Pergamon

Int. J. Multiphase Flow Vol. 23, No. 2, pp. 397–402, 1997

PII: S0301-9322(96)00061-4
0301-9322/97 $17.00 + 0.00

BRIEF COMMUNICATION

PRESSURE DROP MEASUREMENT AND CORRELATION FOR THREE-PHASE FLOW OF SIMULATED NUCLEAR WASTE IN A HORIZONTAL PIPE

F. MAO, F. K. DESIR and M. A. EBADIAN†
Hemispheric Center for Environmental Technology, Florida International University, Miami, FL 33199, U.S.A.

(Received 29 April 1996; in revised form 22 August 1996)

1. INTRODUCTION

In the area of environmental technology development, multiphase pressure drop data is an important technical base for designing waste slurry and sludge processing systems. For instance, a nuclear waste immobilization technology called nitrate to ammonia and ceramic (NAC) process (Mattus *et al.* 1994; Ebadian 1995) produces a mixture of water, hydrogen and ammonia gases, and gibbsite ($Al_2O_3 \cdot 3H_2O$) solid. To scale-up and design the transportation and treatment system for the process, rheological data must be provided. Many operating parameters can effect the pressure drop in a pipe. These include flow velocity of each phase, the solid concentration, particle size and its chemical nature, pH value, and the temperature of the bulk flow. This study has emphasized the investigation of parameters which have the most effect on the viscosity. The solid content of the slurry, the amount of air, and the temperature have been examined.

A review of the research on multiphase pressure drop reveals that many studies have been conducted regarding two-phase (gas/liquid and solid/liquid) flow systems. The rheology of coal slurry was studied by Round and Hessari (1987), who examined the effects of slurry pH and solid particle size distribution on water- and oil-based slurry shear stress using a Haake RV12 viscometer. Sellgren (1987) studied the effect of temperature on pressure drop and determined viscosity using a tube (diameter = 0.5 cm) viscometer.

Temperature-dependent changes in rheological properties were evaluated for clay, coal, and iron ore slurries in low temperature range of 0.5–20°C. Much higher shear stress was observed when the temperature of slurry was close to 0.5°C. Bouzaiene and Hassani (1992) reviewed and classified pressure drop prediction methods reported in literature. Some of the methods were examined using literature data of multiphase flow. For other types of multiphase phase flow systems, Lahey *et al.* (1992) tested the global volumetric phase fraction in horizontal multiphase flows of gas, water, and oil. A detailed set of phasic volume fraction data was measured in a 183 cm length test loop for the various flow regimes. These data were then correlated with generalized mathematical expressions. Unfortunately, no pressure drop measurements and correlation were reported in the paper. Kasturi and Stepanek (1972a, b) made a comprehensive study of multiphase flow of air/corn/sugar/water and air/glycerol/water solutions in helical coil. Their investigation was limited to the influence of liquid properties and flow rates on void fraction and pressures drop. They treated the multiphase phase flow as a two-phase system composed of gas and a uniform solution. The experimental results were correlated by Lockhart–Martinelli and other methods.

To our knowledge, the pressure drop measurement and correlation for three-phase flow of nuclear wastes have not been widely investigated. Therefore, the present study aims to shed light

---

†Author to whom all correspondence should be addressed.

on the complicated three-phase flow system and provide basic rheological data for the design of pump and pipeline system in nuclear waste treatment processes.

2. EXPERIMENTAL

The schematic of experimental apparatus is shown in figure 1. The water/gibbsite slurry was pumped from a mixture reservoir, which was also used as air separator, and passed through a flow meter and a cooling section into the air/slurry mixing unit. The three-phase mixture flowed through a visual section located approximately 30.5 cm downstream from the mixing unit, and then entered the test loop and finally the air separator. A pressure gauge was mounted on the outlet of slurry pump and a thermocouple was inserted into the test section. Compressed air was passed through a pressure regulator, a gas flow meter, and injected into the mixing unit. The three-phase flow entered the air separator through a nozzle on the top. The air is separated from the slurry in the tank and escapes to the ambient through a coil condenser. The condensed liquid in the coil flows back into the tank. There is a 5 m long introducing section between the pump and the test loop. The test loop consisted of a horizontal stainless-steel pipe with an inner diameter of 0.025 and 2.14 m in length. The stainless-steel pipe was electrically heated to maintain the inside mixture at specified temperature. Pressure drop along the test section was measured by a differential pressure transducer (wet–wet) which was routinely calibrated before performing each set of experiments.

Gibbsite/water solution was prepared for each set of experiments at concentrations of 20 and 30 weight percent. The gibbsite particle size distribution was as follows: $d_p > 15\,\mu\text{m}$, 10 wt%; $7 < d_p < 15\,\mu\text{m}$, 40 wt%; $3 < d_p < 7\,\mu\text{m}$, 40 wt%; and $d_p < 3\,\mu\text{m}$, 10 wt%. At each gibbsite concentration level, three temperatures—50, 65 and 80°C—were investigated. For each combination of gibbsite concentration and temperature, experiments were performed at three slurry flow rates and nine air flow rates. The readings of slurry flow rate, air flow rate, temperature, and pressure drop under each experimental case were recorded when the system reached steady state.

3. DATA TREATMENT

To simplify the data correlation, the three-phase flow system was treated as a two-phase flow of gas (air) and liquid (gibbsite slurry). The pressure drop was correlated using the Lockhart–Martinelli method (1949). The variables introduced into the model were the pressure drop multipliers ϕ_L^2 and ϕ_G^2, which are defined as follows:

$$\phi_L^2 = \frac{\left(\frac{\Delta P}{L}\right)_{\text{Mix}}}{\left(\frac{\Delta P}{L}\right)_{\text{L}}} \qquad [1]$$

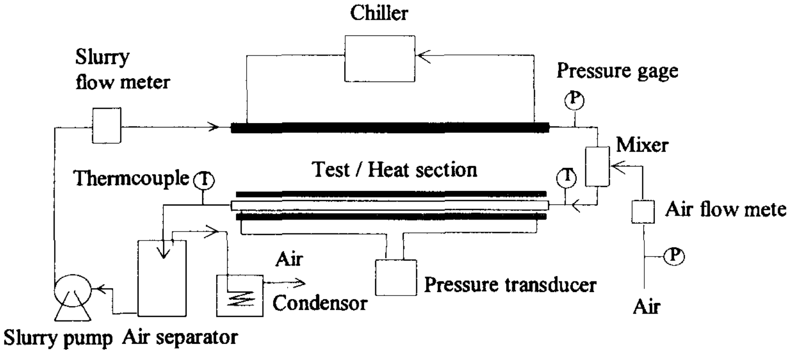

Figure 1. Schematic of experimental setup.

and

$$\phi_G^2 = \frac{\left(\frac{\Delta P}{L}\right)_{\mathrm{Mix}}}{\left(\frac{\Delta P}{L}\right)_{\mathrm{G}}} \qquad [2]$$

where $(\Delta P/L)_{\mathrm{Mix}}$ represents the pressure gradients along the test section. The Lockhart–Martinelli parameter X^2 is defined as:

$$X^2 = \frac{\left(\frac{\Delta P}{L}\right)_{\mathrm{L}}}{\left(\frac{\Delta P}{L}\right)_{\mathrm{G}}} \qquad [3]$$

where $(\Delta P/L)_{\mathrm{L}}$ and $(\Delta P/L)_{\mathrm{G}}$ are the pressure gradients for flow of liquid or gas alone, which can either be measured or calculated from the single-phase flow system. In this investigation, the pressure drop multiplier ϕ_L^2 was used for data correlation. The pressure gradients of $(\Delta P/L)_{\mathrm{Mix}}$ and $(\Delta P/L)_{\mathrm{L}}$ were measured. The parameter X^2 may be evaluated in terms of the air mass fraction, x, and physical properties of each single phase. As quoted in the work of Butterworth and Hewitt (1977), the X^2 was written as:

$$X^2 = \left(\frac{1-x}{x}\right)^{1.8}\left(\frac{\rho_G}{\rho_L}\right)\left(\frac{\mu_L}{\mu_G}\right)^{0.2} \qquad [4]$$

where μ_L and μ_G represent the viscosity of liquid and gas, ρ_L and ρ_G indicate the density of the liquid and gas, D is tube diameter, G is mass flow rate in the tube, and x is mass fraction of air in the mixture calculated by

$$x = \frac{G_{\mathrm{Air}}}{G_{\mathrm{Mix}}}. \qquad [5]$$

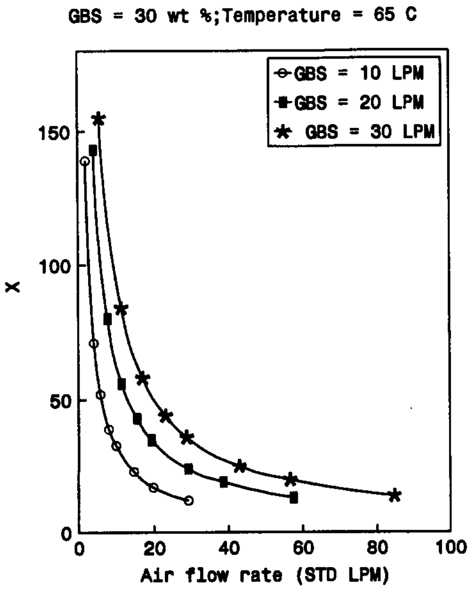

Figure 2. Dependence of Lockhart–Martinelli parameter X on air flow rate (GBS concentration: 30 wt%; temperature: 65°C).

Table 1. Values of parameter C

Gibbsite Concentration	Temperature (°C)		
	50	65	80
20	41.3	52.9	77.6
30	34.9	43.4	47.5

The ρ_L is taken as the average density of gibbsite and the water and calculated by

$$\rho_L = \rho_W(1 - x_{GBS}) + \rho_{GBS} x_{GBS} \qquad [6]$$

where ρ_W is water density, ρ_{GBS} is gibbsite density, and x_{GBS} is the mass fraction of gibbsite in the water–gibbsite slurry. The viscosity for air, μ_G, was found in handbook (Perry and Green 1984). The viscosity of slurry was calculated using two empirical equations obtained from work of Ebadian (1995).

Figure 2 shows the dependence of X on air mass fraction, x. The values of ϕ_L^2 and X^2 were correlated using an empirical equation (Butterworth and Hewitt 1977):

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2}. \qquad [7]$$

Parameter C in this equation was established by performing a least-squares fit to the experimental data.

4. RESULTS AND DISCUSSION

The estimated values of parameter C in [7] are shown in table 1. Comparisons of the data with the Lockhart–Martinelli correlation are shown in figures 3–8. The experimental data and correlation indicate that the amount of air induced into the system exerts a very strong effect on the pressure drop multiplier. When the air flow rate is high enough to make parameter X less than 40, the pressure drop multiplier dramatically increase (see figures 3–8). If the air is reduced to a level close to zero (that is, X increase to infinity), the pressure drop multiplier correspondingly declines to a value of 1. This is true because when there is no air in the system, the $(\Delta P/L)_{Mix}$ equals $(\Delta P/L)_L$ as indicated in [1], and which results in $\phi_L^2 = 1$.

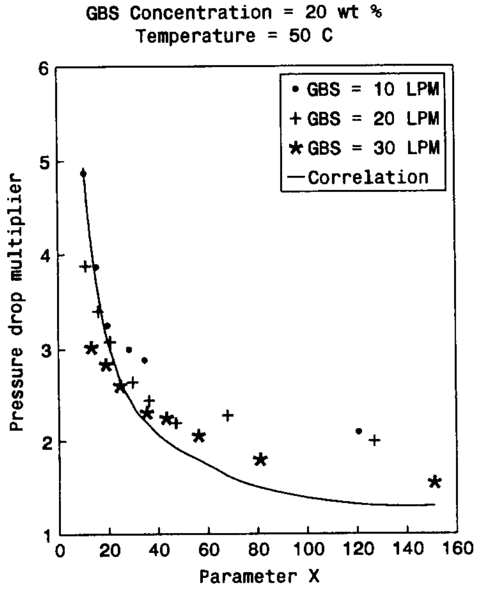

Figure 3. Pressure drop multiplier as a function of parameter X (GBS concentration: 20 wt%; temperature: 50°C).

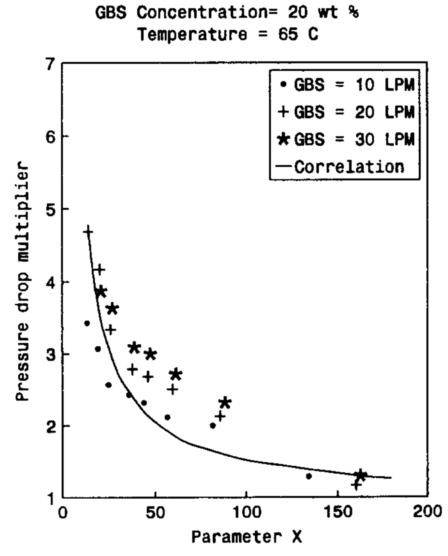

Figure 4. Pressure drop multiplier as a function of parameter X (GBS concentration: 20 wt%; temperature: 65°C).

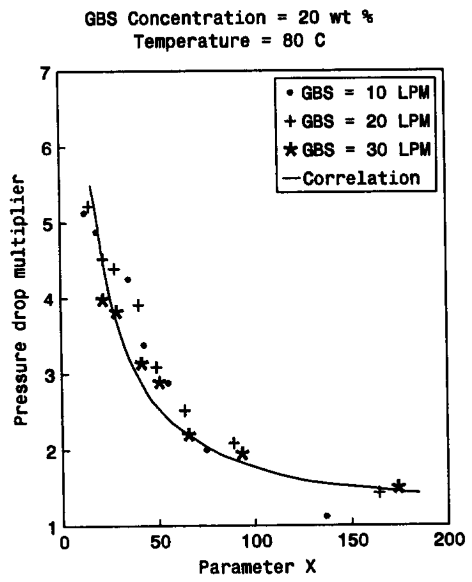

Figure 5. Pressure drop multiplier as a function of parameter X (GBS concentration: 20 wt%; temperature: 80°C).

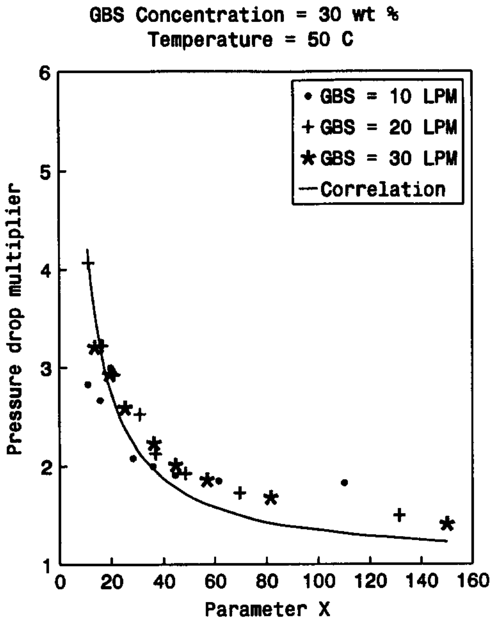

Figure 6. Pressure drop multiplier as a function of parameter X (GBS concentration: 30 wt%; temperature: 50°C).

The effect of temperature on the pressure multiplier can be determined from the C values listed in table 1. As indicated, higher C values were obtained at higher temperatures, and higher ϕ_L^2 resulted from [7]. In fact, when the temperature is high, the volume flow rate of air increases. This results in a higher superficial air velocity and a higher pressure drop (that is, the $(\Delta P/L)_{\mathrm{Mix}}$ is higher). On the other hand, the temperature change has no major effect on the slurry volume flow rate and the $(\Delta P/L)_{\mathrm{L}}$ remains constant. Therefore, the final result is that the pressure drop multiplier increases as the temperature increases.

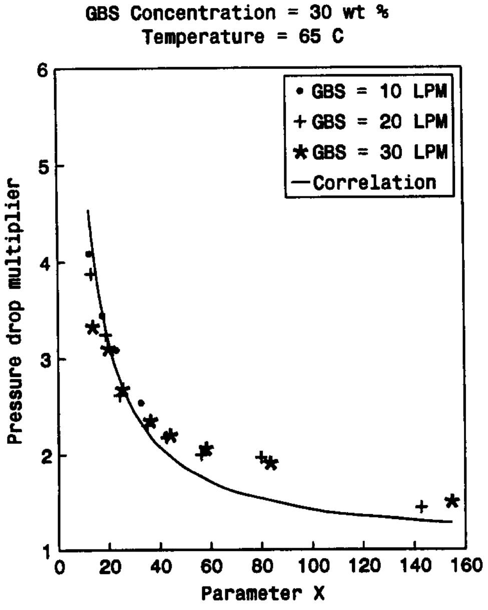

Figure 7. Pressure drop multiplier as a function of parameter X (GBS concentration: 30 wt%; temperature: 65°C).

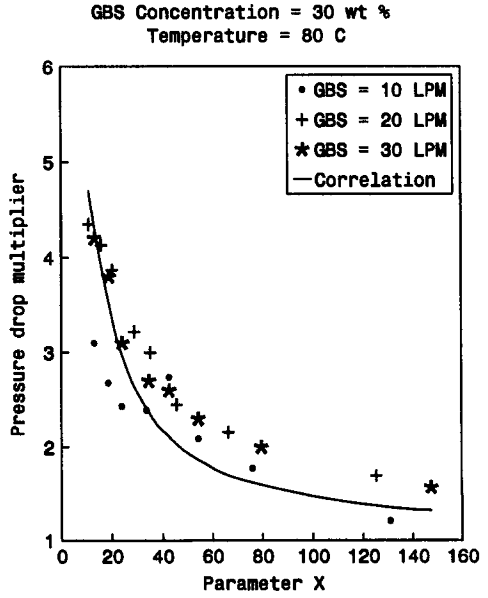

Figure 8. Pressure drop multiplier as a function of parameter X (GBS concentration: 30 wt%; temperature: 80°C).

It is interesting to note that a lower pressure drop multiplier is obtained at a higher gibbsite concentration. For example, at a constant temperature of 50°C, the C value at 20 wt% is about 15% lower than that at 30 wt%. One possible explanation for this phenomenon is that concentrated slurry produce a larger pressure gradient in terms of $(\Delta P/L)_L$ than $(\Delta P/L)_{Mix}$. It appears that the overall effect of gibbsite concentration is to reduce the pressure drop multiplier.

5. CONCLUSIONS

Pressure drop measurements have been carried out in ranges of temperature and solid concentration. The Lockhart–Martinelli method correlates well the data. Both experimental and correlation results indicate that amount of air introduced into the flow system exerts the strongest effect on the pressure drop. The effect of temperature on the pressure drop multiplier through the air velocity was observed in the experiments and represented by the model. It has also been found that the concentration of gibbsite is another factor that influences the pressure drop multiplier. A brief explanation of these effects has been presented based on experimental data and correlation.

Acknowledgements—The work is supported by U.S. Department of Energy, Office of Science and Technology.

REFERENCES

Bouzaiene, R. and Hassani, F. P. (1992) A selection of pressure loss predictions based on slurry/backfill characterization and flow conditions. *CIM Bulletin* **4**, 63–68.

Butterworth, D. and Hewitt, G. F. (1977) *Two-phase Flow and Heat Transfer*. Harwell Series, Oxford University Press, New York.

Ebadian, M. A. (1995) Final report on the nitrate to ammonia and ceramic/glass processes. Hemispheric Center for Environmental Technology, Florida International University.

Kasturi, G. and Stepanek, J. B. (1972a) Two-phase flow—I. Pressure drop and void fraction measurement in concurrent gas–liquid flow in a coil. *Chemical Engineering Science* **27**, 1871–1880.

Kasturi, G. and Stepanek, J. B. (1972b) Two-phase flow—II. Pressure drop and void fraction measurement in concurrent gas–liquid flow in a coil. *Chemical Engineering Science* **27**, 1881–1891.

Lahey, R. T., Jr, Acikgoz, M. and Franca, F. (1992) Global volumetric phase fraction in horizontal three-phase flow. *AICHE Journal* **38**, 1049–1058.

Lockhart, R. W. and Martinelli, R. C. (1949) Proposed correlation of data for isothermal two phase, two components flow in pipes. *Chemical Engineering Progress* **45**, 39–47.

Mattus, A. J., Walker, J. F., Youngblood, E. L., Farr, L. L., Lee, D. D., Dillow, T. A. and Tiegs, T. N. (1994) *ORNL/TM-12631*, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Perry, R. H. and Green, D. (1984) *Perry's Chemical Engineer's Handbook*, 6th Edition. McGraw-Hill, New York.

Round, G. F. and Hessari, A. R. (1987) *Particulate and Multiphase Processes*, eds T. Ariman and T. N. Veziroglu, pp. 329–340. Hemisphere Publishing Corporation, New York.

Sellgren, A. (1987) *Particulate and Multiphase Processes*, eds T. Ariman and T. N. Veziroglu, pp. 235–243. Hemisphere Publishing Corporation, New York.