Int J Multiphase Flow Vol 18, No. 1, pp 149–155, 1992
Printed in Great Britain

0301-9322/92 $5.00 + 0.00

BRIEF COMMUNICATION

AN INVESTIGATION OF TWO-PHASE FLOW MEASUREMENT WITH ORIFICES FOR LOW-QUALITY MIXTURES

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(Received 1 September 1990, in revised form 1 August 1991)

1. INTRODUCTION

Measurement of gas–liquid two-phase flow rates is of interest in many fields of engineering, such as chemical, geothermal engineering, petroleum, power and nuclear energy. Although many methods, including ultrasonic waves, laser techniques, radiation etc., have been studied (Hewitt 1978; Reimann 1982), measurement of two-phase flow rates via orifices has received increasing attention in the last three decades. Numerous orifice equations for gas–liquid mixtures have been developed and some typical equations were proposed by Murdock (1962), James (1965), Chisholm (1967, 1974), Smith & Leang (1975) and Lin (1982). These equations can mostly be described by the following equation:

$$G = \frac{CYAFa}{\sqrt{1-\beta^4}} K_G \sqrt{2\,\Delta P_{TP}\rho_G}, \qquad [1]$$

where G is the mass flow rate of the gas–liquid mixture, C is the orifice discharge coefficient, Y is the compressibility coefficient of the fluid, A is the orifice flow area, Fa is the orifice thermal expansion factor, β is the ratio of the orifice diameter to the internal pipe diameter, ΔP_{TP} is the pressure drop across the orifice for the two-phase mixture, ρ_G is the density of the gas phase and K_G is called the gas phase modified coefficient, which is dependent mainly on quality and the gas–liquid density ratio, and has several different forms (proposed by different authors). Murdock (1962) employed a separated flow model and derived the following two-phase correlation equation:

$$K_G = \frac{1}{\chi + 1.26(1-\chi)\dfrac{C_G Y_G}{C_L}\sqrt{\dfrac{\rho_G}{\rho_L}}}, \qquad [2]$$

where C_G and C_L are the orifice discharge coefficients for gas and liquid, respectively, Y_G is the compressibility coefficient of the gas phase and χ is the quality.

James (1965) used an effective mixture density to modify a homogeneous model, resulting in the expression

$$K_G = \sqrt{\frac{1}{\chi^{1.5}\left(1-\dfrac{\rho_G}{\rho_L}\right)+\dfrac{\rho_G}{\rho_L}}}. \qquad [3]$$

Other authors proposed different modified two-phase correlation equations based on either the separated flow model or the homogeneous flow model. But in previous works, almost all orifice equations were derived from experiments with quality $\chi > 1\%$. Some equations cannot be used particularly well and others become invalid at low quality—see Murdock's (1962) equation [2]. But low quality is widespread if the ratio of gas density to liquid density is small, even though the void fraction ϵ is large. For this reason, our work is aimed at the measurement of two-phase flow with sharp-edged orifices for low quality. The experiments were made with an air–water flow system in the quality range 0.007–1%.

2. THEORY

For low-quality gas–liquid two-phase flow, the orifice equation for metering the mass flow rate has the following form (Zhang 1985):

$$G = \frac{C_{\mathrm{TP}} Y_{\mathrm{TP}} A F a}{\sqrt{1-\beta^4}} K_{\mathrm{L}} \sqrt{2\,\Delta P_{\mathrm{TP}} \rho_{\mathrm{L}}}, \qquad [4]$$

where Y_{TP} is the compressibility coefficient of the two-phase mixture and K_{L} is the liquid modified coefficient. Note that in the above equation the liquid orifice discharge coefficient C_{L} can be used to replace the two-phase mixture orifice discharge coefficient C_{TP} if the Reynolds number for the liquid phase $\mathrm{Re_L}$ is greater than the critical Reynolds number Re_k (Matter *et al.* 1979). But the compressibility coefficient Y_{TP} will be different from the gas and liquid compressibility coefficients Y_{G} and Y_{L} for most cases. A simple theoretical equation for calculating Y_{TP}, proposed by Zhang (1985), is as follows:

$$Y_{\mathrm{TP}} = Y_{\mathrm{L}}(1-\epsilon) + Y_{\mathrm{G}}\epsilon, \qquad [5]$$

where ϵ is the void fraction. Because $Y_{\mathrm{L}} = 1$, [5] becomes

$$Y_{\mathrm{TP}} = 1 - \epsilon + \epsilon Y_{\mathrm{G}}. \qquad [6]$$

It is rather difficult to obtain a simple relationship for the modified coefficient K_{L} from a theoretical analysis, so K_{L} will be determined experimentally. It is thought that K_{L} is a function of the density ratio $\rho_{\mathrm{G}}/\rho_{\mathrm{L}}$ and of void fraction or quality, but for low quality it is better to use the void fraction as a parameter in the modified coefficient K_{L} instead of normal quality, because in such a range of quality the void fraction will increase or decrease significantly with a small change in quality.

3. EXPERIMENTAL APPARATUS AND RESULTS

Experiments were carried out in a two-phase flow measurement apparatus, as shown in figure 1. Air and water were used as the gas and liquid phases, respectively. Before they were mixed, air and water flow rates were measured individually. The test gas mass velocity ranged from 0.9 to 9.1 $\mathrm{kg/m^2 \cdot s}$ with the liquid mass velocity from 840 to 1648 $\mathrm{kg/m^2 \cdot s}$, while the quality ranged from 0.007 to 1%. The sharp-edged orifices used for the tests were mounted on a horizontal pipe with i.d. = 50.8 mm. The diameters of the orifices were 25.36 and 21.42 mm, with a diameter ratio of $\beta = 0.499$ and $\beta = 0.422$, respectively. The pressure taps on each orifice were standard corner taps with carrier rings. Before the tests the orifices were carefully calibrated with single-phase water. During the tests the total mass flow rates and quality were obtained from the readings of the gas and liquid flowmeters. Void fraction was measured by two quick-closing valves which were installed

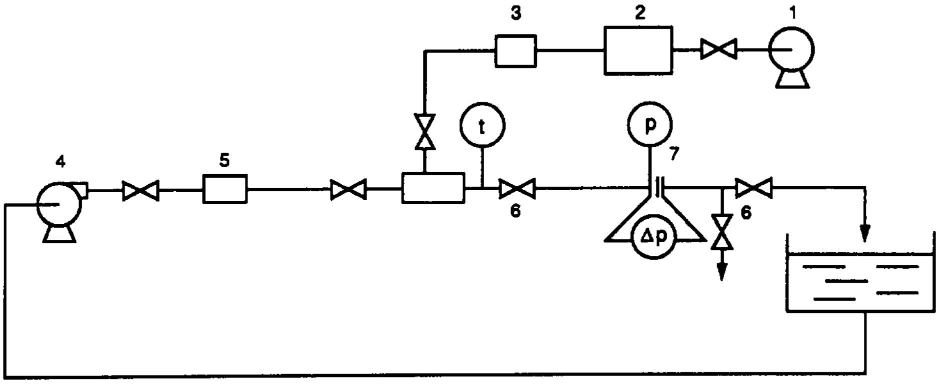


Figure 1. Schematic diagram of the experimental apparatus: 1, compressor; 2, filter; 3, gas flowmeter; 4, pump; 5, liquid flowmeter, 6, quick-closing valves; 7, orifice

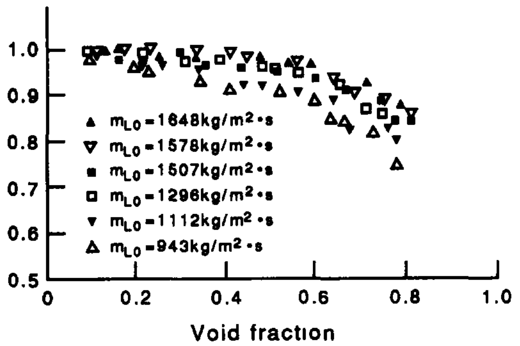


Figure 2 Experimental values of K_L vs void fraction for $\beta = 0.499$

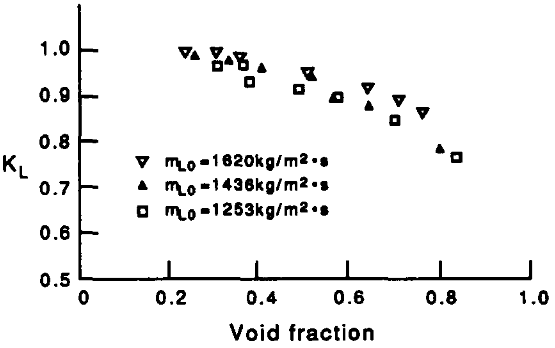


Figure 3. Experimental values of K_L vs void fraction for $\beta = 0.422$.

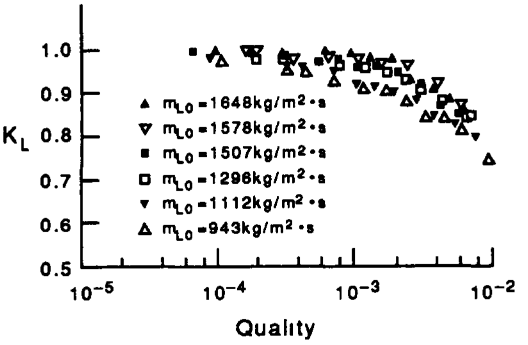


Figure 4 Experimental values of K_L vs quality for $\beta = 0.499$

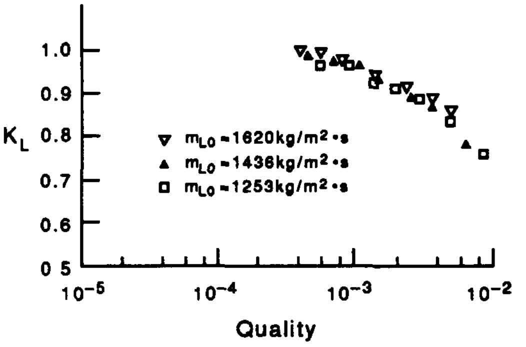


Figure 5 Experimental values of K_L vs quality for $\beta = 0.422$.

on the two sides of the sharp-edged orifice. A pressure gauge was installed before the orifice to indicate the pressure of the two-phase flow. If ΔP_{TP} is measured by a differential pressure transmitter connected to the orifice, K_L can be calculated from [4]. Since the tests were performed at normal temperature, the orifice thermal expansion factor *Fa* is unity and the water density is about 998 kg/m^3. All the experimental data are summarized in table 1. Figures 2 and 3 show the experimental values of K_L vs void fraction, and figures 4 and 5 are the experimental values of K_L vs quality. In figures 2–5, m_{L0} is the liquid mass flow rate per unit area when the gas flow rate is zero; with an increase in the gas flow rate the liquid flow rate will decrease, because the position of the valve for controlling the liquid phase flow rate has not changed.

4. COMPARISON WITH RESULTS FROM PREVIOUS WORK

Because Murdock's (1962) correlation equation for two-phase flow does not apply at low quality, comparisons can only be made with the homogeneous flow model and the James model here. For the homogeneous flow model, the theoretical equation for the liquid phase modified coefficient K_L is as follows:

$$K_L = \sqrt{\frac{1}{\chi^n\left(\frac{\rho_L}{\rho_G} - 1\right) + 1}}, \qquad [7]$$

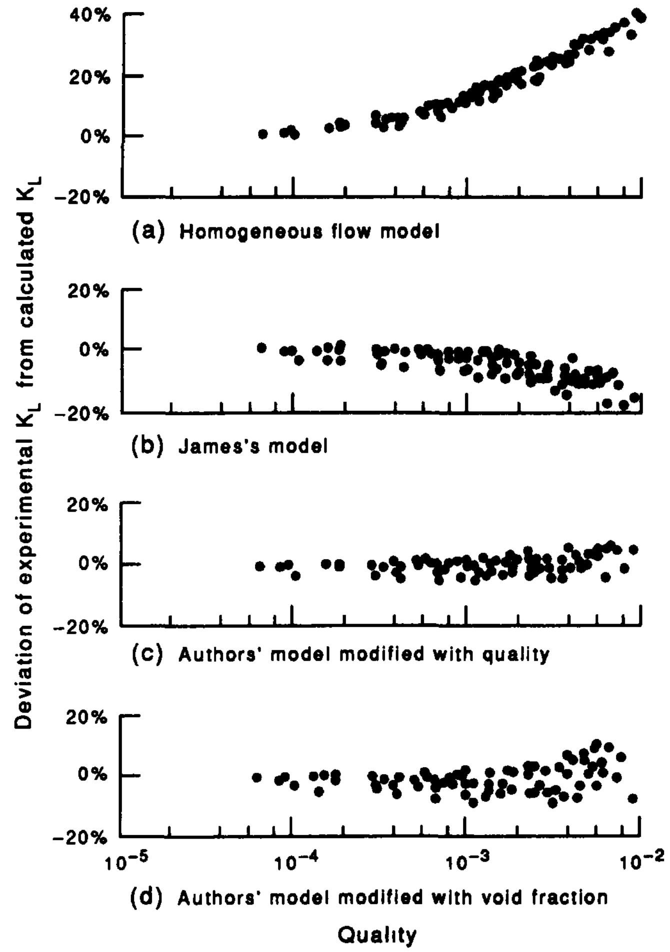
where $n = 1$. Substituting experimental data for χ, ρ_G and ρ_L into [7], the theoretical K_L can be obtained. The errors between the actual K_L and the K_L value calculated from [7] are shown in figure 6(a). Figure 6(a) shows that the actual values are greater than the calculated values and the errors increase with increasing quality.

For the James (1965) model, the equation for K_L is the same as [7], but $n = 1.5$. The deviation of actual K_L values from those given by [7] is shown in figure 6(b). It is seen from the figure that most data are negative, which means that the actual K_L is less than the calculated K_L. It is also found that the absolute errors are less than those for the homogeneous model.

Table 1. Test results

No.	d (mm)	D (mm)	β	P_1 (MPa)	t (°C)	ρ_G (kg/m^3)	G_L (kg/s)	G_G (kg/s)	χ (%)	ϵ	Δp_{TP} (kPa)	Y_G	Y_{TP}	α_L	K_L	G (kg/s)
1	25.36	50.8	0.499	0.231	30	2.44	3.2361	0.0003	0.0095	0.104	52.84	0.925	0.992	0.631	0.997	3.2364
2				0.235	30	2.49	3.2250	0.0006	0.0186	0.170	53.48	0.925	0.987	0.631	0.993	3.2256
3				0.238	30	2.52	3.2222	0.0010	0.0310	0.231	53.48	0.925	0.983	0.631	0.997	3.2232
4				0.242	30	2.56	3.2056	0.0020	0.0624	0.336	53.84	0.926	0.975	0.631	0.997	3.2076
5				0.243	30	2.57	3.1778	0.0030	0.0943	0.405	54.06	0.926	0.970	0.631	0.991	3.1808
6				0.247	30	2.62	3.1444	0.0041	0.1302	0.441	54.28	0.926	0.967	0.631	0.982	3.1468
7				0.250	30	2.65	3.1222	0.0059	0.1886	0.551	55.75	0.925	0.959	0.631	0.971	3.1281
8				0.255	30	2.70	2.9861	0.0079	0.2639	0.637	55.54	0.927	0.953	0.631	0.937	2.9940
9				0.265	30	2.82	2.8833	0.0108	0.3732	0.681	55.60	0.928	0.951	0.631	0.907	2.8971
10				0.275	30	2.93	2.7972	0.0143	0.5086	0.749	54.87	0.930	0.948	0.631	0.890	2.8115
11				0.292	30	3.12	2.7500	0.0163	0.5892	0.801	57.45	0.932	0.943	0.631	0.860	2.7663
12				0.231	31	2.45	3.1139	0.0005	0.0161	0.126	48.84	0.930	0.991	0.631	0.999	3.1144
13				0.228	31	2.42	3.1028	0.0006	0.0193	0.154	48.62	0.930	0.989	0.631	1.000	3.1034
14				0.230	31	2.44	3.0250	0.0011	0.0363	0.248	48.84	0.930	0.983	0.631	0.983	3.0261
15				0.232	31	2.46	3.0194	0.0020	0.0662	0.330	48.47	0.930	0.977	0.631	0.987	3.0214
16				0.237	31	2.52	2.9778	0.0032	0.1073	0.476	48.40	0.932	0.968	0.631	0.984	2.9810
17				0.240	31	2.55	2.9361	0.0045	0.1530	0.536	48.84	0.932	0.964	0.631	0.971	2.9406
18				0.245	31	2.61	2.9194	0.0071	0.2426	0.586	48.92	0.933	0.961	0.631	0.968	2.9425
19				0.257	31	2.74	2.8250	0.0113	0.3984	0.705	50.75	0.933	0.953	0.631	0.929	2.8363
20				0.273	31	2.91	2.6972	0.0169	0.5860	0.779	52.15	0.935	0.949	0.631	0.880	2.7131
21				0.216	35	2.26	2.9694	0.0002	0.0067	0.086	44.36	0.932	0.994	0.631	0.997	2.9696
22				0.223	29	2.39	2.9222	0.0009	0.0308	0.204	44.13	0.933	0.986	0.631	0.992	2.9231
23				0.226	29	2.42	2.8972	0.0016	0.0552	0.305	45.23	0.933	0.980	0.631	0.978	2.8988
24				0.228	29	2.44	2.8722	0.0021	0.0731	0.382	44.50	0.933	0.974	0.631	0.983	2.8743
25				0.230	29	2.47	2.8361	0.0030	0.1057	0.467	45.53	0.933	0.969	0.631	0.965	2.8391
26				0.231	29	2.48	2.8167	0.0041	0.1453	0.501	45.53	0.933	0.966	0.631	0.961	2.8208
27				0.239	29	2.57	2.7944	0.0057	0.2036	0.559	45.97	0.935	0.964	0.631	0.953	2.8001
28				0.245	29	2.63	2.7361	0.0082	0.2988	0.649	47.44	0.934	0.957	0.631	0.975	2.7443
29				0.250	29	2.68	2.6278	0.0107	0.4055	0.707	49.65	0.933	0.953	0.632	0.872	2.6355
30				0.255	29	2.73	2.5944	0.0148	0.5672	0.746	50.38	0.933	0.950	0.632	0.859	2.6092
31				0.203	35	2.15	2.5972	0.0005	0.0192	0.155	35.16	0.941	0.991	0.631	0.983	2.5977
32				0.208	30	2.25	2.5972	0.0008	0.0308	0.206	35.38	0.941	0.988	0.631	0.983	2.5980
33				0.211	30	2.28	2.5833	0.0014	0.0542	0.296	35.68	0.941	0.983	0.632	0.977	2.5947
34				0.216	30	2.33	2.5444	0.0020	0.0785	0.347	35.68	0.943	0.980	0.632	0.965	2.5464
35				0.218	30	2.35	2.5444	0.0030	0.1182	0.429	36.12	0.943	0.976	0.632	0.961	2.5391
36				0.221	30	2.39	2.5025	0.0043	0.1715	0.507	36.41	0.943	0.971	0.632	0.950	2.5071
37				0.228	30	2.47	2.4667	0.0059	0.2386	0.597	36.63	0.944	0.967	0.632	0.938	2.4726
38				0.233	30	2.53	2.4333	0.0074	0.3032	0.664	37.88	0.944	0.963	0.632	0.914	2.4407
39				0.242	30	2.63	2.3639	0.0104	0.4380	0.742	38.62	0.944	0.958	0.632	0.885	2.3743

40				0.251	30	2.72	2.2944	0.0148	0.6409	0.766	40.09	0.944	0.957	0.632	0.846	2.3092
41				0.251	35	2.68	2.2944	0.0159	0.6882	0.801	40.01	0.944	0.955	0.632	0.849	2.3103
42				0.185	35	1.99	2.2528	0.0002	0.0089	0.110	35.62	0.953	0.995	0.633	0.988	2.2530
43				0.194	30	2.13	2.1722	0.0007	0.0322	0.212	25.37	0.955	0.990	0.633	0.965	2.2530
44				0.194	30	2.13	2.1750	0.0009	0.0414	0.257	25.45	0.955	0.988	0.633	0.967	2.1759
45				0.201	30	2.21	2.1389	0.0015	0.0701	0.337	25.38	0.957	0.986	0.633	0.955	2.1404
46				0.203	30	2.22	2.1194	0.0022	0.1037	0.433	27.00	0.955	0.981	0.633	0.923	2.1216
47				0.206	30	2.26	2.1278	0.0030	0.1408	0.472	27.51	0.955	0.979	0.633	0.920	2.1308
48				0.206	30	2.25	2.1028	0.0040	0.1899	0.559	27.80	0.954	0.974	0.633	0.909	2.1068
49				0.211	30	2.31	2.0750	0.0059	0.2835	0.634	28.63	0.954	0.971	0.633	0.888	2.0809
50				0.216	30	2.35	2.0333	0.0077	0.3773	0.669	30.28	0.951	0.967	0.633	0.850	2.0410
51				0.228	30	2.49	1.9917	0.0109	0.5443	0.753	30.30	0.955	0.966	0.633	0.836	2.0026
52				0.228	30	2.50	1.9194	0.0148	0.7652	0.768	30.53	0.955	0.965	0.634	0.802	1.9342
53				0.179	35	1.96	1.8583	0.0002	0.0108	0.096	18.02	0.956	0.997	0.634	0.972	1.8585
54				0.184	35	2.01	1.8306	0.0006	0.0328	0.192	18.09	0.966	0.993	0.634	0.959	1.8312
55				0.188	32	2.08	1.8056	0.0008	0.0433	0.225	18.02	0.967	0.993	0.634	0.948	1.8064
56				0.193	32	2.13	1.7944	0.0013	0.0724	0.343	18.76	0.967	0.989	0.634	0.929	1.7957
57				0.193	32	2.13	1.7917	0.0021	0.1171	0.404	19.50	0.966	0.986	0.634	0.911	1.7938
58				0.194	32	2.14	1.7750	0.0030	0.1687	0.520	19.42	0.966	0.982	0.634	0.909	1.7780
59				0.196	32	2.16	1.7778	0.0043	0.2413	0.596	20.74	0.965	0.979	0.634	0.884	1.7821
60				0.198	32	2.17	1.7361	0.0058	0.3330	0.632	21.70	0.963	0.977	0.635	0.846	1.7419
61				0.203	32	2.23	1.7000	0.0079	0.4626	0.662	21.26	0.955	0.070	0.635	0.843	1.7079
62				0.211	32	2.31	1.7278	0.0104	0.5983	0.726	23.17	0.963	0.973	0.635	0.820	1.7382
63				0.216	32	2.36	1.6556	0.0159	0.9512	0.774	26.11	0.958	0.967	0.635	0.747	1.6715
64	21.42	50.8	0.422	0.294	21	2.96	3.2472	0.0013	0.0400	0.240	111.99	0.878	0.971	0.623	0.998	3.2485
65				0.289	21	2.90	3.2250	0.0018	0.0558	0.304	113.36	0.870	0.060	0.623	0.996	3.2268
66				0.294	21	2.91	3.2639	0.0027	0.0827	0.357	122.19	0.863	0.951	0.623	0.981	3.2666
67				0.299	21	2.93	3.1806	0.0045	0.1413	0.505	130.62	0.860	0.929	0.623	0.946	3.1851
68				0.304	21	2.95	3.0806	0.0075	0.2429	0.641	137.69	0.856	0.908	0.623	0.915	3.0881
69				0.314	21	3.07	2.9639	0.0109	0.3664	0.710	137.69	0.860	0.901	0.623	0.888	2.9748
70				0.324	21	3.07	2.8639	0.0145	0.5037	0.759	137.69	0.860	0.894	0.623	0.866	2.8784
71				0.260	21	2.66	2.8472	0.0013	0.0456	0.259	88.26	0.888	0.971	0.623	0.985	2.8485
72				0.260	21	2.66	2.8056	0.0020	0.0712	0.332	89.24	0.887	0.962	0.623	0.974	2.8076
73				0.260	21	2.65	2.7583	0.0030	0.1086	0.407	90.42	0.887	0.954	0.623	0.961	2.7613
74				0.265	21	2.68	2.7222	0.0041	0.1504	0.519	96.30	0.882	0.939	0.623	0.934	2.7263
75				0.270	21	2.73	2.6139	0.0068	0.2595	0.569	97.87	0.882	0.933	0.623	0.896	2.6207
76				0.278	21	2.81	2.5472	0.0093	0.3638	0.641	100.62	0.882	0.924	0.623	0.870	2.5565
77				0.287	21	2.95	2.3500	0.0152	0.6435	0.799	109.25	0.879	0.908	0.623	0.786	2.3652
78				0.240	21	2.51	2.5000	0.0014	0.0560	0.310	71.20	0.902	0.970	0.623	0.965	2.5014
79				0.245	21	2.57	2.5000	0.0023	0.0919	0.363	71.98	0.902	0.964	0.623	0.965	2.5023
80				0.245	21	2.56	2.4583	0.0034	0.1381	0.381	76.49	0.899	0.962	0.623	0.924	2.4617
81				0.250	21	2.59	2.4528	0.0049	0.1994	0.490	79.24	0.900	0.951	0.623	0.916	2.4577
82				0.260	21	2.70	2.3972	0.0074	0.3077	0.584	81.59	0.899	0.941	0.623	0.893	2.4046
83				0.270	21	2.79	2.3056	0.0113	0.4877	0.700	86.89	0.897	0.928	0.623	0.845	2.3169
84				0.279	21	2.88	2.1000	0.0179	0.8452	0.837	91.40	0.895	0.915	0.623	0.764	2.1179



(a) Homogeneous flow model

(b) James's model

(c) Authors' model modified with quality

(d) Authors' model modified with void fraction

Figure 6 Deviation of experimental K_L values from those from different models.

5. NEW EQUATIONS

Because most errors between actual and calculated K_L values are greater than zero for the homogeneous flow model, but less than zero for the James (1965) model, it is thought that [7] may be appropriate for two-phase flow with n being from 1 to 1.5. Using the experimental data shown in table 1, n is found to be

$$n = 1.25 + 0.25\sqrt[3]{\chi}. \qquad [8]$$

When χ approaches unity, $n = 1.5$, i.e. it becomes the same as the James model. If [8] is used to calculate K_L, we find it is quite close to the experimental K_L shown in figure 6(c).

If the void fraction is employed as a parameter in the modified coefficient K_L then, from the homogeneous flow model, the theoretical equation is

$$K_L = \sqrt{\epsilon^{n_\epsilon}\left(\frac{\rho_G}{\rho_L} - 1\right) + 1}\,, \qquad [9]$$

where $n_\epsilon = 1$. But this equation has significant errors compared with the experimental data. To fit the data, the method of least squares was used and we obtained $n_\epsilon = 4$. Figure 6(d) shows the differences between the actual K_L values and those calculated from [9].

6. DISCUSSION AND CONCLUSIONS

For a gas–liquid mixture of low quality, the two-phase flow rate can be measured with sharp-edged orifices. If the quality is used to modify the orifice equation, then the total mass flow rate of the two-phase mixture can be calculated using the following equation:

$$G = \frac{C_{\mathrm{L}} Y_{\mathrm{TP}} A F a}{\sqrt{1-\beta^4}} \sqrt{\frac{2\,\Delta P_{\mathrm{TP}} \rho_{\mathrm{L}}}{\chi^n\left(\dfrac{\rho_{\mathrm{L}}}{\rho_{\mathrm{G}}} - 1\right) + 1}}, \tag{10}$$

where $n = 1.25 + 0.25\sqrt[3]{\chi}$.

The orifice equation for the single-phase flow rate may be modified using the void fraction when the quality of the mixture is low, because under these conditions the void fraction will change more sharply than the quality and have greater values. Introducing void fraction, the modified orifice equation becomes

$$G = \frac{C_{\mathrm{L}} Y_{\mathrm{TP}} A F a}{\sqrt{1-\beta^4}} \sqrt{2\,\Delta P_{\mathrm{TP}} \rho_{\mathrm{L}}\left[\epsilon^4\left(\frac{\rho_{\mathrm{G}}}{\rho_{\mathrm{L}}} - 1\right) + 1\right]}. \tag{11}$$

Although the deviation of experimental K_{L} values from those calculated by [9] is not sufficiently small [see figure 6(d)], [9] is very useful for low quality. If the void fraction is estimated, the liquid modified coefficient may be evaluated quickly. Moreover, for $\epsilon \leqslant 0.5$, then from [9] we get $K_{\mathrm{L}} \leqslant 0.96$, which means that there is no significant difference between the modified orifice equation for the two-phase flow rate and the common orifice equation for the single-phase liquid flow rate. Furthermore, if the compressibility coefficient Y_{TP} is considered, we can expect that the maximum error in the mass flow rate will be within 10% if the orifice equation of single-phase liquid flow is used to measure the two-phase mass flow rate, because for most cases the compressibility coefficient is <0.95.

The above conclusions are derived from experiments with an air–water two-phase flow system. To contain their general validity additional experiments with different two-phase mixtures, pipe diameters and density ratios are required. However, the present work may be instructive in the further study of the measurement of gas–liquid mixture at low quality.

REFERENCES

CHISHOLM, D. 1967 Pressure gradients during the flow of an incompressible two-phase mixture through pipes, venturis and orifice plates. *Br. Chem. Engng* **12,** 454–457.

CHISHOLM, D. 1974 Pressure drop during steam/water flows through orifices. *J. Mech. Engng Sci.* **16,** 353–355.

HEWITT, G. F. 1978 *Measurements of Two-phase Parameters.* Academic Press, London.

JAMES, R. 1965 Metering of steam–water two-phase flow by sharp-edged orifices. *Proc. Inst Mech. Engrs* **180,** 549–566.

LIN, Z. H. 1982 Two-phase flow measurements with sharp-edged orifices. *Int. J. Multiphase Flow* **8,** 683–693.

MATTER, L., NICHOLSON, M., AZIZ, K. & GREGORY, G. A. 1979 Orifice metering of two-phase flow. *J. Petrol. Technol.* **31,** 955–961.

MURDOCK, J. W. 1962 Two-phase flow measurements with orifices. *J. Bas. Engng* **84,** 419–433.

REIMANN, J. 1982 Developments in two-phase mass flow rate instrumentation. In *Advances in Two-phase Flow and Heat Mass Transfer; Proceedings of the NATO Advanced Research Workshop on the Advances in Two-phase Flow and Heat Transfer,* pp. 339–402.

SMITH, R. V. & LEANG, J. T. 1975 Evaluations of correlations for two-phase flowmeters three current–one new. *ASME Ser. A* **97,** 589–593.

ZHANG, H. J. 1985 Measurement of gas–liquid two-phase flow with the differential pressure method. M.Sc. Thesis, Zhejiang Univ., Hangzhou, P.R.C.