FED - Vol. 36

CAVITATION
and
MULTIPHASE
FLOW FORUM — 1986

presented at

THE AIAA/ASME 4TH FLUID MECHANICS, PLASMA
DYNAMICS, AND LASERS CONFERENCE
ATLANTA, GEORGIA
MAY 11-14, 1986

sponsored by

THE MULTIPHASE FLOW COMMITTEE AND
THE FLUID MACHINERY COMMITTEE,
THE FLUIDS ENGINEERING DIVISION, ASME

edited by

O. FURUYA
TETRA TECH, INC.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

MEASUREMENTS OF FRICTION PRESSURE DROPS IN VERTICAL SLURRY AND BUBBLY FLOWS

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ABSTRACT

A Three Component Flow Facility (TCFF) was used to study friction pressure drops in vertical two component flows of both air bubbles in water and polyester particle-water mixtures. Friction factors of up to two orders in magnitude higher than those at zero volume fraction were observed for both bubbly and slurry flows. This deviation is shown to decrease with increased liquid Reynolds number. Bubbly and slurry flow friction factors were comparably large in magnitude and displayed the same decreasing trend as a function of Reynolds number. The two phase friction multiplier for bubbly flow was shown to attain values up to one order of magnitude higher than the prediction given by Lockhart and Martinelli. Two phase multiplier data is presented for the dispersed flow regime.

1. NOMENCLATURE

A	pipe cross section area ($8.09 \times 10^{-3} m^2$)
D	pipe diameter (4 in.)
f	friction factor
Fm	two phase friction multiplier
g	acceleration due to gravity
j_G	superficial air velocity
j_L	superficial liquid velocity
L	separation between pressure tappings (1.69m)
P_1	static pressure at upper tapping location
P_2	static pressure at lower tapping location
Re	liquid Reynolds number $= j_L D/\nu_L$
α	volume fraction of either air or polyester particles
β	air volume quality $= j_G/(j_G + j_L)$
ε_α	fractional error in volume fraction reading
$\varepsilon_{\Delta h_m}$	fractional error in static pressure reading
$\varepsilon_{\Delta h_{air}}$	fractional error in orifice pressure drop reading
ε_{EMFM}	fractional error in electromagnetic flow meter reading
Δh_m	static pressure manometer head
Δh_{air}	air orifice flow meter manometer head
$\Delta p_{1\phi}$	single phase flow friction pressure drop
$\Delta p_{2\phi}$	two phase flow friction pressure drop
ρ_w	water density
ρ_{air}	air density
ρ_b	bulk density
ρ_s	polyester density

2. APPARATUS

The Three Component Flow Facility (TCFF) at Caltech, shown in Figure 1 was used to study friction pressure drops in both air bubbles in water and polyester particle and water mixtures. The bubbly flows are formed by introducing air through an injector situated inside the vertical 4 in. pipe, 60cm below the test section. The injector consists of an array of twelve 1/8 in. brass tubes perforated with 1/64 in. holes. A 120psi compressed air line supplies the injector through a regulator, orifice plate flow meter (to monitor air mass flow), and valves to control the air flow. The bubbles formed have an average diameter of 4mm (± 1mm). The polyester particles are introduced at the

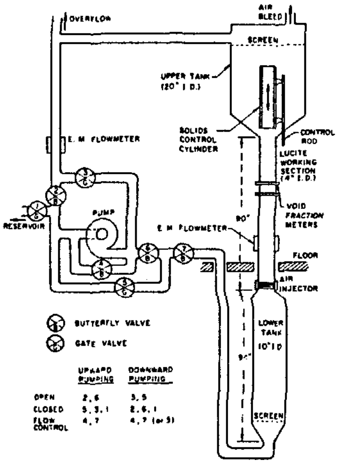

Figure 1 Schematic of the Three Component Flow Facility.

top of the test section from the particle hopper through a particle flow control gate. The particles have an average diameter of 3mm and are cylindrical in shape. A three horse power pump controls the water flow rate which is monitored using an electromagnetic flow meter. The static pressure gradient in the test section is measured with an inverted air on water manometer. The static pressure measurement contains a large hydrostatic pressure component and a smaller contribution from the frictional pressure drop. The volume fraction of the disperse medium is monitored with an impedance volume fraction meter (IVM) which bases its output on a measurement of the electrical impedance of the mixture. The accurate knowledge of the volume fraction allows us to extract the friction pressure drop from the measured static pressure gradient.

3. EXPERIMENTAL PROCEDURE

Experiments with different air and water flow rates were carried out with the air flow held constant and the water flow incremented from $j_L = 0$ to 1m/s. This was done for volume fractions of 0 to 40%. After each adjustment, conditions were allowed to settle for 15 seconds and all monitored quantities were recorded. All air-water flows studied were cocurrent and upward.

The polyester particle slurry flows studied were cocurrent and downward. With a pre-set liquid flow rate the solid fraction was incremented between each run. For each set of conditions, the liquid flow rate, the static pressure gradient in the test section and the solid fraction were monitored. The solid fraction ranged from 0 to 50%. The liquid flow rate was incremented through a range of 0 - .6m/s. In both types of flow the raw data was stored in random access files on a microcomputer floppy disc.

4. PRESSURE LOSSES IN VERTICAL UPWARD AIR WATER FLOW

Pressure losses in vertical upward air-water flow were obtained by subtracting the vertical static pressure difference in the flow from the pressure gradient caused by the gravitational body force. The latter was obtained by calculating the bulk density from the volume fraction and the known densities of air and water.

$$\Delta p_{2\phi} = p_1 - p_2 - \rho_b g L$$
$$= \rho_w g L\left(\frac{\rho_w - \rho_{air}}{\rho_w}\right)\left(\alpha - \frac{\Delta h_m}{L}\right)$$

We have chosen to represent the pressure loss data using both a friction factor and a two phase friction multiplier:

$$\text{friction factor} = f = \frac{\Delta p_{2\phi}}{2\rho_L (j_L)^2}\,\frac{D}{L}$$

$$\text{two phase friction multiplier} = Fm = \frac{\Delta p_{2\phi}}{\Delta p_{1\phi}}$$

Friction Factor

The friction factor is presented as a function of Reynolds number with the volume fraction α as a parameter (Fig. 2). All the two-phase friction factors are significantly larger than the pure liquid ($\alpha = 0$) curve, indicating a trend of increased resistance to flow with large volume fractions. Non-monotonic behavior can be seen within friction factor results which generally decrease with Re. This is best shown by the 5% < α < 10% curve which goes through a minimum at $Re = 2X10^4$ and a maximum at $Re = 4X10^4$. This phenomenon is similar in nature to that observed in pure liquid pipe flow through transition from laminar to turbulent flow. It is generally accepted that bulk two phase viscosity is increased with volume fraction therefore for the higher volume fraction curves, a Reynolds number based on a bulk kinematic viscosity would be much smaller than the one chosen here for simplicity (based on the kinematic viscosity of water). Using such a Reynolds number would then shift constant α curves progressively to the left with increasing α. Ultimately, the bulk Reynolds number will be small enough to be in the transition zone where non-monotonic f/Re behavior is seen. Our results suggest the existence of bulk laminar and turbulent flows.

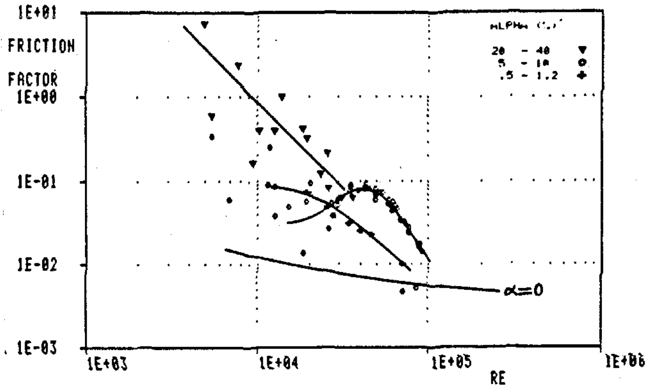

Figure 2 Mixture friction factor versus Reynolds Number.

At higher Reynolds number all the constant α curves coalesce indicating that volume fraction has less of an effect on friction factor at high flow rates than at low flow rates.

The Two-Phase Friction Multiplier

The two phase friction multiplier is the mixture pressure loss normalized with the pure liquid pressure loss at the same liquid flow rate. The pure liquid friction factor curve used (Figs.2 and 4) was a least squares regression fit of measurements of the form:

$$\log f = A + B \log Re + C(\log Re)^2$$

The results shown are for the bubbly flow regime. Though we attempted to take data in the churn turbulent regime there was great scatter in that data and those points have been omitted from the graphs. Figure 3 demonstrates that the friction multiplier takes on dramatically high values at low flow rates. There is a rise and fall off with increasing air volume quality in the form of a "hump" which decreases in size with increasing liquid flow rate. For a Reynolds number of 30000, the friction multiplier has a maximum of 15 where as for Re = 75000 the maximum has diminished to 5. This same phenomenon was documented by Aoki and Inoue (1965) and by Nakoryakov et al (1981) who found friction multiplier maxima of 20 (Re = 6000) and 11 (Re = 19000) respectively. The values of Reynolds number over which Aoki observed this phenomenon ($6 \times 10^3 - 40 \times 10^3$) are much below those of Nakoryakov ($19 \times 10^3 - 177 \times 10^3$) or ours. The discrepancy between the results of the three investigations suggests that in addition to the variation with the Reynolds number, the different bubble to pipe diameter ratios (Aoki .1, Nakoryakov .03, ours .035) in the investigations has a strong effect on the friction multiplier. As can be expected, the results for diameter ratios of .03 and .035 are closest to one another.

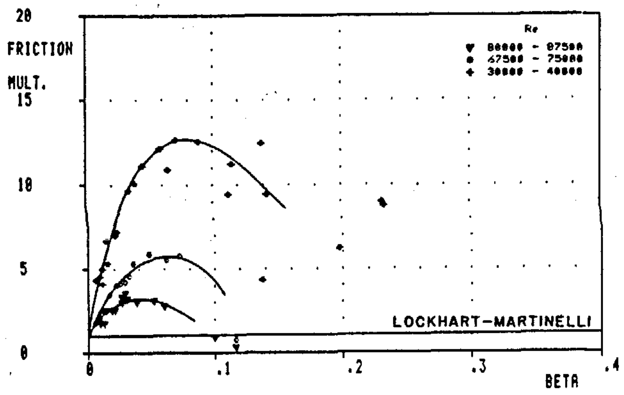

Figure 3 Friction multiplier versus air volume quality

5. PRESSURE LOSSES IN VERTICAL DOWNWARD SLURRY FLOWS

Friction Factor

Frictional pressure drops in polyester particle slurry flows were obtained by subtracting the vertical static pressure difference from the gravitational pressure difference. The latter is derived from the bulk density obtained from the monitored particle volume fraction.

$$\Delta p_{2\phi} = p_2 - p_1 + \rho_b g L$$

$$= \rho_w g L [\alpha \frac{(\rho_s - \rho_L)}{\rho_L} - \frac{\Delta h_m}{L}]$$

$$f = \frac{\Delta p_{2\phi}}{2\rho_L (J_L)^2} \frac{D}{L}$$

$$Fm = \frac{\Delta p_{2\phi}}{\Delta p_{1\phi}}$$

The slurry flow friction factor (Fig.4) reaches values of up to 15 times the zero volume fraction equivalent at the lower Reynolds numbers considered. This represents a static pressure loss gradient 15 times that experienced with the pure liquid (water) alone. The deviation from the zero volume fraction curve decreases with increasing Reynolds number and the constant volume fraction curves asymptotically tend to the zero volume fraction curve. Unlike the bubbly flow friction factor curves, these display a monotonically decreasing trend.

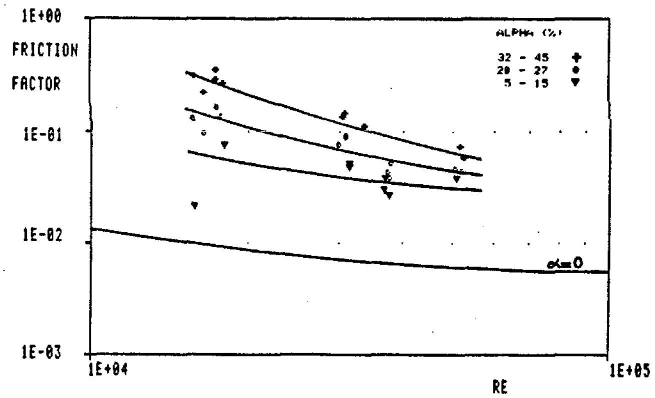

Figure 4 Slurry friction factor/Reynolds Number

6. ERROR ANALYSIS

Error analysis proved to be a vital tool in the presentation of our results through the elimination of points with intolerable error. Such an analysis is imperative whenever arithmetical manipulation and combination of error containing measurements is used. Based on the estimated error in each measurement we obtain an expression for the error in the reduced quantity of interest.

The maximum errors in the volume fraction meter, the static pressure manometer and the electromagnetic flow meter were estimated to be 5% of the readings, and 1% for the air orifice plate manometer.

CONCLUSIONS

The bubbly flow pressure loss measurements display a marked departure from commonly used models (Lockhart-Martinelli (1949), Armand (1950)). At small liquid and air flow rates, the measured pressure drops were up to an order of magnitude higher than predicted by the aforementioned authors. This phenomenon is as yet poorly understood and has only been documented in two other studies (Aoki and Inoue (1965), Nakoryakov et al (1981)) which were carried out for different pipe diameters, making quantitative comparison difficult. High friction multiplier values were shown to correspond to flows with volume fraction peaks in the vicinity of the wall by Nakoryakov et al. This supports the theory of increased wall shear stresses due to enhanced mixing close to the wall caused by the presence of the dispersed medium. A mixing length theory based on this and empirically obtained constants has been developed by N. Clarke (1983), who predicts the sharp rise of friction multiplier with respect to the air volume quality.

The bubbly and slurry flow friction factors were close to one another in magnitude and in both cases were observed to be much more sensitive to the volume fraction of the dispersed medium at low liquid Reynolds numbers than at high Re. At high Reynolds number $(\sim 7 \times 10^4)$ unsteadiness can be observed in the flow on a scale larger than the bubble or particle diameter. This visual evidence of a "bulk turbulence" appears after the point at which it becomes apparent in the friction factor data (Fig.2). Further work is being carried out on the unsteady nature of these flows and their structure by studying the statistical properties of volume fraction signals.

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