Turbulence Modulation in Particle Laden Flows
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Abstract
Addition of particles or droplets to turbulent liquid flows or addition of droplets to turbulent gas flows (spray combustion) can lead to modulation of turbulence characteristics. Corresponding observations were reported already for very small particle volume loadings $\Phi_v$ and therefore may be important when simulating such flows. In this work, a new model that reproduces anisotropic turbulence attenuation effects is presented. The model is validated based on the experiments of Poelma et al. [1] involving light particles [Stokes number $St=O(0.1)$, density ratio $\rho_p/\rho=O(1)$, $\Phi_v=O(10^{-3})$] settling in grid turbulence. The development in this work is restricted to volume loadings where particle collisions are negligible.

Experimental Setup
Poelma et al. have studied anisotropic dissipation effects in a solid/liquid two phase system. In their experiments, particles were settling in a vertical channel at constant mean velocities relative to a uniform, upward fluid flow as sketched in figure 1. Poelma et al. have varied the particle diameter, density, and volume loading $\Phi_v$ and have provided Reynolds stress measurements at different downstream locations $x_1$. In figure 2, the reported Reynolds stresses in streamwise ($x_1$) and spanwise directions ($x_2$) are depicted for two different loadings $\Phi_v$. Increasing $\Phi_v$ leads to larger anisotropy in the Reynolds stress tensor $\langle u'iu'j \rangle$.

Model Formulation
Based on the analysis of Poelma et al., a model expression for an anisotropic dissipation tensor $E$ with elements $\varepsilon_{ij}$ is proposed and validated. The Reynolds stress transport equation for incompressible particle laden flows reads

$$\frac{\partial (u'iu'_j)}{\partial t} + \langle u'_k \frac{\partial (u'iu'_j)}{\partial x_k} \rangle = - \frac{\partial (u'iu'_j)}{\partial x_k} + \tau_{ij} + \Pi_{ij} + \nu \frac{\partial^2 (u'iu'_j)}{\partial x_k \partial x_k} - \varepsilon_{ij} + \langle \tau_{mi}u'_m f_j \rangle + \langle \Pi_{mi}u'_m f_j \rangle$$

For the flow studied by Poelma et al., the model proposed for the dissipation tensor has the following form

$$E \equiv \begin{pmatrix} 2(1-\kappa) & 0 & 0 \\ 0 & \kappa - 1 & 0 \\ 0 & 0 & \kappa - 1 \end{pmatrix} + \begin{pmatrix} 2\kappa \end{pmatrix} \frac{\varepsilon}{3}$$

with

$$\kappa \equiv 1 + C_n MVS \text{ and } MVS \equiv \Phi_v \frac{\rho_p}{\rho} \sqrt{\frac{(\langle u' \rangle - \langle \rho \rangle)(\eta)}{2k/3}}$$

Here, $\kappa$ quantifies the dissipation rate anisotropy and depends on the mass-velocity-size (MVS) coefficient and the model parameter $C_n$ that was set to 28.

References