Three-dimensional gas-solid fluidized bed simulation based on the kinetic theory of granular flow

Maria G. E. Silva[1], Fábio Marini, Milton Mori[1]

[1]University of Campinas, School of Chemical Engineering, Department of Chemical Processes, P.O. Box 6066, 13083-970, Campinas-SP, Brazil

Introduction: Fluidized beds are widely used in many operations in chemical, metallurgical, energy generation and especially petrochemical industries. Major applications are fluid catalytic cracking (FCC) risers and CFB combustor systems. Although fluidized beds are successfully and widely used in commercial industrial operations, much remains to be done due to the complexity of the gas-solid flow. In this study, a three-dimensional two-phase flow model based on the kinetic theory of granular flow (KTGF) was used to predict the behavior of a gas-solid fluidized bed. The model is based on a Eulerian description of the two phases, gas and particles. In this model, the k-epsilon turbulence model and multiphase mixture are used. In order to describe the behavior of several particles in a continuum, the kinetic theory of granular flow was used. Results using this model show that the model agrees with the experimental data and predicts a flow behavior similar to that found experimentally.

Mathematical Model: Based on Eulerian description of the phases, a multiphase computational fluid dynamics model for turbulent gas-solid flow is presented. The Eulerian approach considers the two phases, gas and solid, as a continuum. The *k-ε* turbulence model was applied to determine the influence of turbulence on the gas phase. The gas-solid drag coefficient when $\varepsilon_g \leq 0.8$ is based on the Ergun equation and when $\varepsilon_g \leq 0.8$, based on the Wen and Yu equation.

The conservation equations for the solid phase are based on the kinetic theory for granular flow.

The continuity equation for phase i (= gas, solid)

$$\frac{\partial}{\partial t}(\varepsilon_i\rho_i)+\nabla\cdot(\varepsilon_i\rho_i\vec{\upsilon}_i)=S_i^{\rho}$$

The gas phase momentum equation:

$$\frac{\partial}{\partial t}(\varepsilon_g\rho_g\vec{\upsilon}_g)+\nabla\cdot(\varepsilon_g\rho_g\vec{\upsilon}_g\vec{\upsilon}_g)=-\varepsilon_g\nabla p_g+\nabla\vec{\tau}_g+\varepsilon_g\rho_g\vec{g}+\beta_{gs}^{m}(\vec{\upsilon}_s-\vec{\upsilon}_g)$$

$$\vec{\tau}_g=\varepsilon_g\mu_g\left(\left(\nabla\vec{\upsilon}_g+(\nabla\vec{\upsilon}_g)^T\right)-\frac{2}{3}(\nabla\cdot\vec{\upsilon}_g)\vec{I}\right)$$

The solid phase momentum equation:

$$\frac{\partial}{\partial t}(\varepsilon_s\rho_s\vec{\upsilon}_s)+\nabla\cdot(\varepsilon_s\rho_s\vec{\upsilon}_s\vec{\upsilon}_s)=\nabla\vec{T}_s+\varepsilon_s\rho_s\vec{g}+\beta_{gs}^{m}(\vec{\upsilon}_g-\vec{\upsilon}_s)$$

$$\vec{T}_s=(-p_s+\lambda_s\nabla\cdot\vec{\upsilon}_s)\vec{I}+\mu_s\left(\left(\nabla\vec{\upsilon}_s+(\nabla\vec{\upsilon}_s)^T\right)-\frac{2}{3}(\nabla\cdot\vec{\upsilon}_s)\vec{I}\right)$$

$$p_s^{k+t}=\rho_s\varepsilon_s[1+2(1+e)\varepsilon_s g_o]\theta$$

$$P_p=P_p^{k+t}+P_p^{f}$$

$$P_s^f=Fr\frac{(\varepsilon_s-\varepsilon_{s,min})^n}{(\varepsilon_{s,max}-\varepsilon_s)^p}\qquad g_o=\left(1-\frac{\varepsilon_s}{\varepsilon_{s,max}}\right)^{-2.5\varepsilon_{s,max}}$$

Kinetic theory for granular flow:

Granular temperature: $$\theta=\frac{1}{15(1-e)}d_p^2\left(\frac{1}{2}\left(\nabla\vec{\upsilon}_s+(\nabla\vec{\upsilon}_s)^T\right)\right)$$

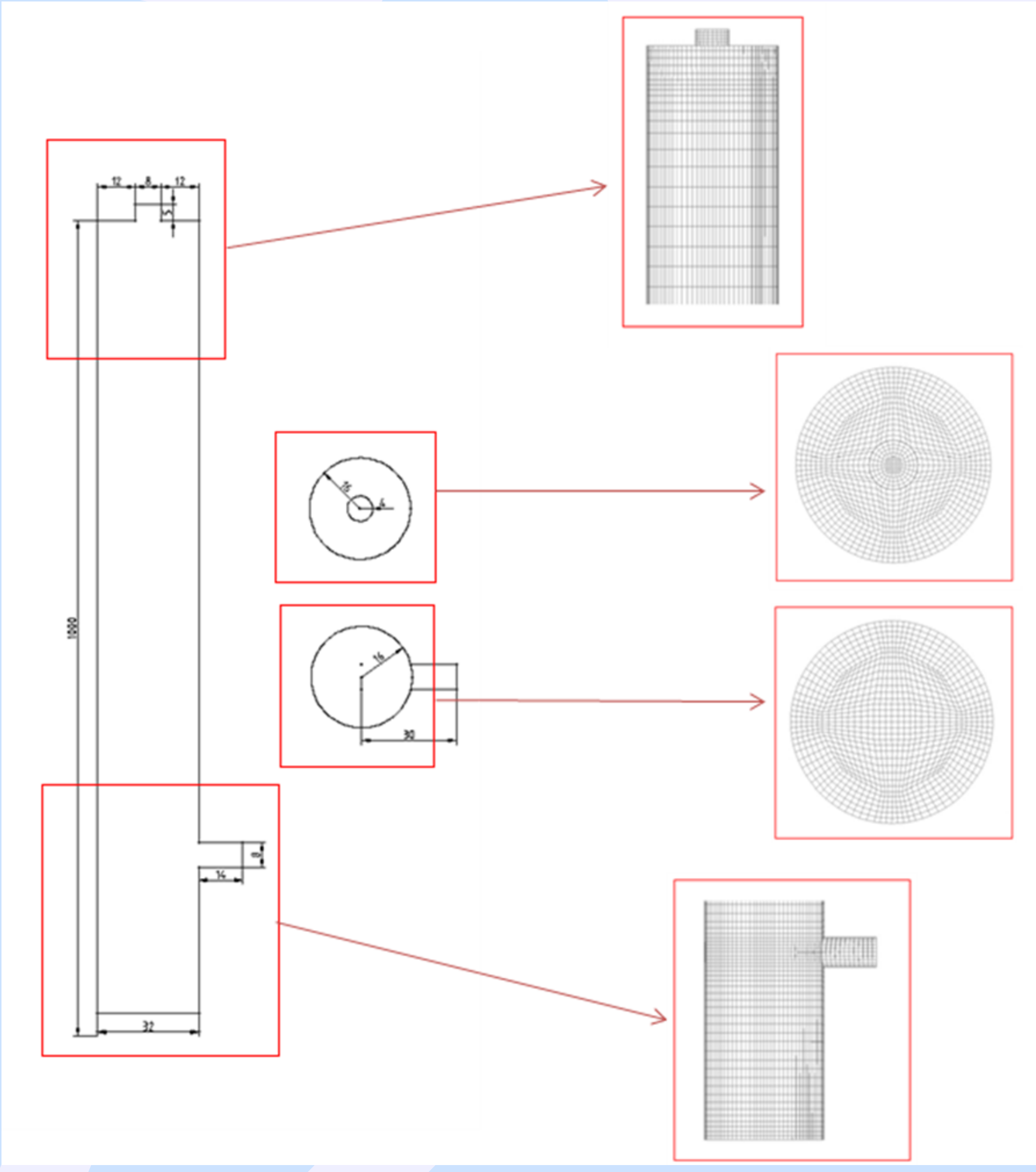
Solid phase bulk viscosity: $$\lambda_s=\frac{4}{3}\varepsilon_s^2\rho_s d_s g_o(1+e)\sqrt{\frac{\theta}{\pi}}$$

Solid phase shear viscosity:

$$\mu_s=\frac{5\sqrt{\pi\theta}}{96}\rho_s d_s\left[\left(\frac{1}{1+\frac{\lambda_{mfs}}{R}}\frac{1}{\eta g_o}+\frac{8\varepsilon_s}{5}\right)\left(\frac{1+\frac{8}{5}\eta(3\eta-2)\varepsilon_s g_o}{2-\eta}\right)+\frac{768}{25\pi}\eta\varepsilon_s^2 g_o\right]$$

Conclusions: A three-dimensional two-phase flow model based on the kinetic theory of granular flow (KTGF) was used to predict the behavior of a gas-solid fluidized bed. The numerical results are compared against the experimental results of Samuelsberg and Hjertager (1996). The agreement is found to be satisfactory in the riser central region. However, in the wall region, the numerical results indicated a significant difference between all results compared.

Calculation domain and grid nodes



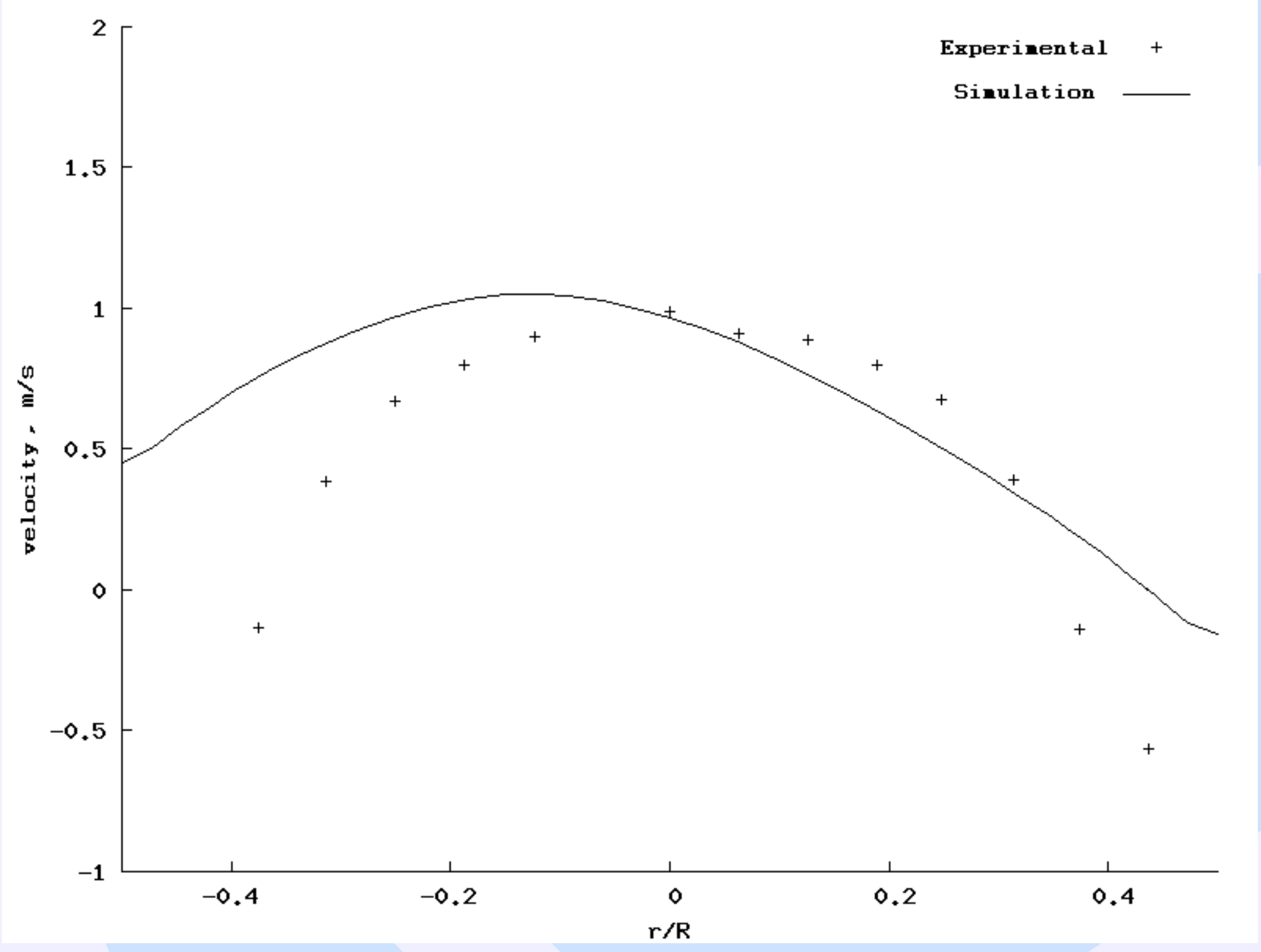
Conditions:

The riser section is 1m high with an inner diameter of d = 0.032m. A secondary air supplier, positioned 0.05m above the gas inlet, feeds the solid back into the riser. The secondary gas inlet and the gas outlet have a diameter of 0.008m. The initial bed height is 0.05m and the initial solid volume fraction is 0.61. The particles have an average diameter of 60μm and a density of 1600kg/m³. At the primary gas inlet, the superficial gas velocity was 0.71m/s.

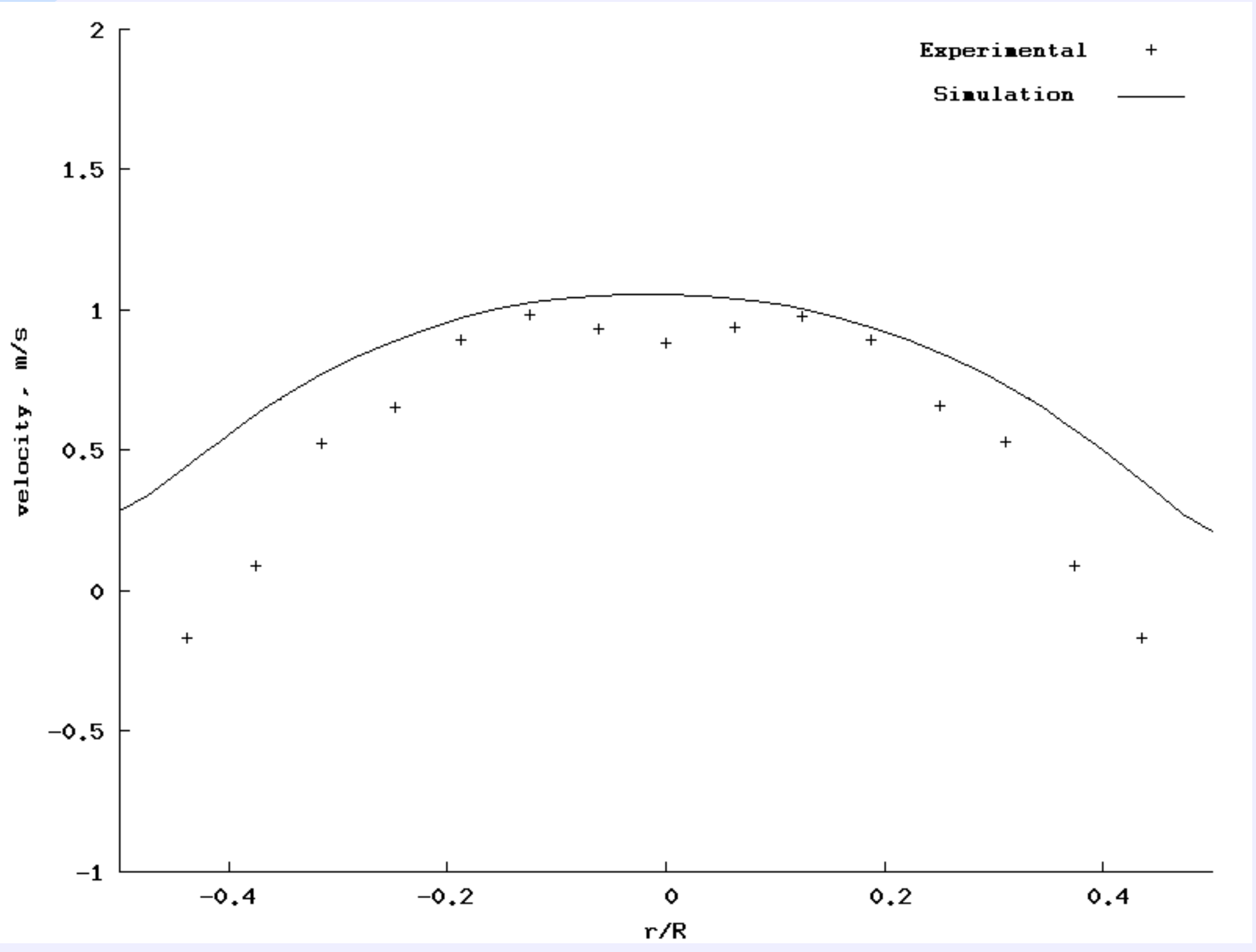
At the secondary gas inlet, the gas velocity and volume fraction were 0.05m/s and 0.6, respectively, and the particle volume fraction was 0.4. All the simulations were run for 7s of real time.

Results:

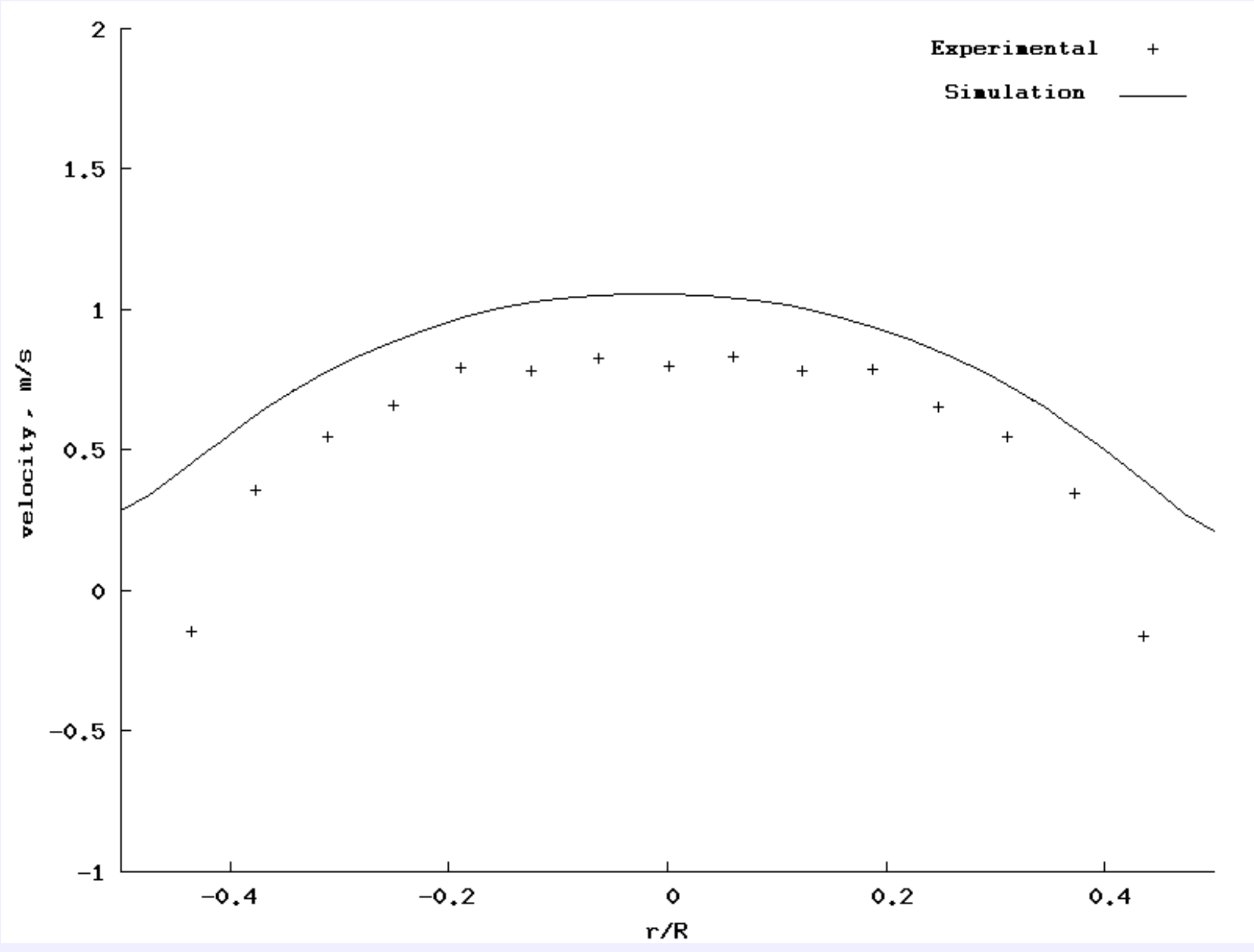
profile of solids velocity at height of:



(a) 0.16m



(b) 0.32m



(c) 0.48m