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Validation Of A One-Dimensional, Two-Fluid Model For Prediction Of Hydrodynamics And Gas-Solid Heat Transfer In Pneumatic Conveying

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Abstract: Pneumatic conveying systemsfind application in several industries for the twin objective of material transportation and interphase heat transfer, leading to better utilization of thermal energy and increasing the overall energy efficiency. A one-dimensional, two-fluid model has been validated for the prediction of hydrodynamics and heat transfer in vertical pneumatic conveying. The results indicate that a simple one-dimensional model can predict axial profiles of gas velocity, solids velocity and solid phase concentration adequately. Use of thermal conductance, instead of heat transfer coefficient can predict the gas temperature profiles adequately.

Keywords: Simulation, Gas-Solid Heat Transfer, Pneumatic Conveying, Gas Temperature.

1 INTRODUCTION

Pneumatic conveying systems have been operational in process industries for several decades providing a means of transporting particulate materials conveniently between process units ensuring a dust-free transportation. A variety of materials can be transported by pneumatic conveying, which can operate in dilute or dense phase mode. Multiple intakes and multiple deliveries, capability to operate under both positive pressure and vacuum add value and versatility to dilute phase conveying, while lower particle attrition, high solids feed rate and low energy consumption augment the capability of dense phase conveying [1]. Industrially important materials like cement, fuel ash, polyethylene powder, flour exhibit dense phase transport [2]. There are several publications that deal with hydrodynamics of pneumatic conveying [3, 4]. Gas-solid heat transfer is accomplished during pneumatic conveying either by contact of hot gas with cold feed for preheating the feed or by contact of hot solid with cold gas for the purpose of cooling the solids. Gas-solid heat transfer in dilute phase regime has received considerable attention in the past decade [5-10].

Computational fluid dynamics (CFD) is a versatile and valuable tool in understanding the physics of industrially important, multiphase system where the scope for experiments with large range of operating conditions is limited. For instance, it may not be feasible to carry out experiments on parametric variation in a large scale or industrial pneumatic dryer. However, assessment of process variables and their interdependencies is required to develop robust control system. Under these circumstances, computational fluid dynamics may help in prediction of behaviour of large-scale and industrial systems without the need for elaborate experimental study. Computational fluid dynamics involves use of appropriate governing equations, complimentary equations and numerical solution algorithms for predictions.

In the present work, a one dimensional, two-fluid model has been utilized to predict solids velocity, solid phase concentration in isothermal gas-solid flow in pneumatic conveying, apart from prediction of gas temperature for the preheating of gypsum using hot air in a vertical pneumatic conveying heat exchanger.

2 SIMULATION MODEL

A one-dimensional, two-fluid model developed in our earlier work [6] has been used for the simulations. Briefly, the general momentum balance equation for a phase is given as:

$$\frac{\partial\left(m_p u_p\right)}{\partial x} + A\frac{dP_p}{dx} = F_p \qquad (1)$$

In Eq. (1), ‘p’ refers to the phase: gas phase or solid phase; m_p and u_p represent mass flow rate and velocity of ‘p’ phase; P_p represents the pressure of phase ‘p’ and F_p represents the sum of forces acting on the phase ‘p’. For the solid phase, pressure is taken as zero and hence P_p does appear in the equation for solid phase.

F_p for the gas phase includes wall-frictional force determined using Blasius equation, drag force between gas phase and solid phase and the gravitational force. F_p for the solid phase includes drag force and gravitational force.

The energy balance for a phase is given as:

$$\frac{\partial\left(m_p C_p T_p\right)}{\partial x} = Q_p \qquad (2)$$

In Eq. (2), C_p and T_p represent the specific heat and temperature of phase ‘p’. Q_p represents the rate of heat transfer between gas and solid phases, with $Q_g = -Q_S$, where Q_S is the rate of heat gained by solid phase. The governing equations were solved as illustrated in our earlier work [6-7].

3 RESULTS AND DISCUSSION

3.1 SIMULATION RESULTS FOR HYDRODYNAMICS

For comparison of predictions of solids velocity, gas velocity and solid volume concentration with experiments, data of Hariu and Molstad [11] in a vertical lift line as reported in Theologos and Markatos[12] has been used. These experiments and simulations correspond to isothermal gas-solid flow in vertical pneumatic conveying.The details of the experiments of Hariu and Molstad[11] used for validation of simulation are as follows:

<u>Lift line dimensions:</u> Diameter = 13.5 mm; Height = 1.368 m

<u>Particle characteristics:</u>Density = 2643 kg/m^3; Diameter = 503 m; Free-fall velocity = 3.9 m/s

Figure 1 shows the velocity profiles of the two phases along the axial direction for the lift line. The initial gas velocity is 12.3 m/s and the solids feed rate is 3.02 g/s. The simulations (shown as lines in Fig. 1) predict the experimental data for both phases’ velocities reasonably well.

It can be seen from Figure 1 that the particles are accelerated faster in the initial axial locations of the duct, after which the change in solids velocity is less. In vertical pneumatic conveying, pressure drop in the lower portion of the duct is higher compared to that in the later portions of the duct. This is due to the acceleration of particles from an initial very low velocity to a higher velocity [5, 13]. This region is called acceleration region characterized by higher pressure drop, rapid increase in solids velocity and a rapid decrease in solid volume concentration. The gas velocity is practically constant as the loss of momentum in particle acceleration is recovered due to the pressure drop in the duct.

Figure 2 shows the comparison of the present simulations with the data of Hariu and Molstad[11] for solid phase velocity. It is clear from Figure 2 that solids are rapidly accelerated in the lower portions of the duct (acceleration region) and the height of the acceleration region depends on the gas velocity and solids feed rate. Figure 3 shows the comparison of simulated solid volume concentration with the experimental data of Hariu and

Molstad[11].At the bottom of the lift line, it is higher due to very low solids velocity. Rapid decline in solid volume concentration with height in the initial portion is due to the acceleration of solids.

Figures 2 and 3 show that the predictions are reasonably good for wide range of air velocity and solids feed rates. Prediction near the solid inlet (at the duct bottom) may not be good due to lack of information on solid volume fraction or solids velocity at the solid inlet.

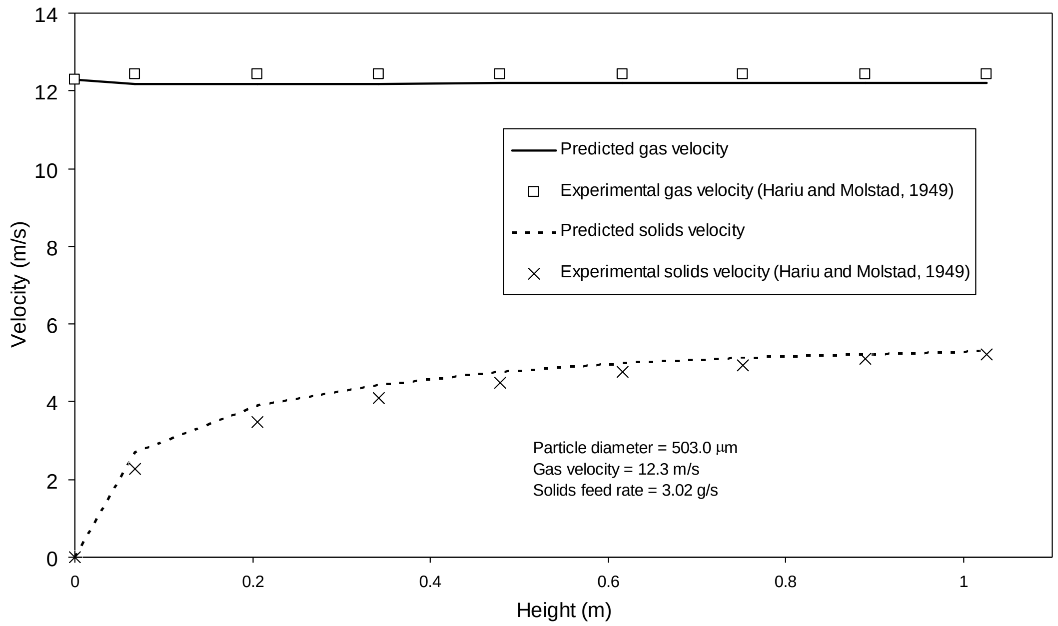

Figure 1. Comparison between the predictions and experimental data of Hariu and Molstad[11] for conveying of 503 m size particles through a lift line of 13.5 mm diameter

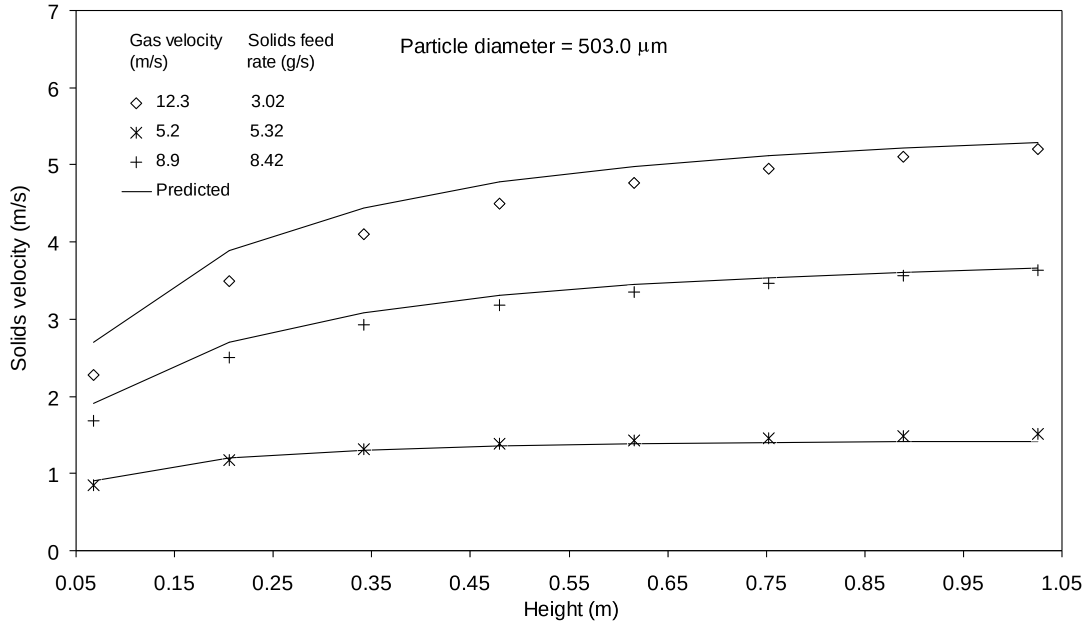

Figure 2. Comparison between the predictions and the data of Hariu and Molstad[11] for solid phase velocity

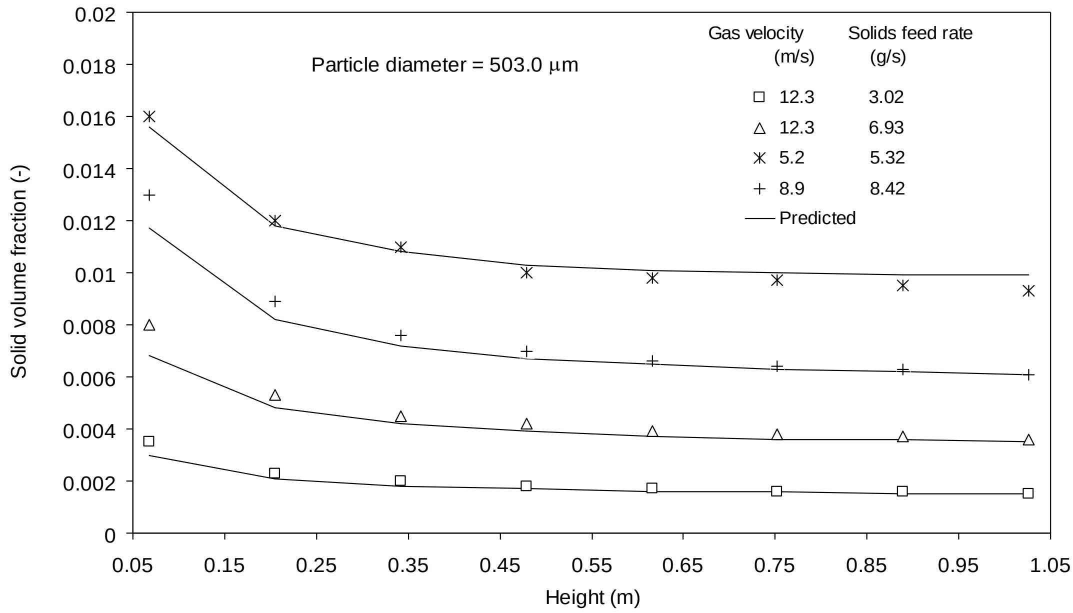

Figure 3. Comparison between the predictions and the data of Hariu and Molstad[11] for solid volume fraction

3.2 SIMULATION RESULTS FOR AXIAL AIR TEMPERATURE PROFILES:

From the above discussions it is evident that the present model and simulation algorithm predict the experimental data well for hydrodynamics. The ability of the two-fluid model utilized to predict gas-solid heat transfer in vertical pneumatic conveying was tested by performing simulations to predict temperature profile of air measured in the vertical pneumatic conveying rig described in our earlier work [8-10].

For simulation of gas-solid heat transfer, Q_S is given by

$$Q = h_p S_h \left(T_g - T_s\right) = \left(\frac{h_p A_h}{L}\right)\left(T_g - T_s\right) = \left(\frac{h_p A_h}{k_g L}\right)\left(T_g - T_s\right)\left(k_g\right) \tag{3}$$

Rajan et al. [10] have proposed an empirical correlation for prediction of thermal conductance in pneumatic conveying heat exchanger. This correlation has been used in Eq. (3) for one-dimensional simulation of gas-solid heat transfer in vertical pneumatic conveying. Correlation for gas-solid heat transfer coefficient has not been used for the simulations as it would require determination of regime of conveying.

Figures 4 to 7 show the comparison between the predicted and experimental temperature profile of air in the vertical pneumatic conveying duct for heat transfer to cold particles of different sizes [14] at similar solid loading ratios (solids feed rate to air mass flow rate). Figures 4 to 7 show some error in the predictions for the lower portion of the duct. This may be attributed to higher particle concentrations in the acceleration region after the ‘Tee’ in the experimental setup [8]. Since the correlation for thermal conductance was developed by taking the average air-solid heat transfer rate for the entire duct height, the predictions of simulations for gas-solid heat transfer are less than actual values in lower portions of the duct.

Predictions for relatively higher solid loading ratio (~0.8) for heat transfer to 460 and 547.5 μm particles are shown in Figures 8 and 9. Predictions are reasonably good for these experiments also, illustrating the applicability of the model and simulation procedure.

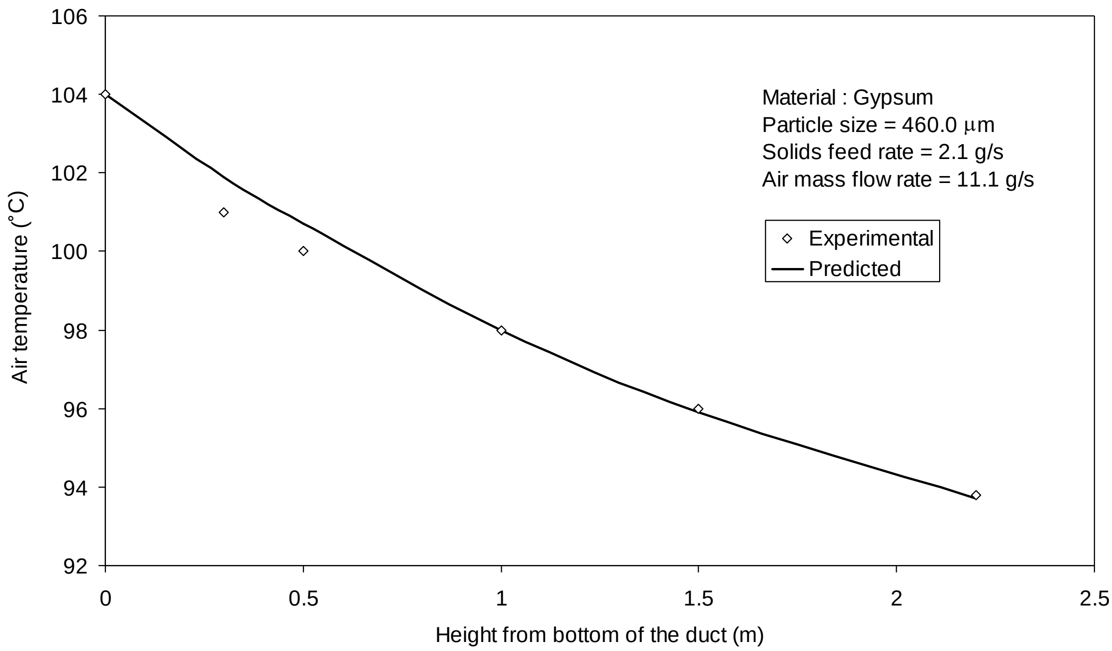

Figure 4: Comparison of predicted air temperature profile with the experimental data for air-gypsum heat transfer in vertical pneumatic conveying of 460 m particles at lower solid loading ratio [14]

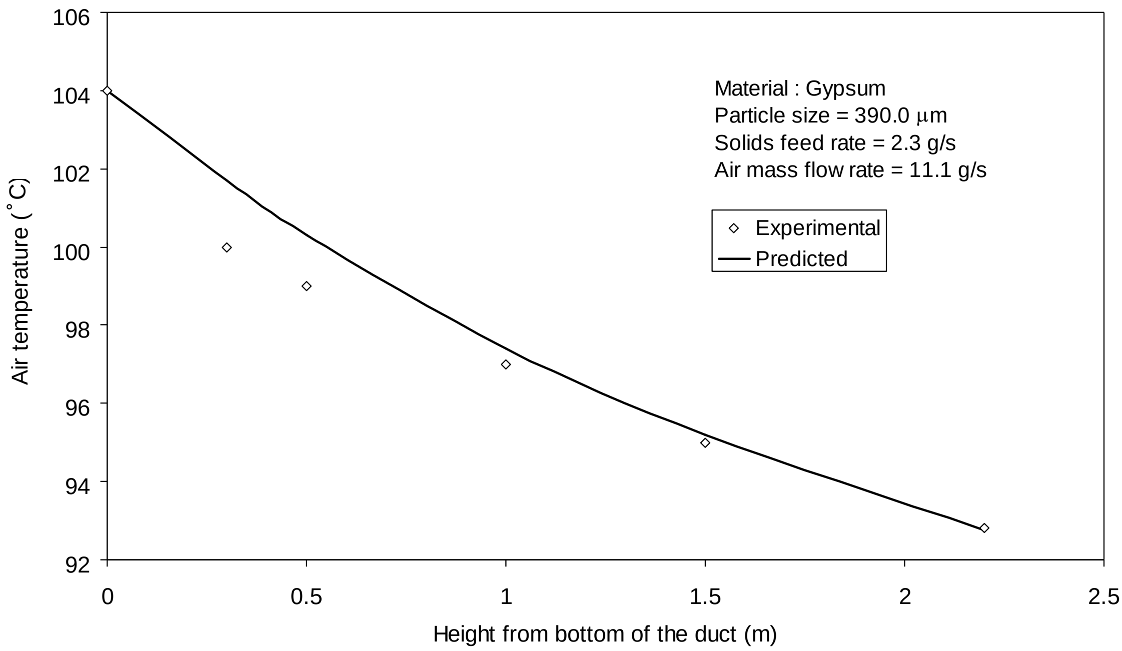

Figure 5: Comparison of predicted air temperature profile with the experimental data for air-gypsum heat transfer in vertical pneumatic conveying of 390 m particles at lower solid loading ratio [14]

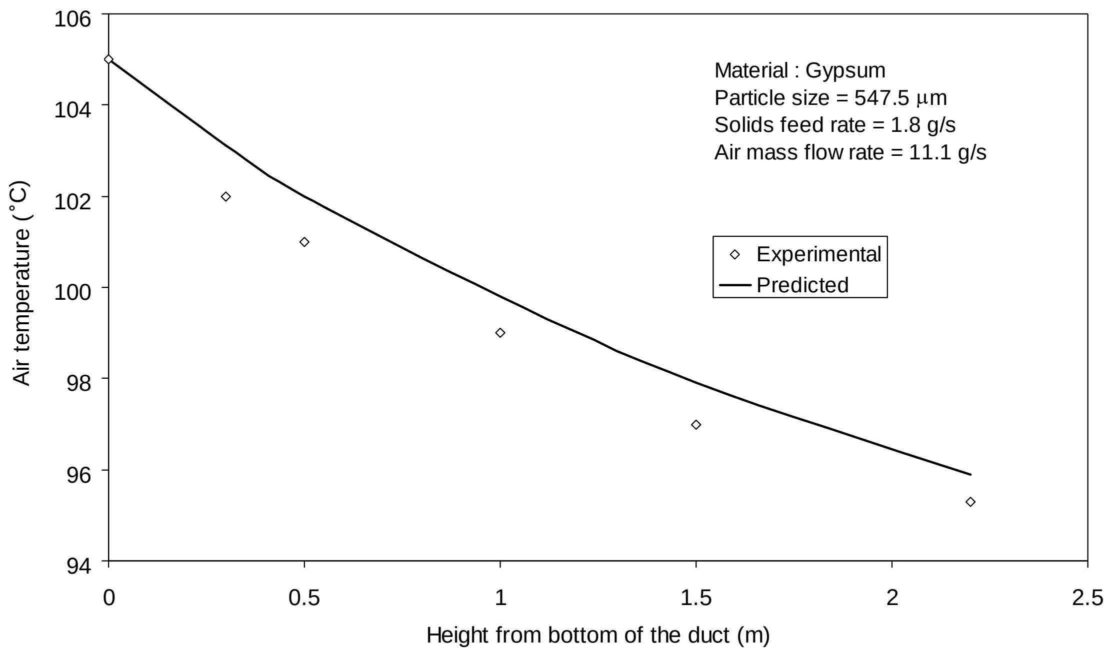

Figure 6: Comparison of predicted air temperature profile with the experimental data for air-gypsum heat transfer in vertical pneumatic conveying of 547.5 m particles at lower solid loading ratio [14]

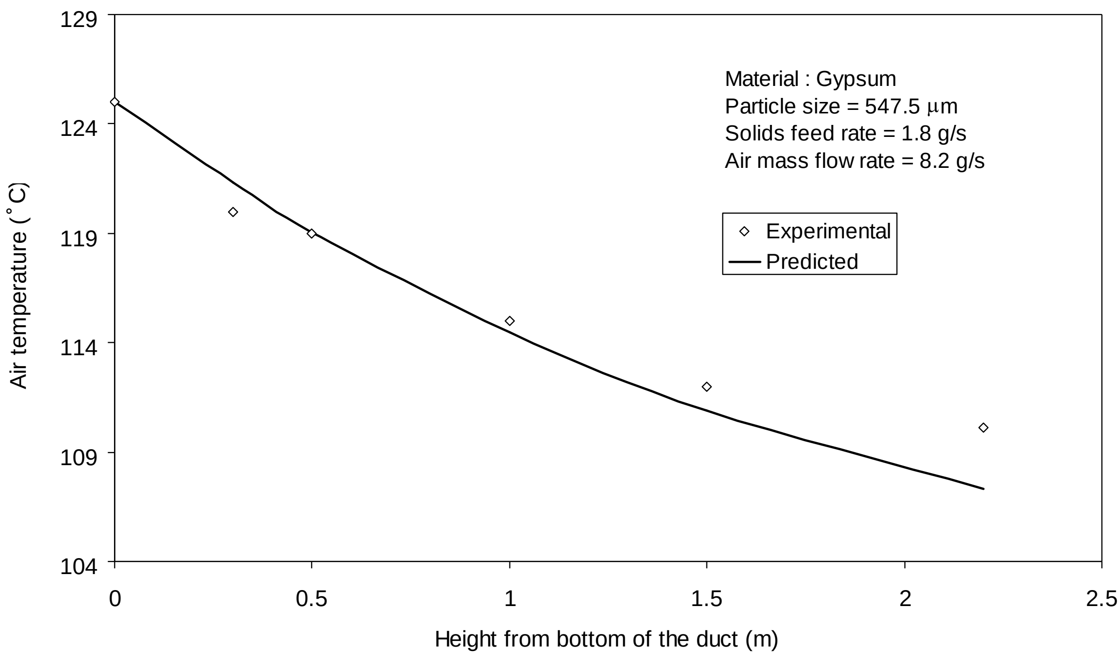

Figure 7: Comparison of predicted air temperature profile with the experimental data for air-gypsum heat transfer in vertical pneumatic conveying of 547.5 m particles at lower solid loading ratio [14]

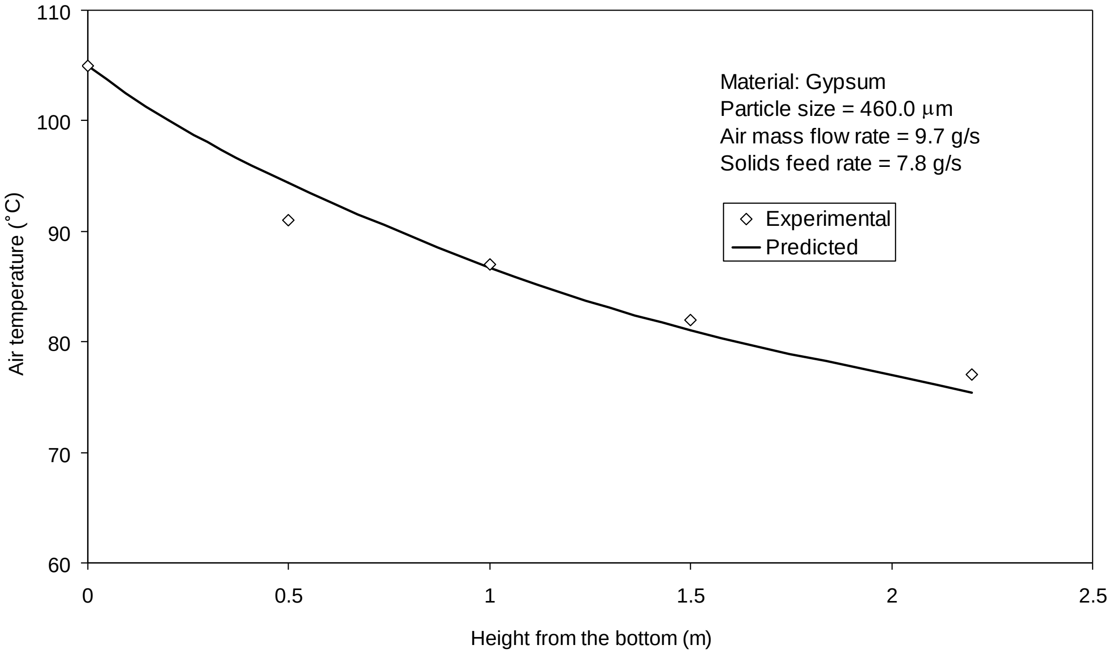

Figure 8: Comparison of predicted air temperature profile with the experimental data for air-gypsum heat transfer in vertical pneumatic conveying of 460 m particles at solid loading ratio of 0.8 [14]

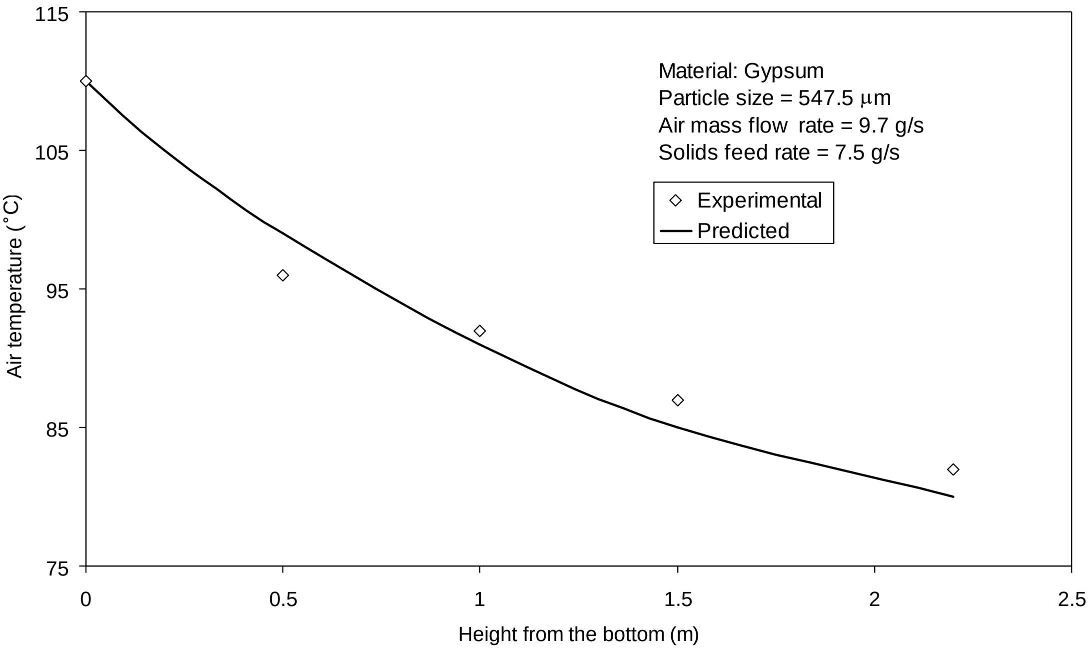

Figure 9: Comparison of predicted air temperature profile with the experimental data for air-gypsum heat transfer in vertical pneumatic conveying of 547.5 m particles at solid loading ratio of 0.8 [14]

4 CONCLUSIONS

A one-dimensional, two-fluid for simulation of hydrodynamics and heat transfer in pneumatic conveying has been validated by comparison with experimental literature data. The predictions of air velocity, solid velocity and solid phase concentration were highly satisfactory for gas-solid flow up to a solid loading ratio of ~ 1.7. Prediction of gas temperature profiles were also in conformity with the experimental air temperature data for the range of solid loading ratio between 0.15 and 0.8. Another important finding of this study is the use of thermal conductance instead of heat transfer coefficient for the estimation of heat transfer rate and the gas phase temperature in control volumes.

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