Experimental verification of a theoretical model for the influence of particle inertia and gravity on decaying turbulence in a particle-laden flow

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Outlook

review of theoretical model

gravity term

relevant parameters

comparison with experiments

conclusions

Review of theoretical model

one-fluid equation of motion for particle-laden flow:

$$\rho_{eff}(k)\left[\frac{\partial}{\partial t}+\gamma_p(k)+\gamma_0(k)\right]\mathbf{u}(t,\mathbf{k}) = -\mathbf{N}\{\mathbf{u},\mathbf{u}\}_{t,\mathbf{k}}+\mathbf{f}\{t,\mathbf{k}\}$$

with

$$\rho_{eff}(k) = \rho_f\left(1-\psi+\phi\frac{1+2\tau_p\gamma(k)}{(1+\tau_p\gamma(k))^2}\right)$$

$$\gamma_p(k) = \frac{(\phi/\tau_p)[1+\tau_p\gamma(k)-2\{\tau_p\gamma(k)\}^2]/[2-2\{\tau_p\gamma(k)\}^2]}{1-\psi+\phi[1-\tau_p\gamma(k)]/[2-2\{\tau_p\gamma(k)\}^2]}$$

$$\gamma_0(k) = \nu_{eff}(k)k^2 \quad \text{and} \quad \nu_{eff}(k) = \nu\rho_f/\rho_{eff}(k)$$

Review of theoretical model (cont.)

from the previous equation a budget equation for the turbulent kinetic energy can be derived:

$$\frac{1}{2}\frac{\partial E_s(t,k)}{\partial t} + [\gamma_0(k) + \gamma_p(k)]E_s(t,k) = W(t,k) + R(t,k)$$

with gravity this equation can be extended to:

$$\frac{1}{2}\frac{\partial E_s(t,k)}{\partial t} + [\gamma_0(k) + \gamma_p(k)]\,E(t,k) = W(t,k) + R(t,k) + G(t,k)$$

Gravity term

the turbulence generated by the settling particles can be modelled as:

$$G(k,t) = \frac{\rho_f \phi v_{tv}^2}{\tau_p} \left[\frac{1}{\sigma (2\pi)^{1/2}} exp \left(\frac{-\frac{1}{2}(k-2\pi/\Lambda)^2}{(\sigma)^2} \right) \right]$$

σ represents the width of the turbulence spectrum generated by the settling particles

$2\pi/\Lambda$ is the mean wave number of the turbulence spectrum

Closure relations

$$E_s(t,k) = C_1 \left[\epsilon^2(t,k)\rho_{eff}(t,k)/k^5\right]^{1/3}$$

$$\gamma(t,k) = \gamma_0(t,k) + \gamma_c(t,k)$$

with

$$\gamma_c(t,k) = C_2 \left[k^2\epsilon(t,k)/\rho_{eff}(t,k)\right]^{1/3}$$

$\epsilon(t,k)$ represents the energy flux through the eddies

Equation for energy flux through eddies

the non-linear term is assumed to be conservative:

$$R(t,k) = -\frac{\partial \epsilon(t,k)}{\partial k}$$

the dimensionless equation for the energy flux through the eddies is then given by:

$$f(\tau,\kappa)\frac{\partial \epsilon_\kappa(\tau,\kappa)}{\partial \tau} + \frac{\partial \epsilon_\kappa(\tau,\kappa)}{\partial \kappa} + g(\tau,\kappa) = G_\kappa(\kappa))$$

initial condition and boundary condition

the initial condition (at $\tau = 0$) is given by:

$$\epsilon_\kappa = \left(1 - \frac{C_1}{4Re_f}\kappa^{4/3}\right)^3 \Big/ \left(1 - \frac{C_1}{4Re_f}\right)^3$$

the boundary condition is as follows:

energy flux $\epsilon_\kappa = 0$ at $\kappa = 1$

relevant dimensionless parameters

δ: dimensionless particle response time $[\delta = \tau_p \gamma_L]$

Re_f: fluid Reynolds number $\left[Re_f = u_L L/\nu\right]$

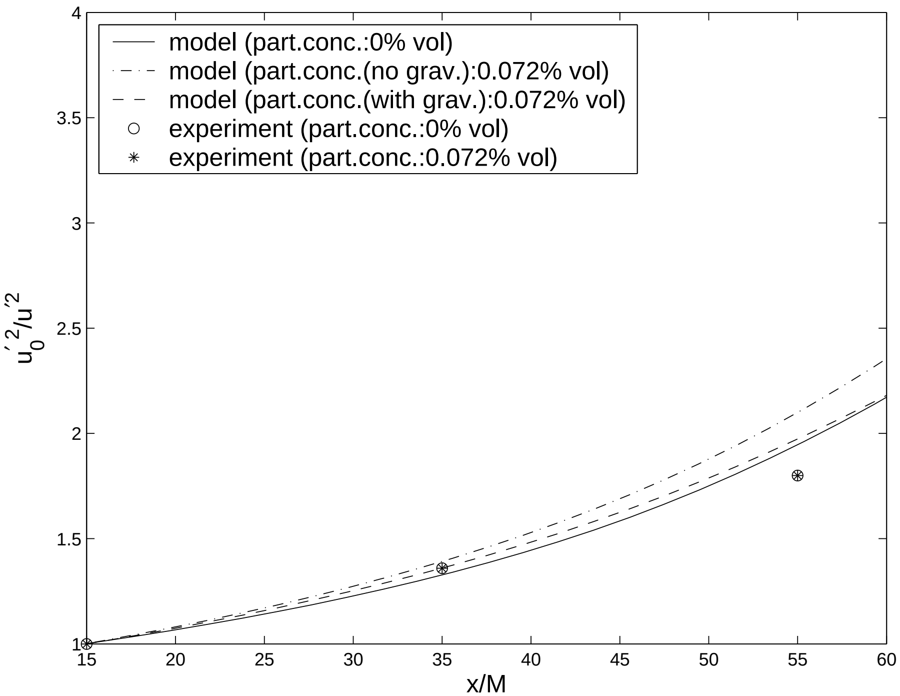
Fr: Froude number $\left[Fr = (\rho_p u_L^2)/(\Delta \rho g L)\right]$

ψ: particle volume fraction

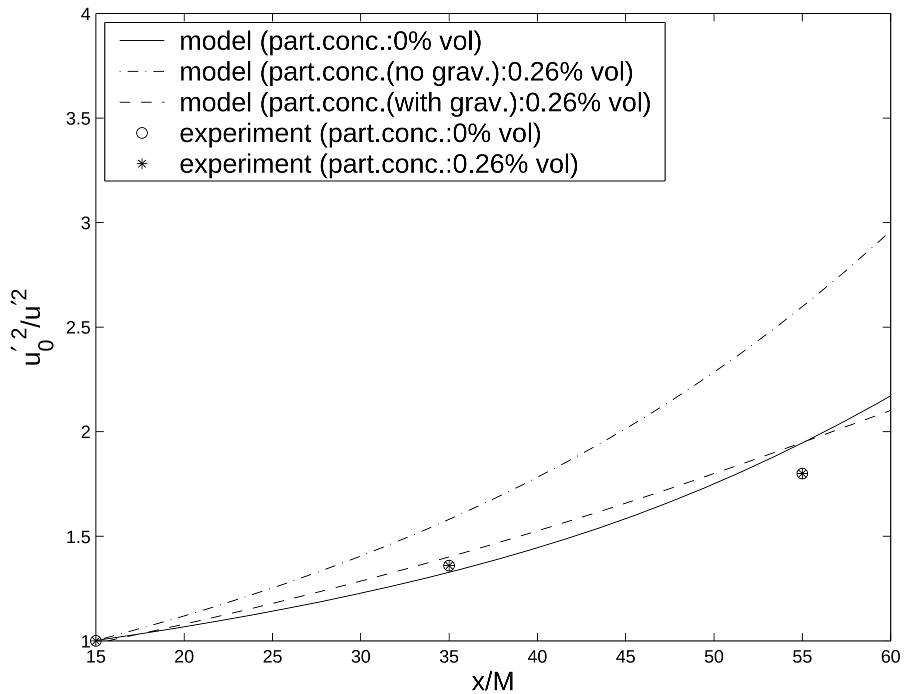
ϕ: particle mass fraction

Λ/L: dimensionless particle-generated turbulence length scale

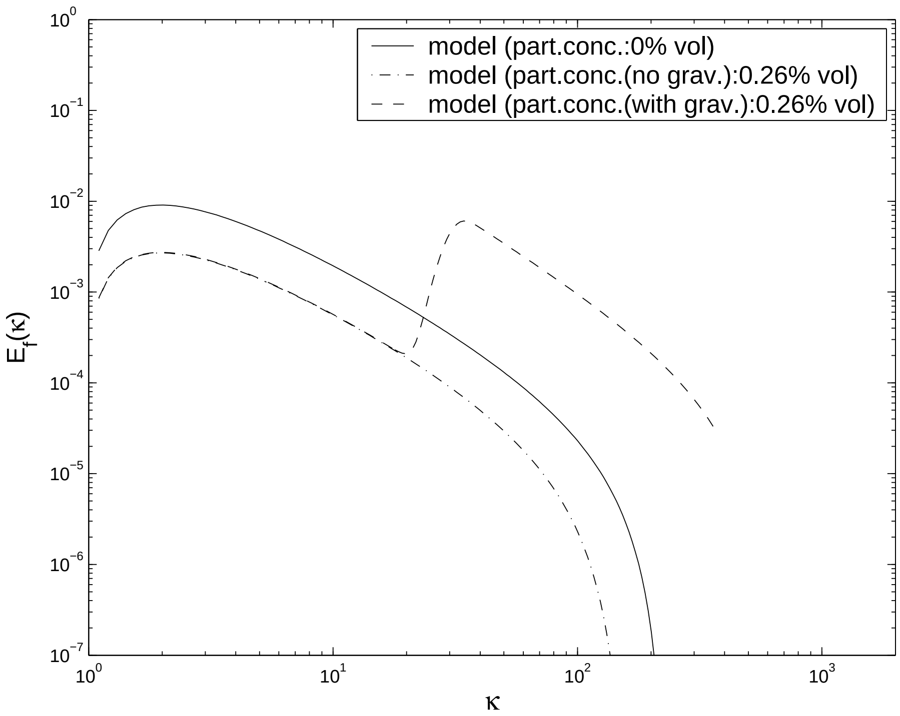
$\phi\delta/Fr^2$ and Λ/L are the determing parameters for the importance of particle-generated turbulence



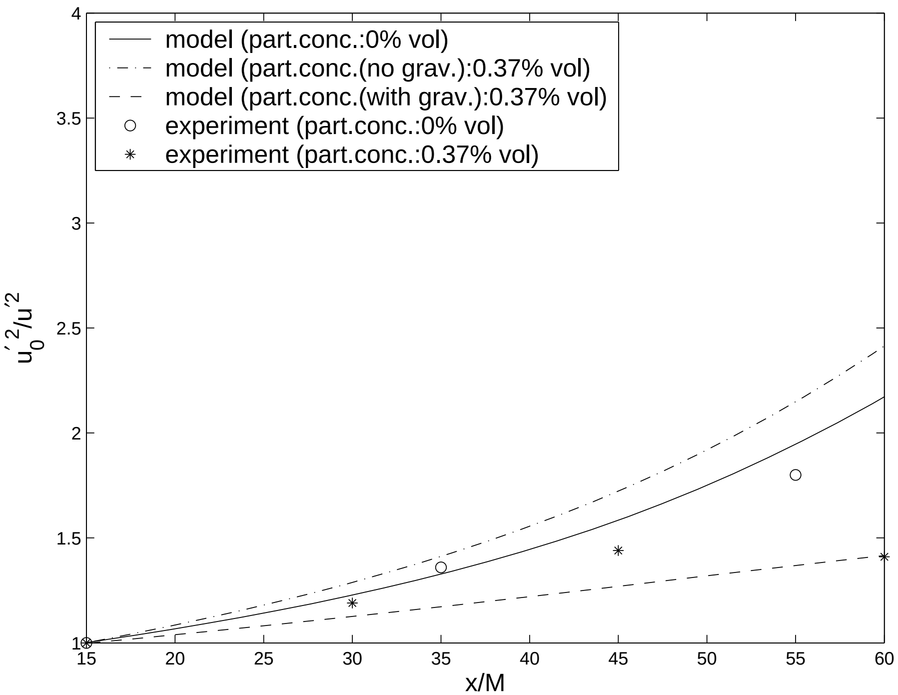
Comparison with Poelma et al. (glass particles in water), $\psi = 0.00072$, $\phi = 0.0018$, $\delta = 0.0044$, $Re_f = 800$, $Fr = 0.0017$ and $\Lambda/L = 0.17$. $\phi\delta/Fr^2 = 2.74$.



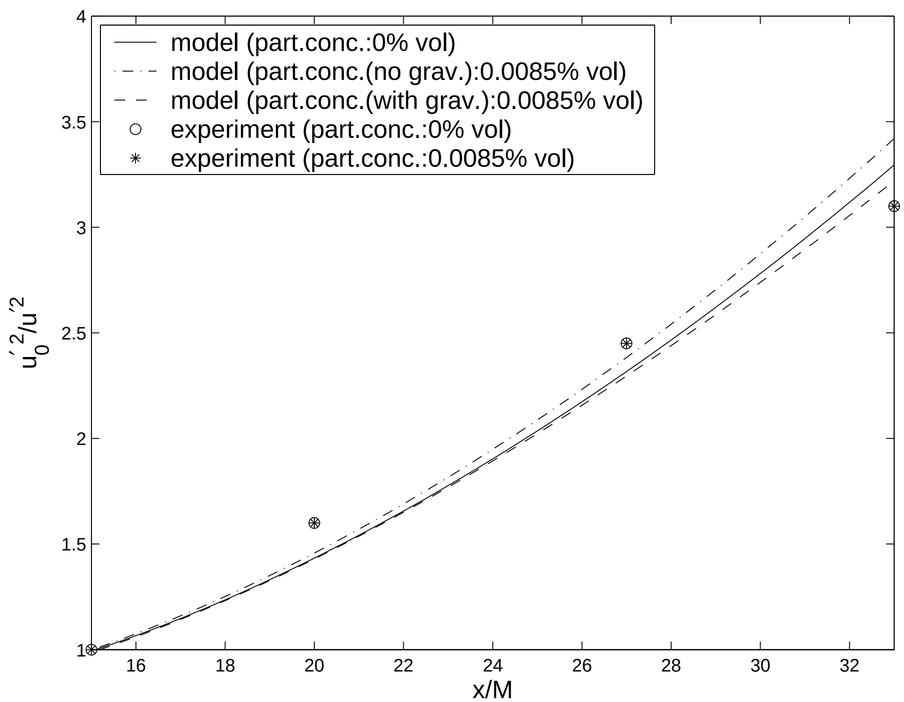
Comparison with Poelma et al. (glass particles in water), $\psi = 0.0026$, $\phi = 0.0065$, $\delta = 0.0044$, $Re_f = 800$, $Fr = 0.0017$ and $\Lambda/L = 0.2$. $\phi\delta/Fr^2 = 9.9$.



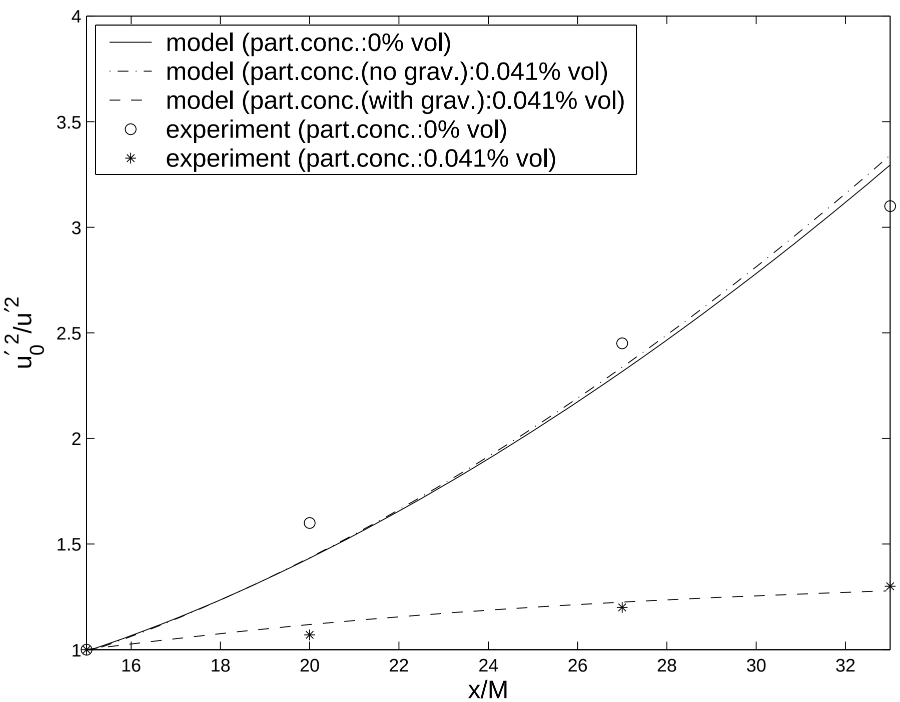
Turbulent energy spectrum of the carrier fluid as a function of the (dimensionless) wave number, $\psi = 0.0026$, $\phi = 0.0065$, $\delta = 0.0044$, $Re_f = 800$, $Fr = 0.0017$ and $\Lambda/L = 0.2$. $\phi\delta/Fr^2 = 9.9$.



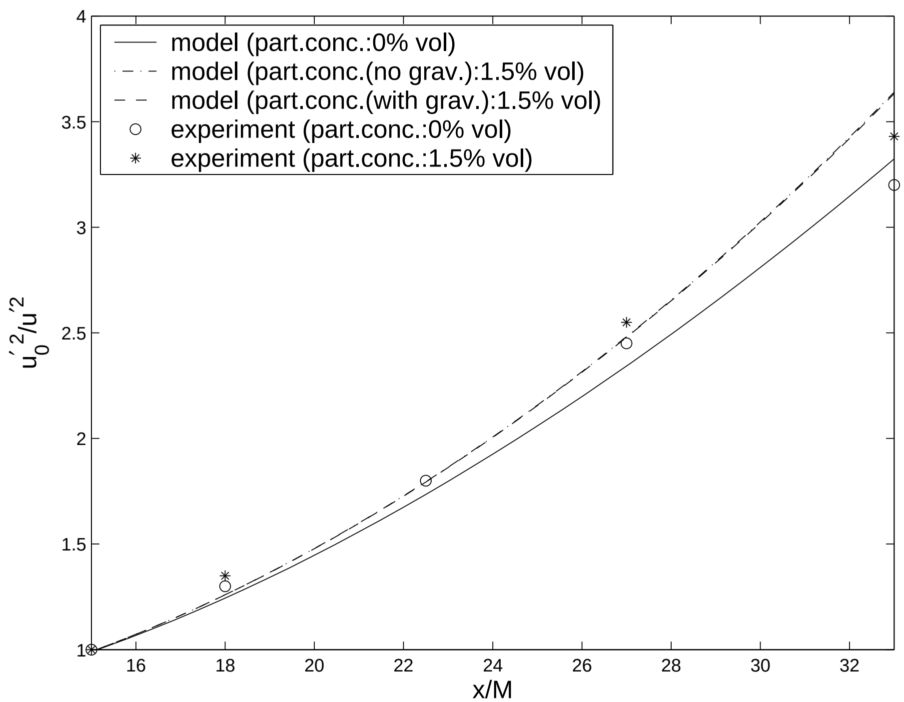
Comparison with Poelma et al. (glass particles in water), $\psi = 0.0037$, $\phi = 0.0092$, $\delta = 0.0176$, $Re_f = 800$, $Fr = 0.0017$ and $\Lambda/L = 0.25$. $\phi\delta/Fr^2 = 56$.



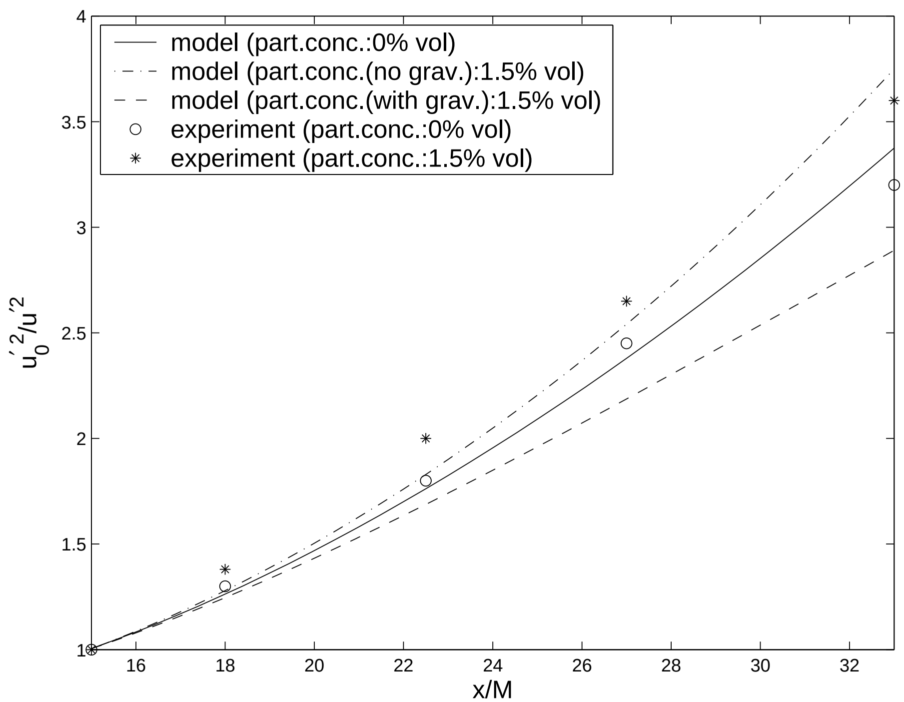
Comparison with Geiss et al. (glass particles in air), $\psi = 0.000085$, $\phi = 0.166$, $\delta = 1.8$, $Re_f = 1060$, $Fr = 1.2$ and $\Lambda/L = 0.27$. $\phi\delta/Fr^2 = 0.2$.



Comparison with Geiss et al. (glass particles in air), $\psi = 0.00041$, $\phi = 0.8$, $\delta = 29.4$, $Re_f = 1060$, $Fr = 1.2$ and $\Lambda/L = 0.72$. $\phi\delta/Fr^2 = 16.5$.



Comparison with Schreck and Kleis (plastic particles in water), $\psi = 0.0150$, $\phi = 0.0157$, $\delta = 0.036$, $Re_f = 7000$, $Fr = 0.33$ and $\Lambda/L = 0.2$. $\phi\delta/Fr^2 = 0.0051$.



Comparison with Schreck and Kleis (glass particles in water), $\psi = 0.0150$, $\phi = 0.036$, $\delta = 0.070$, $Re_f = 7000$, $Fr = 0.024$ and $\Lambda/L = 0.06$. $\phi\delta/Fr^2 = 4.3$.

Conclusions

$\phi\delta/Fr^2$ and Λ/L are the factors determining the influence of gravity.

Gravity can play an important role and the energy spectrum is then influenced by turbulence generation due to particle settling.

Grid-generated turbulence decays downstream, whereas particle-generated turbulence remains constant. So far downstream of the grid particle-generated turbulence becomes dominant. This is the reason why the inverse (dimensionless) turbulence intensity does not continue to increase downstream, but becomes constant.