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Technical Note

PRESSURE LOSS DURING AIR/WATER MIST FLOW ACROSS A STAGGERED BANK OF TUBES

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1. Introduction

This paper reports on measurements of pressure loss during air/water mist flow across a staggered bank of tubes. These measurements have relevance to the pressure losses occurring within cross-flow condensers [1], air conditioning coils where the surface temperature falls below the dew point [2] and certain types of evaporatively cooled heat exchanger [3, 4].

2. Apparatus

A wind tunnel was used to provide a controllable flow of air to a test section. Water, atomized in compressed air operated nozzles, was injected upstream of the test section to produce mist flow. The temperature and flow-rate of the water feed to the nozzles were accurately measured and could be controlled and adjusted as required. The wind tunnel was arranged in open circuit with the two-phase mixture exhausted to atmosphere, and was instrumented to enable air mass flowrates, temperatures and other parameters to be determined.

The test section was a bank of forty-nine tubes, seven rows deep, arranged in staggered 1½ × diameter, equilateral pitching as shown in Fig. 1.

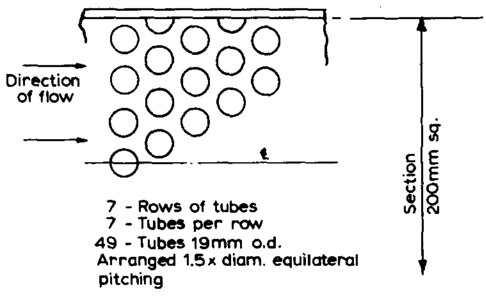

Fig. 1. Arrangement of tube bank.

3. Tests with single-phase flow

Prior to the tests with two-phase flow, the pressure loss across the test section was measured during single-phase (air) flow. Friction factors calculated from the measured data over the Reynolds number range 10^4 to 10^5 are shown on Fig. 2. Also shown on this figure are correlations obtained by Kays and Lo [5] and Grimison [6]. Our experimental data are in good agreement with the Kays and Lo correlation up to a Reynolds number of 3×10^4 and agree within 14% when the correlation is extrapolated to a Reynolds number of 10^5. The Grimison correlation is about 20% higher than the values given here at a Reynolds number of 10^4 but agreement improves considerably with increase in Reynolds number. The friction factor as used in Fig. 2 is defined by the equation

$$f_G = \frac{\Delta p}{2\left(\frac{DX_L}{4r_h}\right) NV^2 \rho_G} \tag{1}$$

4. Tests with two-phase flow

The pressure losses during flow of an air/water mist through the test section were measured over ranges of air and water flows.

Pressure drops were measured using a differential water manometer. A slow bleed-out through the tappings was arranged during these measurements to eliminate errors resulting from bubbles or slugs collecting at the pressure tapping points. Throughout the tests care was taken to remove all liquid flowing along the walls of the ducting leading to the test section. Under conditions of high liquid flowrate it was found that failure to remove this

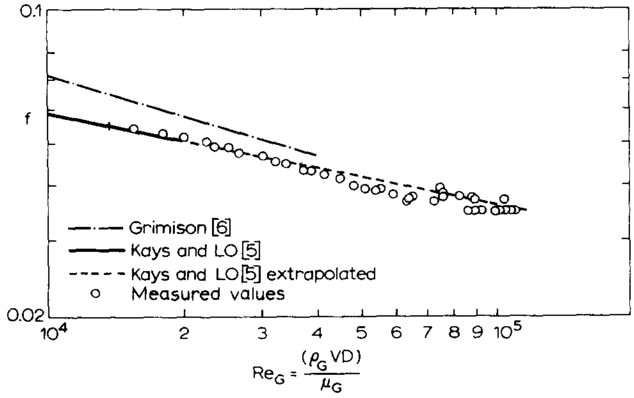

Fig. 2. Friction factor data obtained during flow of air across a bank of tubes arranged as shown in Fig. 1. Comparison with data of Grimison [6] and Kays and Lo [5].

separated liquid resulted in an increased $\Delta p_{TP}/\Delta p_G$ ratio of approximately 10–15%.

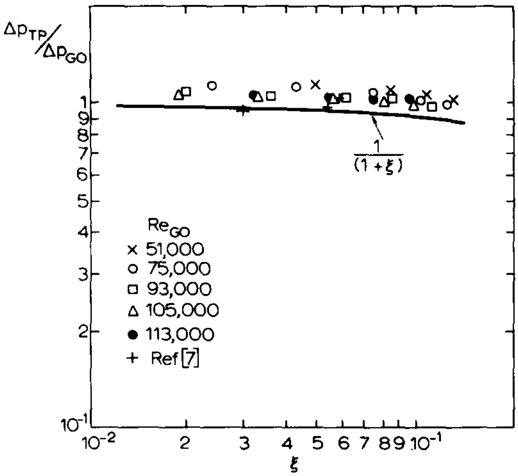

Fig. 3. Correlation of two-phase pressure drop.

The data obtained are listed in Table 1 and plotted on Fig. 3 in terms of the parameters used by Diehl and Unruh [7]. Collier and Wallis [8] have shown that these parameters may be re-interpreted in terms of a homogeneous model. Writing the two-phase pressure drop as

$$\Delta p_{TP} = 2f_{TP}\left(\frac{DX_L}{4r_h}\right)\frac{N}{\rho_m}\left(\frac{W}{A_c}\right)^2 \quad . \tag{2}$$

and the pressure drop for the same flowing mass of gas as

$$\Delta p_{GO} = 2f_{GO}\left(\frac{DX_L}{4r_h}\right)\frac{N}{\rho_G}\left(\frac{W}{A_c}\right)^2 \tag{3}$$

then using the parameter

$$\xi = \frac{Q_L\rho_L}{(Q_G + Q_L)\rho_G} \tag{4}$$

the mean density can be written as

$$\rho_m = \rho_G\left\{\xi + \left(1 - \frac{\rho_G}{\rho_L}\xi\right)\right\} \tag{5}$$

TABLE 1

Measured pressure loss data

Mass flowrate (kg/s)		Re_{GO}	Measured Δp_{TP} (mm w.g.)	Δp_{GO} (mm w.g.)	$\frac{\Delta p_{TP}}{\Delta p_{GO}}$	ξ	$\frac{1}{1+\xi}$
Air	Water						
0.60	0.079	53 300	187	181	1.04	0.132	0.884
0.60	0.066	52 300	188	175	1.07	0.11	0.90
0.60	0.051	51 200	188	170	1.10	0.084	0.92
0.60	0.030	49 500	185	161	1.15	0.050	0.953
0.88	0.11	78 300	363	360	1.01	0.127	0.887
0.88	0.093	76 500	363	345	1.05	0.105	0.905
0.88	0.067	74 700	361	330	1.09	0.076	0.93
0.89	0.039	72 800	359	320	1.10	0.043	0.96
0.90	0.021	71 900	354	310	1.15	0.024	0.98
1.10	0.125	96 000	528	530	1.00	0.114	0.90
1.10	0.093	93 900	521	510	1.05	0.085	0.921
1.11	0.069	92 600	516	495	1.05	0.062	0.94
1.12	0.04	91 000	512	475	1.08	0.036	0.96
1.12	0.022	90 200	508	470	1.08	0.020	0.98
1.26	0.125	109 000	673	670	1.01	0.10	0.91
1.26	0.103	107 600	666	650	1.02	0.082	0.92
1.28	0.072	106 300	662	635	1.04	0.057	0.95
1.29	0.043	104 800	658	620	1.06	0.033	0.97
1.30	0.025	103 800	650	610	1.06	0.02	0.98
1.33	0.130	114 800	773	750	1.03	0.097	0.91
1.35	0.10	114 000	779	735	1.06	0.074	0.93
1.36	0.074	113 000	762	720	1.06	0.055	0.95
1.38	0.044	112 000	761	710	1.07	0.032	0.97

and the ratio

$$\frac{\Delta p_{TP}}{\Delta p_{GO}} = \frac{1}{\left\{\xi\left(1 - \frac{\rho_G}{\rho_L}\right) + 1\right\}} \quad \text{if } f_{TP} = f_{GO} \qquad (6)$$

For air and water at atmospheric pressure ρ_G/ρ_L is small compared with unity so that

$$\frac{\Delta p_{TP}}{\Delta p_{GO}} = \frac{1}{(1+\xi)} \qquad (7)$$

From the friction factor data reported in Section 3 the "all gas" pressure drop was computed. The ratio $\Delta p_{TP}/\Delta p_{GO}$ was then plotted against the parameter ξ as shown in Fig. 3. The data clearly correlate well on this basis and lie some 10% above the homogeneous curve $1/(1 + \xi)$. This is in agreement with the few data reported by Diehl and Unruh [7] in the range of ξ between 0.02 and 0.2.

An alternative way of presenting the data is to plot the parameter $\{(\Delta p_{TP}/\Delta p_{LO}) - 1\}/(\Gamma^2 - 1)$ against the quality. On this basis the homogeneous model is a straight line running from 0 to 1. This type of plot was first used by Chisholm [9, 10] and subsequently by Grant [11] to correlate data obtained during two-phase flow across banks of tubes. For the data presented here which are limited to the mist-flow regime and thus a restricted range of quality this type of plot offers no advantages.

Acknowledgements

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Nomenclature

A	heat transfer area, m^2
A_c	minimum free flow area (either transverse or diagonal whichever is smaller), m^2
D	outer diameter of tube, m
f	friction factor, dimensionless
N	number of tubes in direction of flow, dimensionless
Δp	change in pressure, N/m^2
Q	volumetric flowrate, m^3/s
Re	Reynolds number, dimensionless
r_h	hydraulic radius, m $(= NDX_L \ A_c/A)$
V	velocity at minimum section, m/s
W	mass flowrate of both phases, kg/s
X_L	ratio of longitudinal tube spacing to tube diameter, dimensionless
Γ	parameter, dimensionless $(\Delta p_{GO}/\Delta p_{LO})^{0.5}$
ξ	parameter defined by eqn. (4), dimensionless
ρ	density, kg/m^3
μ	viscosity, Ns/m^2

Subscripts

G	of air
L	of liquid phase
m	mean
TP	two-phase
LO	total mass flowing as liquid
GO	total mass flowing as gas

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