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ONE DIMENSIONAL SIMULATION OF CAPSULE TRAIN FLOW

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

ABSTRACT
In this study, one dimensional model is developed for capsule train flow in a horizontal pipe. Simulation model calculates the pressure drop of the flow of solid-water two-phase mixture inside the pipe. Through this model, effects of different suspension viscosity models and suspension to wall friction coefficients on the pressure drop of the capsule train flow are investigated. The simulation results are compared and validated with the results obtained from two different experimental analyses. The simulation results are compared and validated with the results obtained from the experiment which has been performed with anomalous shape capsules having higher 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 1D model can be applicable to pressure drop solid-water two phase mixture with sufficient accuracy.
Keywords: two-phase flow, pressure drop, capsule train, simulation

1. INTRODUCTION
Mathematical modeling of two phase flows, especially liquid-solid flows is very complex. Therefore, it is necessary to develop simplified modeling approaches, which can describe the liquid-solid two-phase flow structure with sufficient accuracy. The publications in the literature about the liquid-solid two-phase flow may be subdivided into those that consider the hydrodynamic behavior [1-3], and others that investigate the heat transfer phenomena [4-6].
Although there are numerous experimental investigations on the liquid-solid two-phase flow, theoretical studies are very rare which characterizes flow behavior due to the mathematical modeling of capsule train flow is very complex [5]. From this point of view, in the present study, one dimensional model is developed for capsule train flow in a horizontal pipe. Simulation model calculates the pressure drop of the flow of capsule train-water two-phase mixture inside the pipe. Through this model, effects of different suspension viscosity models and suspension to wall friction coefficients on the pressure drop of the capsule flow are investigated. The simulation results are compared with experimental results obtained from the Vlasak [7]'s experiment with capsules of anomalous shape with a density higher than the carrier liquid and developed model has been validated.

2. MODEL DESCRIPTION
The model considers: a) The flow is homogenous, b) The flow is fully developed, c) There is no influence of the heat transfer or pressure drop along the pipe on the concentration of solid phase, d) 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 $\dot{m} = \rho_m U_m A = \dot{m}_w + \dot{m}_{cap} = const$ (1)

Momentum $\dot{m}\frac{dU_m}{dx} = -A\frac{dP}{dx} - P_t\tau_{wall}$ (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. In the model, mean mixture velocity U_m calculated from the continuity equation Eq.(1):

$$U_m = \frac{\rho_w \dot{V}_w + \rho_{cap}\dot{V}_{cap}}{\rho_m A} = \frac{\dot{V}_w + \rho_w + \rho_{cap}\left(\frac{C}{1-C}\right)}{\rho_m A} \quad (4)$$

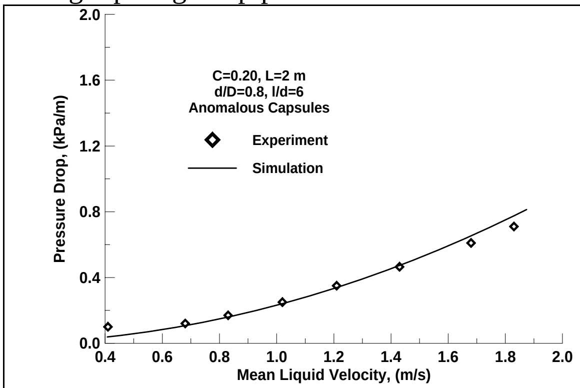
where C presents the concentration of the solid phase in a solid-liquid mixture. In the model, average capsule-water flow suspension density is considered with the following equation:

$$\rho_m = \varepsilon\rho_w + (1-\varepsilon)\rho_{cap} \quad (5)$$

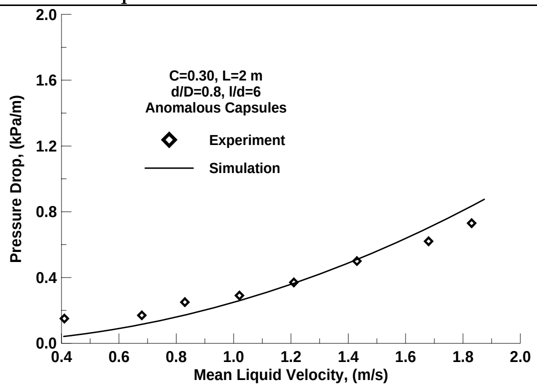
where ε is the radially averaged voidage in the pipe.

3. RESULTS AND DISCUSSION

The developed model has been validated by comparing the simulation results with the results obtained from Vlasak [7]'s experiment. In the experiment, measurements have been carried out in a horizontal straight plexiglass pipe and water has been used as a carrier liquid.



(a)



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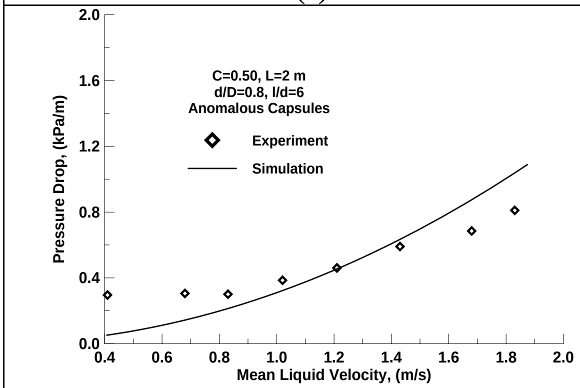

(c)

Table 1. Parameters used in experimental setups [7].

Capsule shape	Anomalous
L (for measuring pressure losses) (m)	2
D (m)	0.05
d/D (-)	0.8
ρ_c (kg/m^3)	1200
C (-)	0.20÷0.50
Reynolds number (-)	$2.5\times10^4 < \mathrm{Re} < 1.5\times10^5$
Water temperature (°C)	20±2

Fig. 1. Comparison of simulation results with Vlasak [7]'s experimental data

Vlasak [7] has reported that, for the velocity of liquid, accuracy was better than 2.5%, the flowmeter was checked by volumetric measurement. Capsule velocities were measured with accuracy within 1.5%. Also, the accuracy of pressure drop measurements was better than 3%. In his experiments, capsules of anomalous shape with a density higher than that of the carrier liquid were used. The main parameters and the range of the experimental conditions are given in Table 1.

Fig.1 shows the comparison of simulation results with Vlasak [7]'s experimental data. Pressure drop increases with increasing carrier liquid velocity, in which capsules of anomalous shape with a density higher than that of the carrier liquid and simulation results are in good agreement with experiments at each capsule concentration; 0.20, 0.30 and 0.50 respectively. At low capsule concentration values, homogeneous model approach calculates pressure drop sufficiently, as the concentration increases over 30% it shows that this model can not be applied with confidence. Since this situation affects the hydrodynamic behavior of the flow due to the interactions between the phases. For anomalous capsule concentration ratios higher than 30%, separated flow model for pressure drop can be suggested as a further approach even though homogenous flow model can give an idea about the pressure drop variation for solid-liquid two-phase mixture.

Table 2. The cases considered in the model.

		Suspension viscosity μ_m	Suspension-wall friction factor f
Case A	Case A1	$\mu_m = \mu_{liquid}\,(1+2.5\cdot C)$	$f = 64/\mathrm{Re}_m$ $\mathrm{Re}_m < 2300$
	Case A2	$\mu_m = \mu_{liquid}\cdot\exp\left(\frac{5(1-\varepsilon)}{3\varepsilon}\right)$	$f = 0.0791/\mathrm{Re}_m^{0.25}$ $\mathrm{Re}_m \geq 2300$
Case B	Case B1	$\mu_m = \mu_{liquid}\,(1+2.5\cdot C)$	$f/2 = 6565/\mathrm{Re}_m^{1.50}$ $2800 < \mathrm{Re}_m < 15000$
	Case B2 (Base Case)	$\mu_m = \mu_{liquid}\cdot\exp\left(\frac{5(1-\varepsilon)}{3\varepsilon}\right)$	$f/2 = 0.0395/\mathrm{Re}_m^{0.25}$ $15000 < \mathrm{Re}_m < 32000$

The suspension to wall friction coefficients and volumetric concentrations of solid phase are important parameters in pressure analysis of capsule train flow. In order to compare the effects and applicability of different suspension viscosity models and suspension to wall friction coefficients on the pressure drop of two-phase mixture, two major cases, Case A and Case B have been taken into consideration through the analysis. The cases considered are summarized in Table 2 assuming the Case B2 as the Base Case used in the model validation. The analyses are performed for the spherical ice particle sized d=0.08 m and carrier liquid of water at temperature of 20°C for various cases related both to the suspension viscosity (Case A2 and Case B2) and to the suspension-wall friction factors (Case A1 and Case A2).

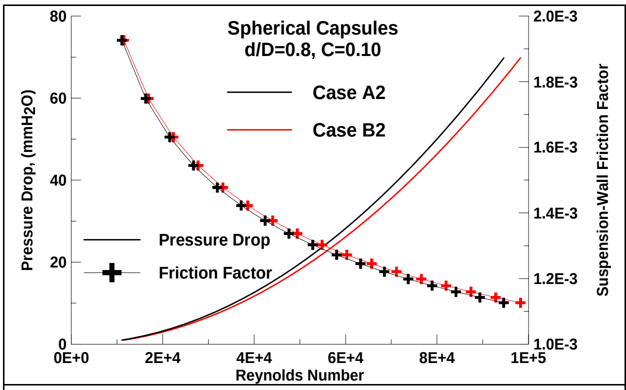

Fig. 2. Effects of suspension viscosities on the pressure drop

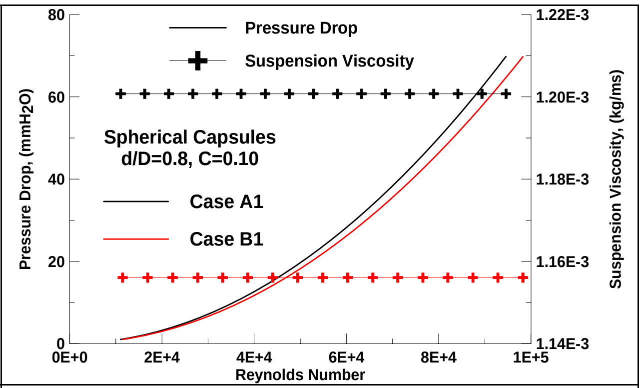

Fig. 3. Effects of suspension to wall friction coefficients on the pressure drop

The effect of friction factor on pressure drop is shown in Fig.2. Even though the variation of pressure drop with respect to Reynolds number values show the same trend at each case (Case A2 and Case

B2), using Blasius friction factor correlation in pressure drop calculation causes over prediction especially at higher Reynolds number values and it deviates from the actual values.

The effect and applicability of empirical suspension viscosity formulas on pressure drop has been shown in Fig.3 for Case A1 and Case A2.Both suspension viscosity formulas in these cases calculate almost the same values for ice-water two-phase mixture and its effect on pressure drop values are about 10.7% in maximum. This shows us that the both formulas can be used in homogeneous model calculations for ice water mixtures. Even though there is no significant difference for low Reynolds number values. With an increase in Reynolds number, suspension to wall friction contribution and suspension viscosity effect on pressure drop increases significantly.

4. CONCLUSION

In the present study, one dimensional model is developed for capsule train flow in a horizontal pipe. Simulation model calculates the pressure drop of the flow of capsule train-water two-phase mixture inside the pipe. Through this model, effects of different suspension viscosity models and suspension to wall friction coefficients on the pressure drop of the capsule flow are investigated. The simulation results are compared with experimental results obtained from the Vlasak [7]'s experiment with capsules of anomalous shape with a density higher than the carrier liquid and developed model has been validated. Through this model, it has been observed that one dimensional homogenous flow model can be used with confidence for pressure drop calculations of solid-liquid two-phase mixture in horizontal pipe especially for anomalous capsules at low concentration values ($C<50\%$), but it shows deviation as the capsule rate increases.

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