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International Journal of Heat and Mass Transfer 48 (2005) 2911–2921
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

The effect on pressure drop across horizontal pipe and control valve for air/palm oil two-phase flow

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Received 5 February 2003; received in revised form 28 October 2004

Abstract

Studies on operating characteristics of control valves with two-phase flow have not been given much attention in the literature despite its industrial importance during design and selection as well as during plant operation. However, literature shows considerable work with two-phase flow through pipes and different geometrical shapes of flow ducts. The present work attempts to study experimentally the effect of two-phase flow on pressure drop across the control valve for different volume fractions of the fluids. A typical fluid system of palm oil (liquid phase) and air (gas phase) has been used for the studies. The pressure drop in a horizontal straight pipe upstream of the valve is also considered to test the correlations from the literature on two-phase pressure drop. The same is extended to represent the pressure drop across the valve. The operating characteristics are obtained from the pressure drop relationship and valve opening. It is found that Lockhart–Martini (L–M) parameter and the quality (fraction of liquid) are found to correlate well with the two-phase multiplier defined based on pressure drop with gas phase. The installed characteristics of the valve for varying pressure drop and quality is presented.

1. Introduction

Simultaneous flow of two or more immiscible phases is termed as multiphase flow. The common class of multiphase flow is he two-phase flow such as gas–liquid, gas–solid, liquid–liquid and solid–liquid flows. Gas–liquid flow is complex because of the existence of deformable interfaces and the fact that one of the phases is compressible. A wide range of interfacial configurations is possible in such two-phase flow.

Systems involving multiphase fluid flow occur widely in nature and in industry. Two-phase flows occur in many engineering applications, particularly in equipment related to oil, chemical processes and power generation industries. This type of flow is encountered in an increasing number of important situations and a clear understanding of the rates of transfer of momentum, heat and mass will be required for logical and careful design of operation of a very wide variety of engineering equipment and processes. Thus an understanding of multiphase phenomena is essential and hence extensive research is being pursued in this area. However, one important area, which has received little attention, is the study of pressure losses in control valves due to two-phase flow.

The studies in two-phase flow through pipes have been conducted for the past 60 years. The first detailed

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0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2004.11.012

Nomenclature

C	C factor in Eq. (10)	μ	dynamic viscosity liquid/gas, N s/m^2
D	diameter of pipe, m	ΔP	pressure drop, Pa
D_e	equivalent diameter of valve opening, m	χ_{tt}^2	Lockhart–Martinelli (L–M) parameter
D_o	Orifice diameter, m	ϕ_l	two-phase multiplier based on pure liquids Eqs. (7a) and (12)
f	friction factor	ϕ_a	two-phase multiplier based on pure gases Eq. (7b)
l	length of pipe, m		
L	valve stem position (or lift)		
m	exponent		
Q_a	air flow rate, m^3/s	*Subscripts*	
Q_l	liquid flow rate, m^3/s	a	air
NRe	Reynolds number	l	liquid, palm oil
V	velocity of flow, m/s	p	pipe section
X	quality	v	valve section
		TPf	two-phase flow
Greek symbols			
ρ	density of liquid/gas, kg/m^3		

study on two-phase flow was carried out by Lockhart and Martinelli in 1949. Design of pipeline for the simultaneous flow of oil and gas was discussed by Baker [3] and Hoogendoorn [12] has studied the gas–liquid flow in horizontal pipes. The two-phase slug flow in horizontal and inclined tubes was discussed by Vermeulen and Ryan [20]. Beretta et al. [4] has studied pressure drop for horizontal oil–water flow in small diameter tubes. In another study Awwad et al. [1] analyzed flow patterns and pressure drop with air–water in horizontal helicoidal pipes. A comparison of existing theories on two-phase flow was analyzed by Kordyban [14]. Pressure gradient due to friction for the two-phase mixtures in smooth tubes and channels was studied by Chisolm [5]. They are the successors in the field of two-phase flow and the studies were concentrated on developing the flow pattern model for horizontal, inclined and vertical flow in pipes.

Oliemans and Ooms [16] gave a semi-empirical model for the Core-annular flow of oil and water through a pipeline. Core-annular flow of two immiscible fluids through pipeline was studied by Bai et al. [2] and they used an oil with viscosity of 600 times the water viscosity and found that the reduction of drag force on the order one thousand. Hewitt [11] studied pressure gradients in liquid–liquid flows and displayed significant peaks when plotted as a function of water fraction for a given velocity; the response depends on the mixing processes between the phases. Sotgia et al. [19] experimented in oil–water viscosity ratios from about 560 to about 1300 and reported that the thorough mixing of the two liquids, which served to eliminate entrance effects on the test section, was attained in a calming section ($L/D = 200$) before entering the test section. The structure of two-phase flow in ducts with sudden contractions and its effects on the pressure drop was studied by Guglieminі et al. [10].

Literature scanned has not reported two-phase flow through control valves. Hence, this study will be relevant for guiding the selection, design and setting the parameters from operating characteristics.

In the present study, the pressure drop characteristics have been experimentally investigated for air–palm oil through a control valve. The data are compared with earlier research carried out by Dowlati et al. [6], Awwad et al. [1], Salcudean et al. [17], Fairhurs [7] and Simpson et al. [18].

2. The experimental setup and procedure

A schematic diagram of the experimental set up is shown in Fig. 1. The test section is a GI 40 schedule pipe of 1 m length and 23.5 mm inside diameter. The upstream section of this pipe, of length 0.5 m, ensures fully developed conditions. The control valve is fitted at the down stream end of the test pipe. The fluids are discharged to a tank where discharge pressure is constant. The liquid is metered through Krone Marshall magnetic flow meter. Purified dry air from an Ingersoll Rand compressor with a pressure regulator (0–2.5 kg/cm^2) pressure regulator was metered through a non-return valve using a Placka rotameter. The pressure drop across the valve and the pipe was measured with a differential pressure transducer. An electro pneumatic converter is used to actuate the pressure valve. The density and kinematic viscosity of palm oil used in the experiments are 888.25 kg/m^3 and 4.44×10^{-2} N s/m^2. During experi-

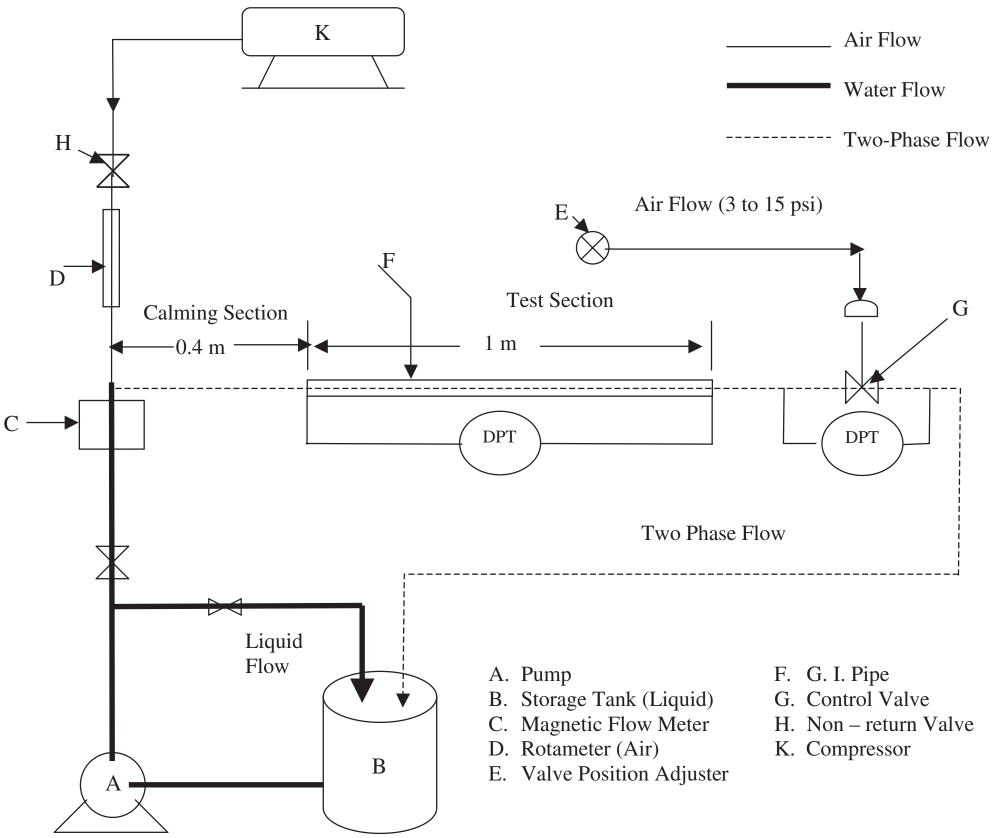

Fig. 1. Experimental set up.

mentation the temperature of two-phase flow varies at ±3 °C.

The experiments were carried out for four different valve openings and different volume fractions. Air and palm oil flow rates varied from 50 to 150 l/h and 25 to 100 l/h respectively (non-uniform flow) with varying valve openings from 25% to 100%.

The system was initially tested with palm oil (single-phase flow) for different control valve openings. In subsequent experiments, the volume fraction of palm oil was varied by dispersing filtered dry air into palm oil into the calming section. The airflow rates are maintained at constant pressure and measured using calibrated rotameter.

3. Results and discussion

3.1. Single phase flow (liquid flow)

The friction factor for both pipe section and valve section is estimated from the measured pressure drop and corresponding flow velocity, using the relationships (Eqs. (1)–(3)). The subscripts 'P' and 'V' refer to pipe section and valve section respectively.

$$NRe = \frac{\rho_1 V_1 D}{\mu_1} \tag{1}$$

$$f_P = \frac{\Delta P_P}{2\rho_1 V_1^2}\left(\frac{D}{l}\right) \tag{2}$$

$$f_V = \frac{\Delta P_V}{2\rho_1 V_1^2}(D_e) \tag{3}$$

where, the equivalent diameter, D_e for valve is determined based on the geometry of the control valve. The turbulent flow is observed in the air phase and laminar flow is observed in the oil phase, as the viscosity of oil is less.

3.1.1. Definition of equivalent diameter for valve opening

The valve assembly was dismantled and the orifice opening and trim configuration was measured for different lift positions. The maximum valve opening was 0.125 m. Fig. 2 shows the details of stem contour and opening. For the valve section based on valve opening,

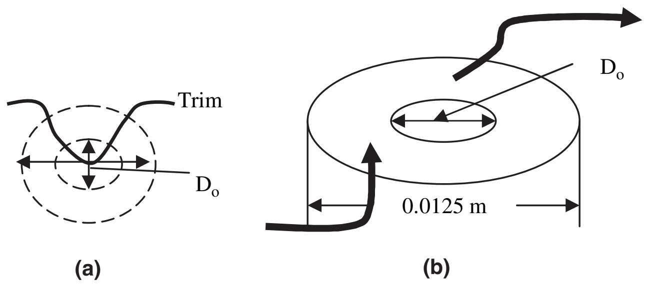

Fig. 2. (a) Definition of equivalent diameter. (b) Flow through valve.

an equivalent diameter was determined defined by Eq. (4).

Equivalent diameter $d_e = 4 \times$ hydraulic radius where

$$D_e = 4\left(\frac{\frac{\pi}{4}(0.0125^2 - D_o^2)}{\pi(0.0125 + D_o)}\right)$$

$$D_e = 0.0125 - D_o \tag{4}$$

The value of equivalent diameter for various lifts is given in Table 1.

The friction factor f–NRe relation for the pipe section is shown in Fig. 3 for pure liquid. From this graph a general relation of the form.

$$f = aNRe^m \tag{5}$$

Table 1
Equivalent diameters for valve opening

Percentage of lift	Orifice diameter (D_o) (m)	Equivalent diameter (D_e) (m)
100	0	0.0125
75	0.0094	0.0031
50	0.0063	0.0063
25	0.0031	0.0094

was established for pure liquid and the constants 'a' and 'm' are determined by regression analysis. The estimated values of 'a' and 'm' are 0.304 and −0.077 respectively. For the valve section, the data could not be fitted with a single set of constants, as it could be possible with flow through the pipe. The constants are different for different valve openings. Fig. 4 shows the graph for friction factor vs Reynolds number for palm oil in the valve section for different valve openings. The values of constants of Eq. (5) 'a' and 'm' for pure liquid and valve section are given in Table 2.

3.2. Two-phase flow (pressure drop vs Q_l/Q_a)

The measured pressure drop across pipe section and across control valve for different liquid to air ratios (Q_l/Q_a) are plotted and shown in Figs. 5 and 6 respectively. It is observed that maximum pressure drop for the valve side (23.57 kN/m^2) is nearly 68 times greater than that for pipe side (0.346 kN/m^2).

3.3. Pressure drop vs quality X

The term quality defines the fraction of dispersed phase in two-phase flow and can estimated as given by Eq. (6).

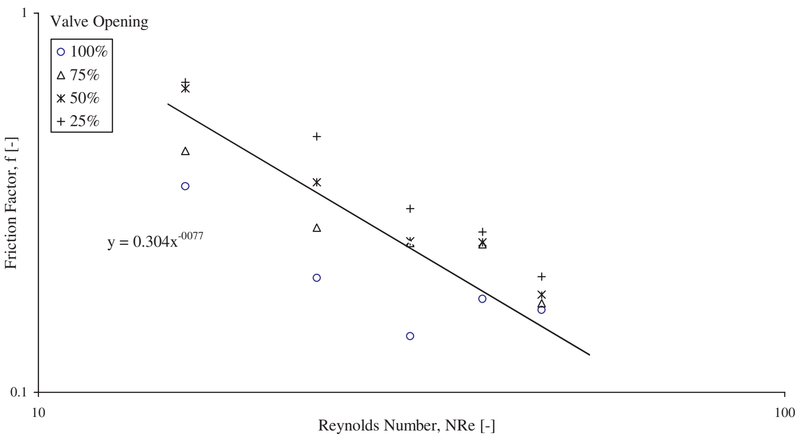

Fig. 3. Friction factor vs Reynolds number in the pipe section.

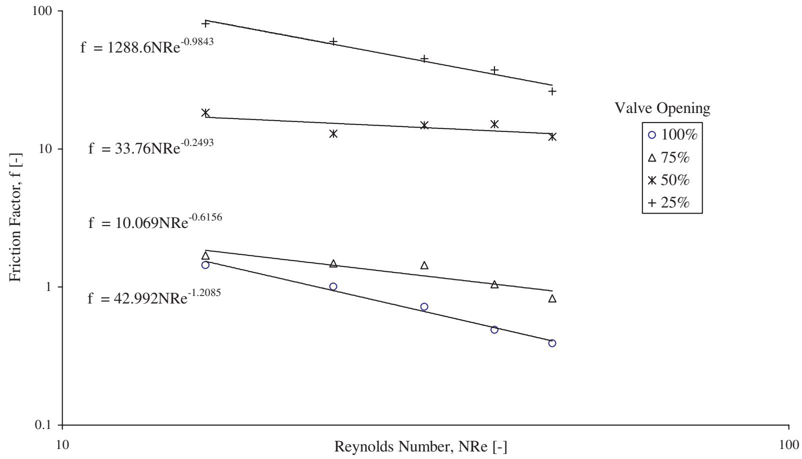

Fig. 4. Friction factor vs Reynolds number in the valve section.

Table 2
Constants for Eq. (5) for various valve opening for valve section

Constants	Valve opening (%)			
	25	50	75	100
a	1288.6	33.76	10.07	42.99
m	−0.98	−0.25	−0.59	−1.21

$$X = \frac{1}{\left(1 + \frac{\rho_l}{\rho_a}\frac{Q_l}{Q_a}\right)} \quad (6)$$

The experimentally measured pressure drop variation with quality, X is plotted and shown in Figs. 7 and 8 for the pipe section and for the control valve section respectively. The pressure drop varies linearly with flow rate linearly for both valve and pipe section as observed from the Figs. 7 and 8.

For pipe section, ΔP is observed to decrease with increase in quality. However, as valve opening increases, the pressure drop is found to increase. This is due to the increase in flow with valve opening.

For valve section, the pressure drop across the valve is observed to decreases linearly with quality and valve opening. The rate of change is more pronounced at lower valve opening than at valve opening more than 50 percent. Relatively, the variation is insignificant at valve openings 75% and 100%.

The maximum pressure drop across pipe is 0.363 kN/m^2 at quality of 0.064 whereas the pressure drop across

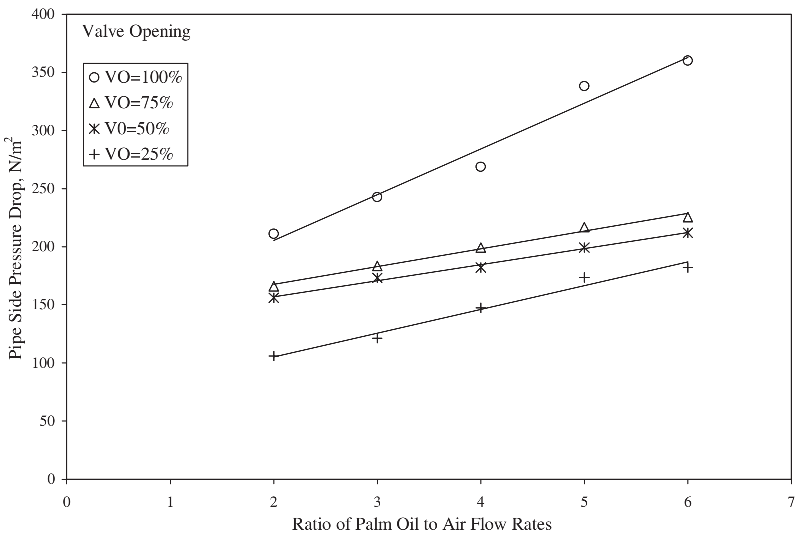

Fig. 5. Effect of pressure drop in pipeline for different valve opening at air flow rate of 25 lph.

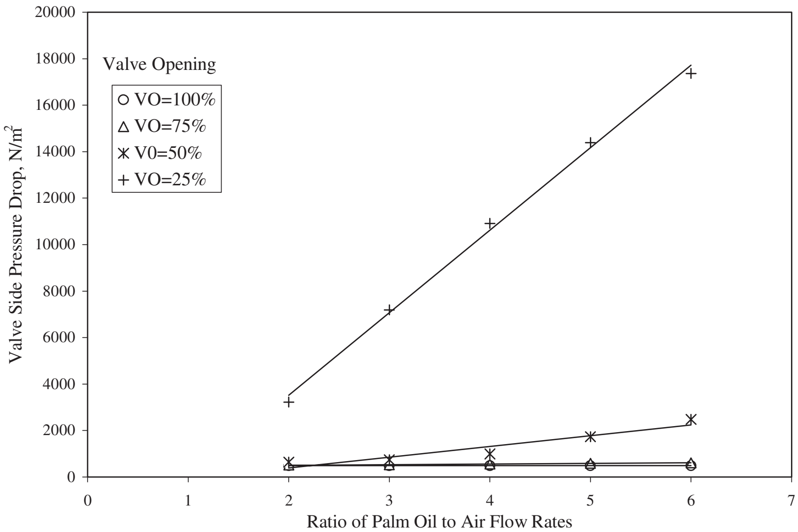

Fig. 6. Effect of pressure drop in valve section for different valve opening at air flow rate of 25 lph.

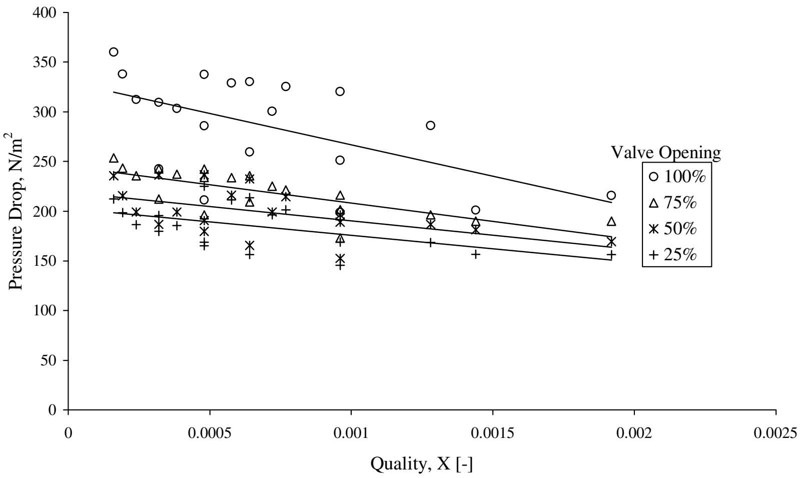

Fig. 7. Two-phase pressure drop vs quality for pipe section.

the valve is 23.56 kN/m^2 at the same quality. The variation of pressure drop with quality, X is in agreement with literature [17].

3.4. Two-phase multiplier vs quality X [7]

Another relationship useful in two-phase studies is the two-phase multiplier for

$$\phi_a = \frac{(dp/dz)_{TPf}}{(dp/dz)_a} \tag{7a}$$

$$\phi_l = \frac{(dp/dz)_{TPf}}{(dp/dz)_l} \tag{7b}$$

correlating the pressure drop and quality. The two-phase multiplier is defined as the ratio of pressure drop with two-phase flow and pressure drop with single phase either gas or liquid and is given by the Eq. (7).

The pressure drop with single phase in the denominator of Eq. (7) can be estimated using friction factor, f and velocity, V_a or V_l as given by Eq. (8).

$$\left(\frac{dp}{dz}\right)_l = 2f_l\rho_l V_l^2/D \tag{8a}$$

$$\left(\frac{dp}{dz}\right)_a = 2f_a\rho_a V_a^2/D \tag{8b}$$

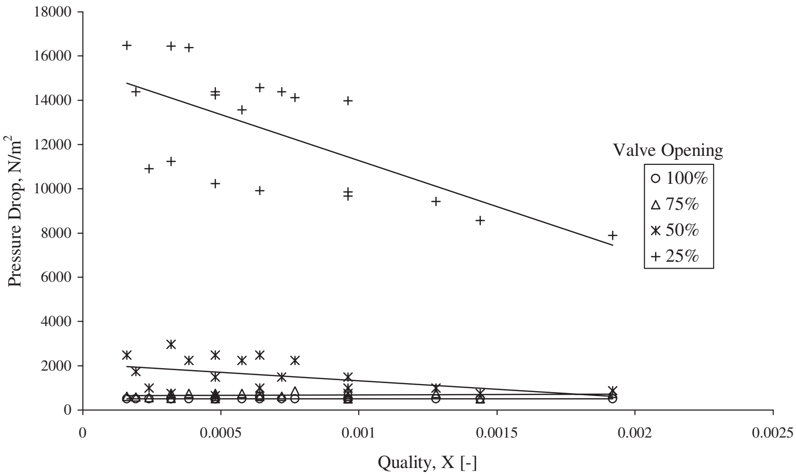

Fig. 8. Two-phase pressure drop vs quality for valve section.

Here ϕ_l is two-phase multiplier based on liquid, which can be palm oil (in the present case) or can be any other liquid under study. In this study ϕ_l is related to the quality for the two-phase system in pipe section and valve section. The ϕ_l observed experimentally are plotted against quality and shown in Figs. 9 and 10. The two-phase multiplier increases with quality for both pipe section and valve section and in agreement with literature [17].

3.5. Relation between two phase multiplier and Lockhart–Martinelli (L–M) parameter

A method of predicting pressure drop in two-phase flow from the studies on one of the single phase has been suggested [15] in terms of L–M parameter χ_{tt} defined by Eqs. (9) and (10).

$$\chi_{tt}^2 = \left[\frac{(1-X)}{X}\right]^{2-m}\left(\frac{\rho_a}{\rho_l}\right)\left(\frac{\mu_l}{\mu_a}\right)^m \tag{9}$$

where "m" is the value obtained for single phase flow from the relation $f = aNRe^m$. The two-phase multiplier ϕ_l is related to L–M parameters by the Eq. (10):

$$\phi_l^2 = \frac{\Delta P_{TPf}}{\Delta P_l} = 1 + \frac{C}{\chi_{tt}} + \frac{1}{\chi_{tt}^2} \tag{10}$$

Grant and coworkers [8,9,13] have reported a value of 8 for 'C' for $\chi_{tt} < 0.2$ for their study with good results. For $\chi_{tt} > 0.2$, the ΔP_{TPf} predicted from single-phase flow, the results with $C = 8$ are not satisfactory. Figs. 11 and 12 presents ϕ_l vs χ_{tt} graphically for both pipe section and valve section respectively. The two-phase multiplier is observed to decrease with increase in Lockart–Maritinelli parameter (χ_{tt}).

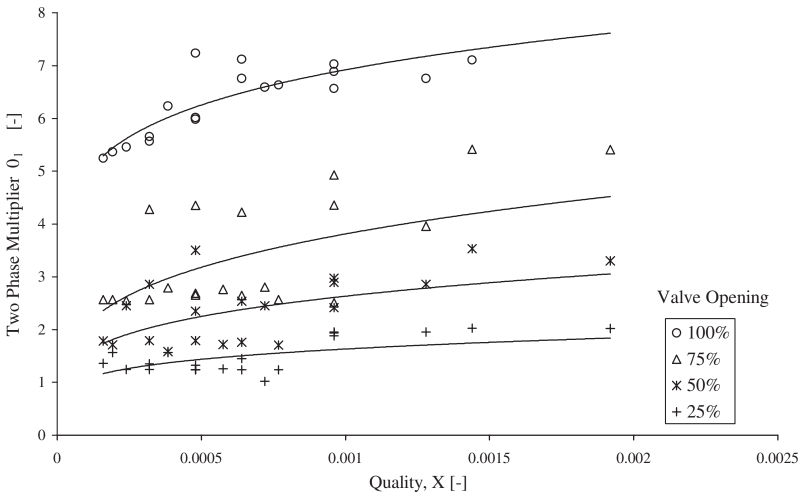

Fig. 9. Two-phase multiplier vs quality for pipe section (palm oil).

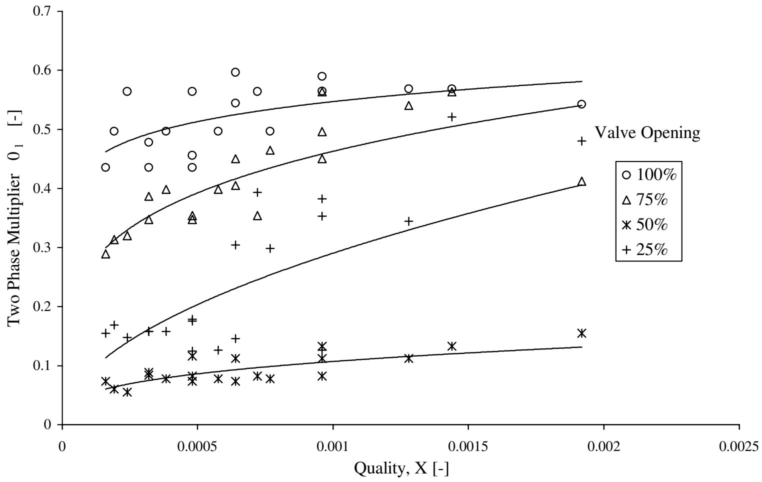

Fig. 10. Two-phase multiplier vs quality for valve section.

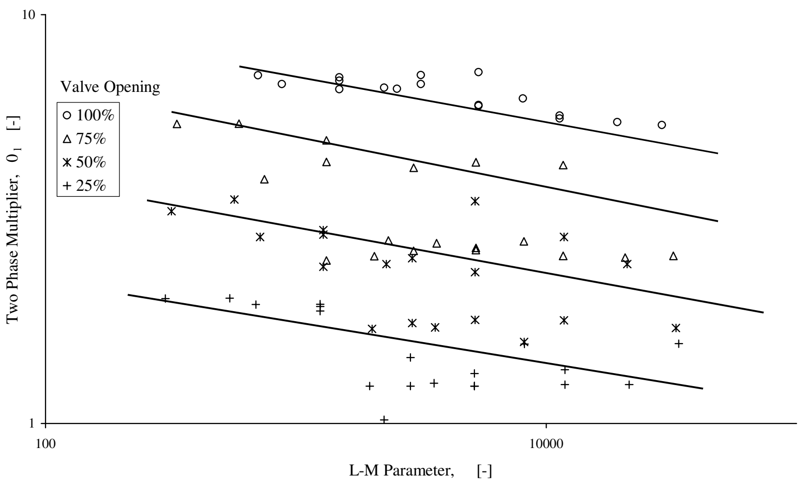

Fig. 11. Variation of two-phase multiplier vs L–M parameter for pipe section.

The relationship given by Eq. (10) is fitted by regression analysis and the value of '*C*' is estimated and given in Table 3 for pipe section and valve section. The "*C*" values are different for both pipe section and valve section. The correlation coefficient for the parameter '*C*' is found to be 0.89.

Thus the two-phase multiplier can be used to predict the pressure drop across control valve section for different fractions of gas–liquid system.

3.6. Valve characteristics

The installed characteristics of the valve are the plots for fraction of maximum flow rate vs the fraction of valve opening at different pressure drop across the control valve. These plots are useful to determine the suitability of the valve under study and generally used in the selection of the type of valve during the process design.

Using the correlations, the installed characteristics of the control valve with two-phase flow are estimated and are shown in Figs. 13 and 14. Fig. 13 shows the characteristics at constant quality of 0.5. This figure is helpful in identifying the operability or gain of the valve at given conditions.

Similarly, Fig. 14 shows the characteristics at constant pressure drop of 600 Pa for different quality of the two-phase system. This plot is helpful to identify the operating region of quality range for which the valve is suitable under given conditions.

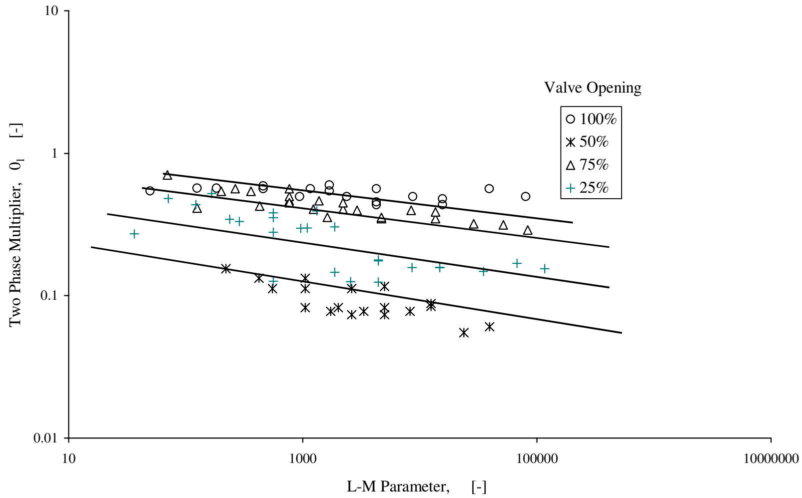

Fig. 12. Variation of two-phase multiplier vs L–M parameter for valve section.

Table 3
Values of C used in Eq. (10) for pipe section and valve section

Valve opening (%)	Pipe section	Valve section
25	120	1
50	120	1
75	75	1
100	75	1

From both Figs. 13 and 14, it can be concluded that maximum permissible ΔP for the valve for full range applicability is 600 Pa and for a quality of 0.2.

4. Conclusions

Two-phase flow through control valve in series with pipe has been studied for different quality of two-phase system. Pressure drop has been related to quality. However, the two-phase multiplier and L–M parameter correlation is found to be in good agreement with the results. The installed characteristics of the valve are represented for different quality and pressure drop. The study has been specific to the experimental set-up used in this work. The correlations especially between two-phase multiplier based on liquid phase and L–M parameter will be useful in design of process piping and control valves for two-phase flow. The study enables one to predict the required pressure drop information from the data with single-phase flow through pipe/valve. The valve used being an equal percentage valve, the data can be extended to other types of valves such as linear and quick opening by appropriate definition of equivalent diameter for valve opening. The valve characteristics in terms of pressure drop and quality clearly

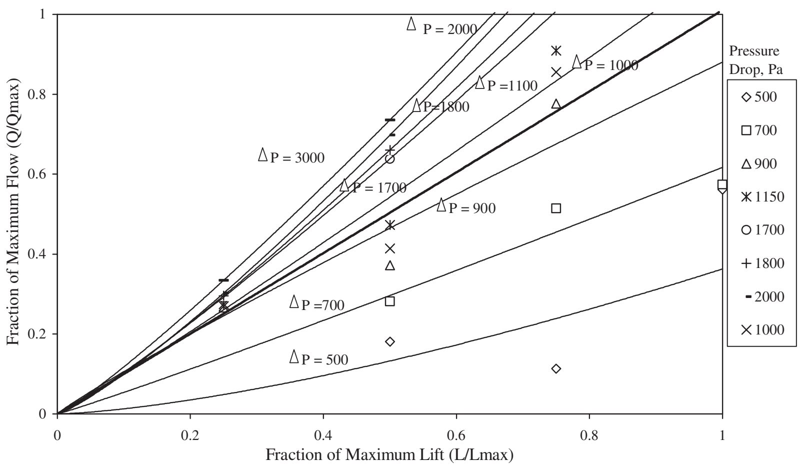

Fig. 13. Valve characteristics at constant quality of 0.5.

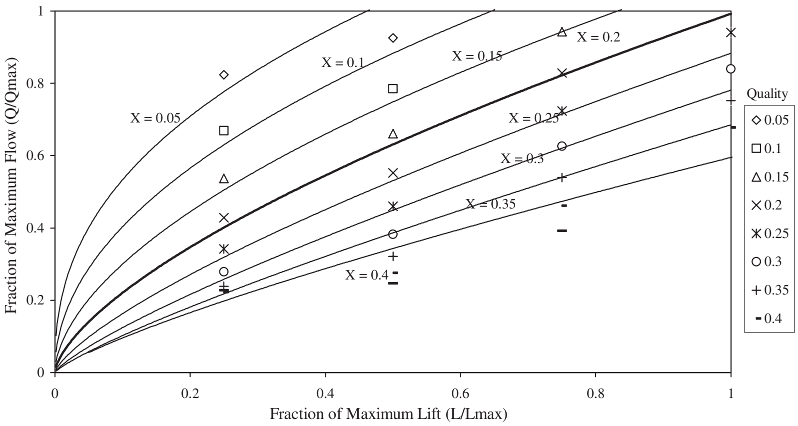

Fig. 14. Valve characteristics at constant pressure drop of 600 Pa.

indicates the maximum value, which the specific control valve can accommodate for proper utilization of the valve. These correlations can be tried for other types and size of valves also and their useful range can be established. In this study, a straight pipe was used in the upstream of the control valve. Further work in this area using coiled pipes before and /or after the control valve is being carried out to assess their effect on the valve characteristics.

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