was provided at the end of the assembly for visual observation of flow. Aqueous glycerol solution of viscosity 0.6 Pa·s and 1% Na-CMC in water were used as test fluids. The rheological properties were measured with HAAKE RV 3 Rotoviscometer over the shear rate range of 10 s^{-1} to 10^3 s^{-1}. Rheological properties were expressed by a power-law model,

$$\tau = K(\gamma)^n \tag{1}$$

The rheological data were collected immediately before and after the flow experiment, for each type of static mixer assembly. No change in K and n was noticed. However, over the

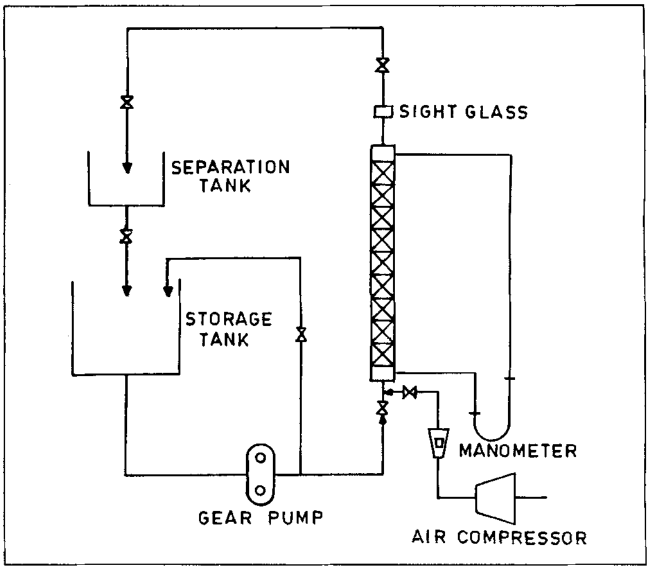

Figure 1. Experimental arrangement.

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Table 1. Constants Used in Eq. 2

Mixer Type	A	B	m	ϵ
Kenics	$64.06\ n$	$3.68\ n^4/n+1$	$1.36\ n/n+3$	0.91*
Sulzer	$350.00\ n$	$10.26\ n/n+1$	$2.32\ n/n+3$	0.87*
Komax	$176.49\ n$	$2.56\ n/n+1$	$1.72\ n/n+3$	0.90**

* Shah and Kale (1991)
** Gokulchandra and Kale (1991)

time period, when static mixing elements were changed and the experimental arrangement was reassembled, some change in K and n did take place. Hence, appropriate values of K and n were used in each experiment.

Manometer readings were corrected for the presence of air and the change in static heads. Other details of experimental work are given by Shah (1990).

Results and Discussion

Various non-Newtonian fluids were pumped through the static mixer assembly, and the pressure drop was measured. The pressure drop results were correlated as:

$$f_{SM}=\frac{A}{Re}+\frac{B}{Re^m} \tag{2}$$

The constants A, B, and m are given in Table 1. Equation 1 was found to be valid over the Reynolds number range of 0.01 to 300.

For the two-phase flow, the correction factor was applied for the manometer reading assuming the gas holdup to be proportional to $Q_G/(Q_G+Q_L)$. It is known that the actual holdup is less than this value. For empty pipe, the gas holdup is about 0.83 times this quantity, $Q_G/(Q_G+Q_L)$. The % error in estimating the pressure drop is less than 10% on the average. Thus, by using this correction factor, the estimated pressure drop is always on a higher side giving a conservative estimate. No data were collected using empty pipe alone for any of the fluids.

Chisholm (1967) has recommended the use of Lockhart-Martinelli (1949)-type correlation for a cocurrent two-phase, gas-liquid flow in a pipe. Thus,

$$(\Delta P)_{TP}=\phi_L^2\,\Delta P_L=\phi_G^2\,\Delta P_G \tag{3}$$

and

$$X=(\Delta P_L/\Delta P_G)^{0.5} \tag{4}$$

He correlated ϕ_L^2 with X as:

$$\phi_L^2=1+\frac{C}{X}+\frac{1}{X^2} \tag{5}$$

and recommended the value of $C=5$ for laminar-laminar flow in an empty pipe.

In this study, the values of ratio X and ϕ_L^2 were experimentally determined. Variation of ϕ_L vs. X is shown in Figure 2. The value of C for three elements was found to be 2.50 ± 0.3 for glycerol and 3.27 ± 0.17 for the CMC solution. The C values are slightly higher for non-Newtonian, shearing-thinning fluid, suggesting that C might be a function of the power-law index, n.

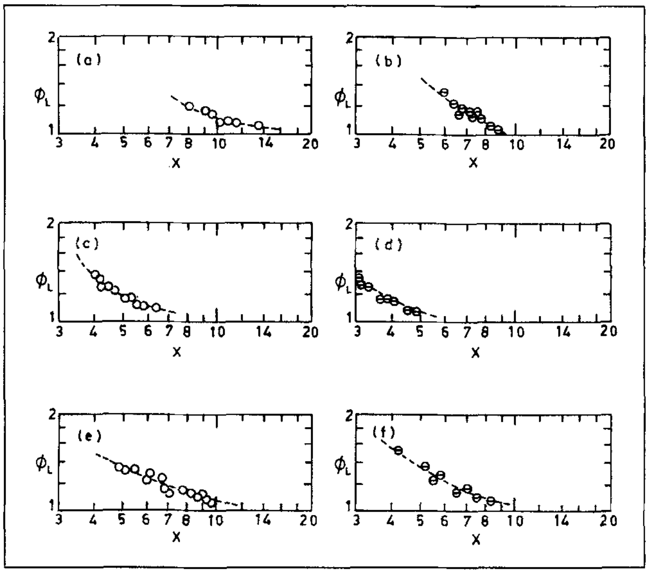

Figure 2. Variation of ϕ_L with X for various static mixers.

O = Glycerol-air; a = Kenics; c = Sulzer; e = Komax
Θ = CMC-air; b = Kenics; d = Sulzer; f = Komax

Smith (1976) has also presented his data in the form of the Lockhart-Martinelli (1949) correlation. He used a modified Kenics mixer which did not show any significant difference between the two-phase and the single-phase pressure drop. Wang and Fan (1978) observed that the gas holdup in a packed column was more than that in an empty pipe due to smaller bubble size and hindering action of the packings. Similar effects are observed in static mixers which reduce the effective static head of gas-liquid mixture. Since actual holdup was not measured in this work but was assumed to be in the same ratio of individual air-liquid flow rates in correcting the manometer reading, the value of C will be still lower. Thus, the correlation proposed in Eq. 5 will always yield a conservative estimate of the two-phase pressure drop.

Conclusions

Lockhart-Martinelli type of correlation can be used for estimating two-phase pressure drop in static mixers. The method of Chisolm (1967) for correlating ϕ_L^2 vs. X appears to be adequate.

Acknowledgment

CSIR, India, provided financial assistance to this work.

Notation

- A = constant in Eq. 2, dimensionless
- B = constant in Eq. 2, dimensionless
- C = constant in Eq. 5, dimensionless
- D = inside pipe diameter, m
- f = friction factor defined as $(\Delta P_{SM} D\epsilon^2)/2L\rho V^2)$, dimensionless
- K = consistency index, dimensionless
- L = total length of the mixing elements, m

l = length of one mixing element, m
m = constant in Eq. 2, dimensionless
n = power-law index, dimensionless
ΔP = pressure drop, Pa
Q = volumetric flow rate, m^3/s
Re = Reynolds number defined as $(D^n V^{2-n} \rho)/(K 8^{n-1} \epsilon^{2-n})$, dimensionless
V = superficial velocity of the fluid, m/s
X = pressure drop ratio, dimensionless

Greek letters

γ = shear rate, s^{-1}
ϵ = porosity of the mixer assembly, dimensionless
ρ = density of the fluid, kg/m^3
τ = shear stress, Pa
ϕ = parameter defined in Eq. 3, dimensionless

Subscripts

G = gas phase
L = liquid phase
SM = static mixer
TP = two-phase

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Manuscript received July 16, 1991, and revision received Nov. 14, 1991.