10th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2006, Lloret de Mar, Spain, 11-15 September, 2006

PRESSURE DROP ANALYSIS IN THE HORIZONTAL PIPES WITH SPHERICAL CAPSULE TRAIN FLOW

Afsin Gungor
Nurdil Eskin
İstanbul Technical University, Mechanical Engineering Faculty
İnönü Cad., No.81, Gümüşsuyu, 34437, İstanbul
Turkey

ABSTRACT
Horizontal hydraulic transport of ice particles suspended in water which is used in cooling systems has several advantages, such as its friendliness to the environment and its relatively low operation and maintenance costs. In this study, as a first approximation one dimensional model is developed. Simulation model calculates the pressure drop of the flow of solid-water two-phase mixture inside the pipe. Through this model, effects of different volumetric concentrations of solid phase on the pressure drop of the capsule flow are investigated. The simulation results are compared and validated with the results obtained from the experiment which has been performed with spherical capsules having lower density than the carrier liquid. In the experiment, measurements have been carried out in a horizontal straight plexiglass pipe and water has been used as a carrier liquid. The results show that the homogenous model can be applicable to pressure drop solid-water two phase mixture with sufficient accuracy.
Keywords: two-phase flow, pressure drop, capsule flow

1. INTRODUCTION
The understanding of the horizontal two-phase liquid-solids flow and related phenomena is of general importance in engineering, chemical and biochemical process [1-5]. Among these processes, ice-water two-phase flow in cylindrical tubes is widely used in cooling systems as one of the important engineering applications. The large energy capacity of ice-water slurries, when compared to conventional chilled-water systems, can potentially reduce the distribution flow rate by over 80% in existing plants while maintaining the same cooling load and pumping water, or it can increase the cooling capacity up to 600% at the same flow rate and pumping water [6]. However using the ice capsules instead of ice slurry have significant advantages; blocking due to dispersion of ice particles in ice-water slurry flow is not experienced in ice capsules flow, the concentration rate velocity of the ice capsules are considerable higher than the concentration rate and mixture velocity obtained by ice-water slurry flow and thus the cooling capacity of the district system is getting higher. The publications in the literature about the two-phase ice-water flow may be subdivided into those that consider the hydrodynamic behaviour [1, 3-9], and others that investigate the heat transfer phenomena [6, 10-12].

Although there are numerous experimental investigations on the ice-water two-phase flow, theoretical studies are very rare which characterizes flow behaviour due to the mathematical modelling of ice-water two-phase flow is very complex [10, 13]. From this point of view, in the present study, as a first approximation one dimensional model is developed. Simulation model calculates the pressure drop of the flow of ice-water two-phase mixture inside the pipe.

Through this model, effects of different volumetric concentrations of solid phase on the pressure drop of the capsule flow are investigated. The simulation results are compared with the experimental results and developed model has been validated [9].

2. MODEL

Modelling of ice-water two-phase flow is rather difficult. Therefore, it is necessary to develop simplified modelling approaches, which can describe the ice-water two-phase flow structure with sufficient accuracy. From this point of view, in the present study, as a first approximation one dimensional model has been developed. The model considers:

- The flow is homogenous.
- The flow is fully developed.
- There is no influence of the heat transfer or pressure drop along the pipe on the concentration of solid phase.
- The suspension-wall friction term is unaffected by the water temperature in the model.

The basic equations for steady one-dimensional homogeneous equilibrium flow in a horizontal pipe are:

Continuity $\dot{m} = \rho_m U_m A = \dot{m}_w + \dot{m}_{ice} = const$ (1)

Momentum $\dot{m}\dfrac{dU_m}{dx} = -A\dfrac{dP}{dx} - P_t \tau_{wall}$ (2)

where A and P_t represent the duct area and perimeter, τ_w is the average wall shear stress. Eq. (2) is often rewritten as an explicit equation for pressure gradient. Thus, the total pressure drop per unit length dx along the tube, assumed to be comprised of two main components:

$$\left(\frac{dP}{dx}\right)_{total} = \left(\frac{dP}{dx}\right)_{acc} + \left(\frac{dP}{dx}\right)_{fric} \quad (3)$$

where $(dP/dx)_{acc}$ is the pressure drop due to the acceleration, and $(dP/dx)_{fric}$ is the pressure drop due to suspension-wall friction, respectively. Acceleration component of the pressure drop is:

$$\left(\frac{dP}{dx}\right)_{acc} = \frac{1}{2}\rho_m U_m^2 \quad (4)$$

and the pressure drops due to suspension-wall friction is calculated as follows:

$$\left(\frac{dP}{dx}\right)_{fric} = \tau_{wall}\frac{P_t}{A} = \frac{1}{2}\rho_m U_m^2 \frac{P_t}{A} \quad (5)$$

In the model, mean mixture velocity U_m calculated from the continuity equation Eq.(1):

$$U_m = \frac{\rho_w \dot{V}_w + \rho_{ice}\dot{V}_{ice}}{\rho_m A} = \frac{\dot{V}_w + \rho_w + \rho_{ice}\left(\dfrac{C}{1-C}\right)}{\rho_m A} \quad (6)$$

where C presents the concentration of the solid phase in a solid-liquid mixture:

$$C = \frac{\dot{V}_{ice}}{\dot{V}_w + \dot{V}_{ice}} \quad (7)$$

where $\dot{V}_{ice}$ and $\dot{V}_w$ are the volumetric flow rates of ice and water phases respectively. In the model, average ice-water flow suspension density is considered with the following equation:

$$\rho_m = \varepsilon\rho_w + (1-\varepsilon)\rho_{ice} \quad (8)$$

where ε is the radially averaged voidage in the pipe.

$$\varepsilon = \frac{\dot{V}_w}{\dot{V}_w + \dot{V}_{ice}} \quad (9)$$

The suspension-wall friction factor, f is a function of Reynolds number and there are various empirical correlations given in the literature [10, 14 and 15]. Garic-Grulovic et al. [10] are proposed a correlation which is considered in the model for suspension-wall friction factor:

$$\left.\begin{aligned} f/2 &= 6565/\mathrm{Re}^{1.50} \qquad 2800 < \mathrm{Re} < 15000 \\ f/2 &= 0.0395/\mathrm{Re}^{0.25} \qquad 15000 < \mathrm{Re} < 32000 \end{aligned}\right\} \quad (10)$$

They are noted that the form of the correlation for two-phase flow for Re>15000 is the same as the Blasius equation for single-phase flow. In this equation, the Reynolds number is based on the averaged suspension velocity. In the literature, many different models have also been used for the calculation of the suspension viscosity values. In the model, the effective flowing suspension viscosity is obtained according Barnea and Mizrahi [16];

$$\mu_m = \mu_{liquid} \cdot \exp\left(\frac{5(1-\varepsilon)}{3\varepsilon}\right) \qquad (11)$$

3. RESULTS AND CONCLUSION

The developed homogenous model has been validated by comparing the simulation results with the results obtained from Ulusarslan and Teke [9]'s experiment. In the experiment, measurements have been carried out in a horizontal straight plexiglass pipe and using spherical capsules fabricated from polypropylene, with density close to that of ice which is lower than carrier liquid and they have reported that, the amount of flow rate was measured by water flow meters having an average variation of 0.5% (max. 0.1%) from the actual values. The accuracy of the pressure drop measurements has not been reported in their study [9]. The main parameters and the range of the experimental conditions of these experiments are given in Table 1.

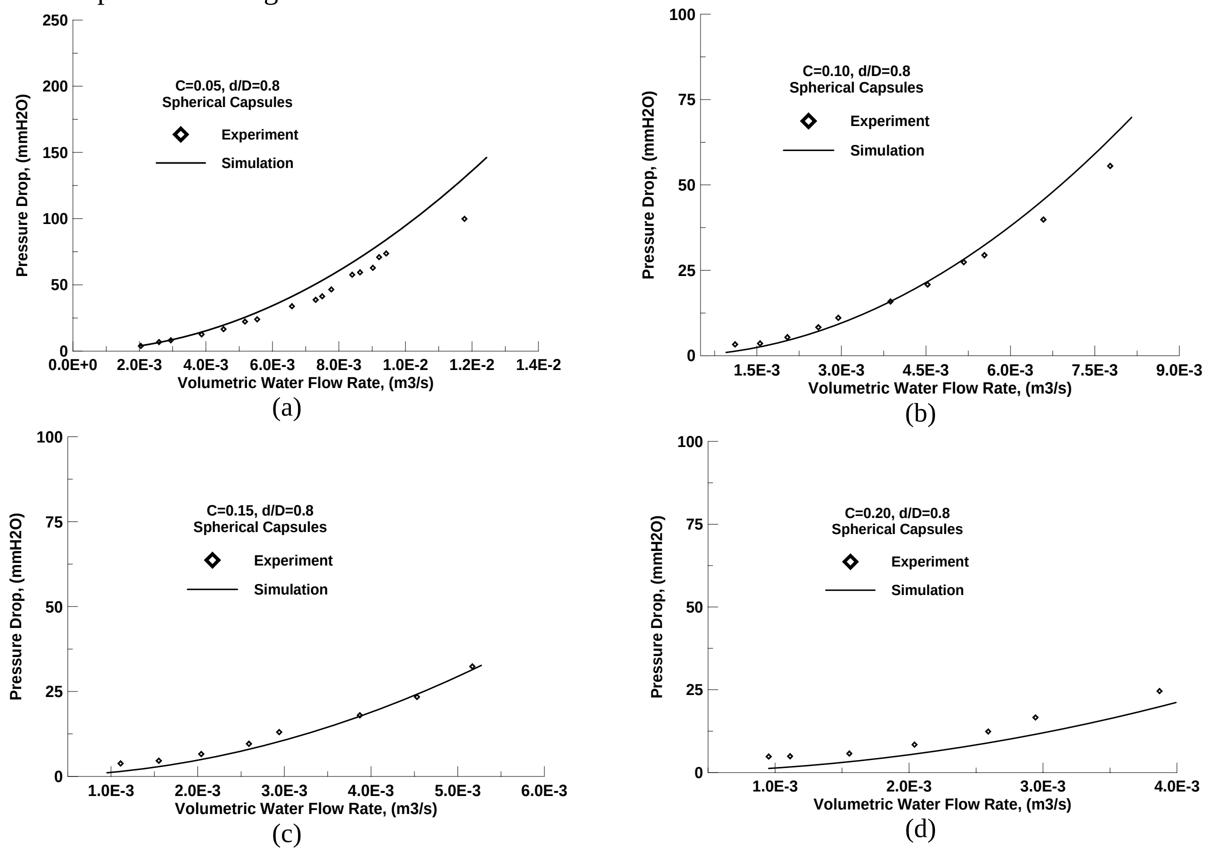

Fig. 1. Comparison of simulation results with Ulusarslan and Teke [9]'s experimental data.

The comparison of simulation results with Ulusarslan and Teke [9]'s experimental data are given in Fig. 1. As it is seen from the figure, pressure gradient increases with increasing carrier liquid velocity in which capsules of spherical shape with a density lower than that of the carrier liquid and simulation results are in good agreement with experiments for different capsule concentrations; 0.05, 0.10, 0.15 and 0.20, although the simulation results show a little discrepancy at 0.05 and 0.20 capsule concentration values.

The suspension to wall friction coefficients and volumetric concentrations of solid phase are important parameters in pressure analysis of ice-water two-phase flow. Pressure drop increases with capsule concentration in ice-water two-phase mixtures at constant Reynolds number values as well as suspension to wall friction factor values (Fig. 2). It reaches higher values as Reynolds number values increases.

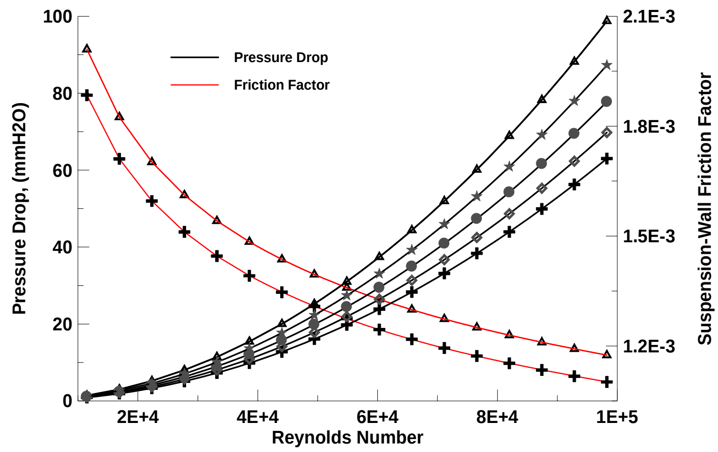

Table 1. Parameters used in experimental setups [9].

Capsule shape	Spherical
L	4
D	0.1
d/D	0.8
ρ_c	870
C	0.05÷0.30
Reynolds number	$1.2\times10^4 < Re < 1.5\times10^5$
Water temperature	20±2°C

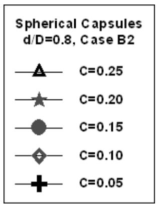

Fig. 2. Effects of volumetric concentrations of solid phase on the pressure drop.

In this study, as a first approximation one dimensional model has been developed. Simulation model calculates the pressure drop of the flow of solid-water two-phase mixture inside the pipe. Through this model, effects of different volumetric concentrations of solid phase on the pressure drop of the capsule flow are investigated. The simulation results are compared with the experimental results and developed model has been validated [9]. Homogenous model approach can be used with confidence for pressure drop calculations of solid-liquid two-phase mixture in horizontal pipe especially for spherical capsules at each concentration up to 25%

4. REFERENCES

[1] Lan, Q., Bassi, A.S., Zhu, J.X., Margaritis, A.: Continuous Protein Recovery with a Liquid-Solid Circulating Fluidized Bed Ion Exchanger, AIChE Journal 48, 2002, 252-261.

[2] Karamanev, D.G., Nagamune, T., Endo, I.: Hydrodynamic and Mass Transfer Study of a Gas-Liquid-Solid Draft Tube Spouted Bed Bioreactor, Chemical Engineering Science 47, 1992, 3581-3588.

[3] Shamlou, P.A.: Hydraulic Transport of Particulate Solids, Chem. Eng. Communications 62, 1987, 233-240.

[4] Seki, M.S., Skalak, R.: Asymmetric Flows of Spherical Particles in a Cylindrical Tube, Biorheology 34, 1997, 155-169.

[5] Seki, M.S.: Motion of a Sphere in a Cylindrical Tube Filled with a Brinkman Medium, Fluid Dynamics Research 34, 2004, 59-76.

[6] Knodel, B.D., France, D.M., Choi, U.S., Wambsganss M.W.: Heat Transfer and Pressure Drop in Ice-Water Slurries, Applied Thermal Engineering 20, 2000, 671-685.

[7] Vlasak, P.: An Experimental Investigation of Capsules of Anomalous Shape Conveyed by Liquid in a Pipe, Powder Technology 104, 1999, 207-213.

[8] Vardy, A.E., Brown, J.M.B.: Transient Turbulent Friction in Fully Rough Pipe Flows, Journal of Sound and Vibration 270, 2004, 233-257.

[9] Ulusarslan, D., Teke, I.: An Experimental Investigation of the Capsule Velocity, Concentration Rate and the Spacing between the Capsules for Spherical Capsule Train Flow in a Horizontal Circular Pipe, Powder Technology 159, 2005, 27-34.

[10] Garic-Grulovic, R.V., Grbavcic, Z.B., Arsenijevic, Z.L.: Heat Transfer and Flow Pattern in Vertical Liquid-Solids Flow, Powder technology 145, 2004, 163-171.

[11] Ismail, K.A.R., Henriquez, J.R.: Solidification of PCM inside a Spherical Capsule, Energy Conversion and Management 41, 2000, 173-187.

[12] Wilchinsky, A.V., Fomin, S.A., Hashida, T.: Contact Melting Inside an Elastic Capsule, International Journal of Heat and Mass Transfer 45, 2002, 4097-4106.

[13] Ling, J., Skudarnov, P.V., Lin, C.X., Ebadian, M.A.: Numerical Investigations of Liquid-Solid Slurry Flows in a Fully Developed Turbulent Flow Region, Int. J. of Heat and Fluid Flow 24, 2003, 389-398.

[14] Gnielinski, V.: Forced Convection in Ducts, in: G.F. Hewitt, Ed.,, Handbook of Heat Exchanger Design, Begell House, New York, 1992.

[15] Bird, R.B., Steward, W.E., Lightfoot, E.N.: Transport Phenomena, J. Wiley, New York, 1960.

[16] Barnea, E., Mizrahi, J.: A Generalized Approach to the Fluid Dynamics of Particulate Systems, Chem. Eng. J. 5, 1973, 171-189.