基于直接数值模拟数据的多相流雷诺应力模型研究

夏严 余钊圣*

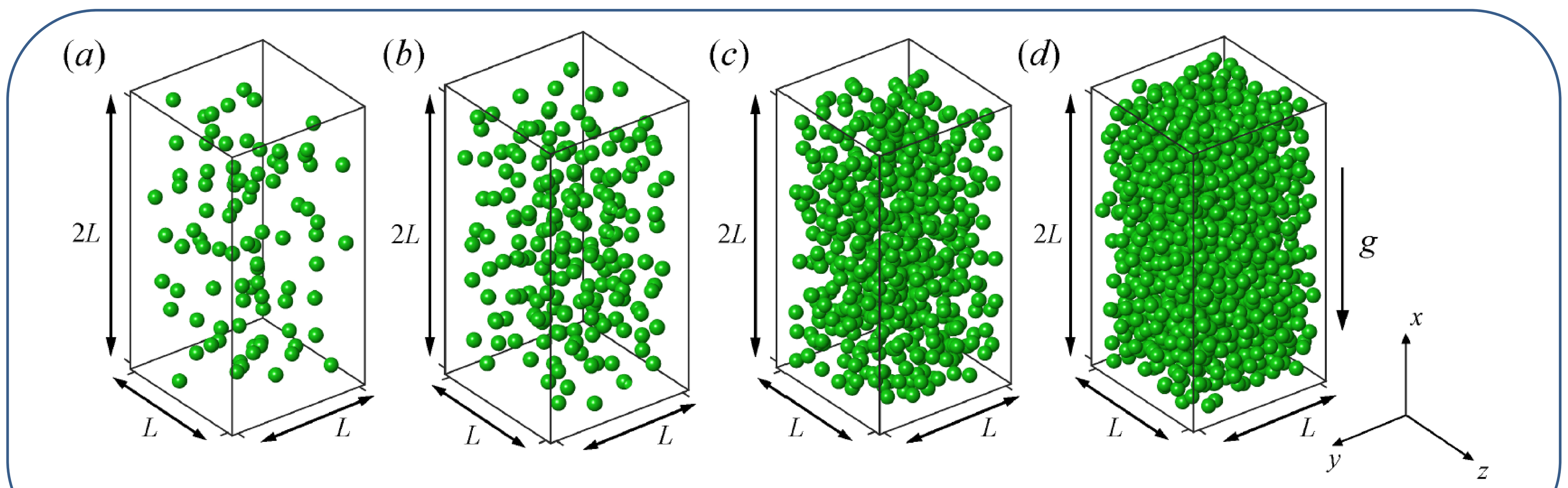
浙江大学 流体工程研究所

*yuzhaosheng@zju.edu.cn

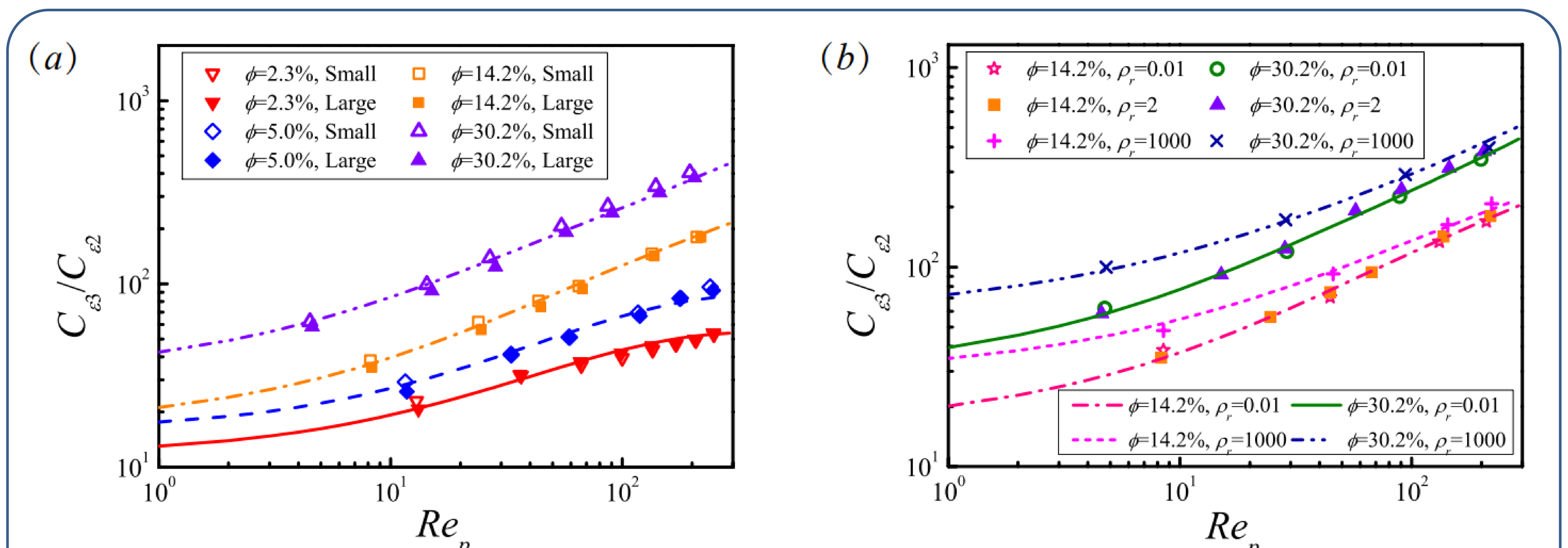
介绍

本文通过对球形颗粒在周期域粘性流体中沉降的直接数值模拟（密度比0.01-1000，颗粒体积分数2.3%-30.2%，颗粒雷诺数小于250），得到了流体相湍动能、雷诺应力和耗散率输运方程中的界面项模型。然后，本文将所得界面项模型应用于双流体雷诺应力模型中，并对有限尺度颗粒竖直湍槽流进行了数值模拟。结果表明，采用所得界面项模型的近壁雷诺应力模型可以较为精确地计算颗粒对竖直湍槽流的增强或削弱作用。

均匀沉降悬浮流



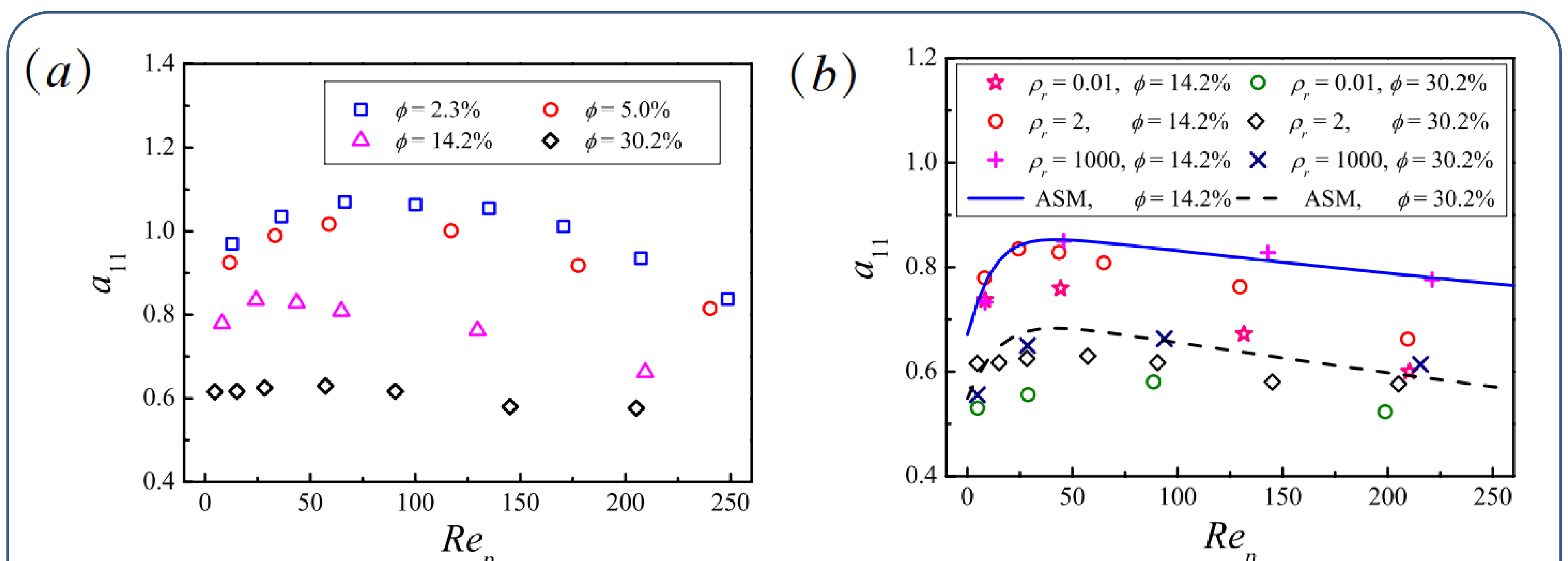
沉降悬浮流示意图



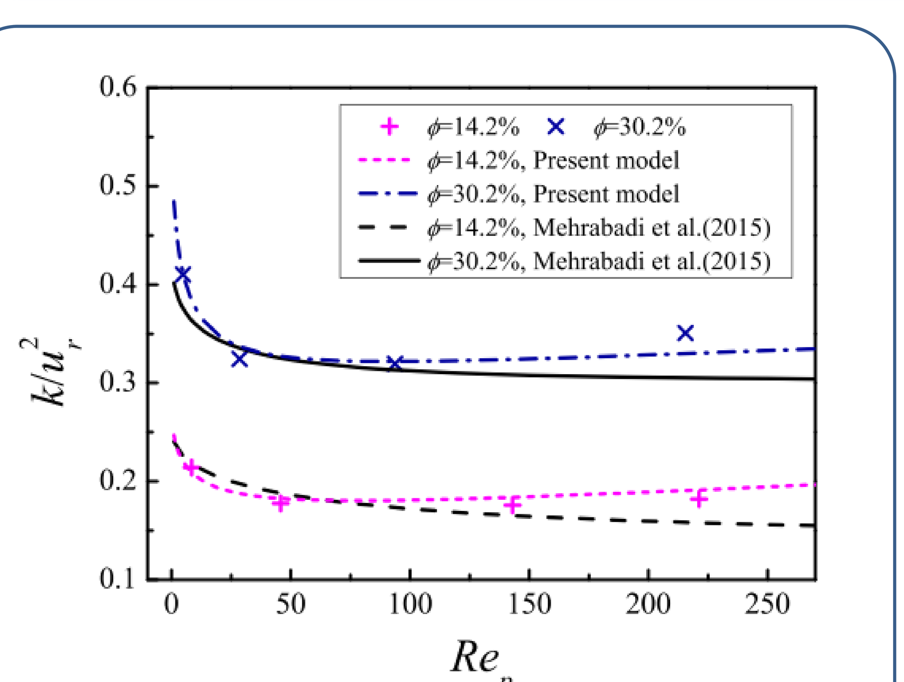
耗散率界面项系数与耗散项系数比率

$$I_k = \phi_f \rho_f \varepsilon, I_\varepsilon = C_{\varepsilon3}\frac{\nu}{d_p^2}I_k.$$

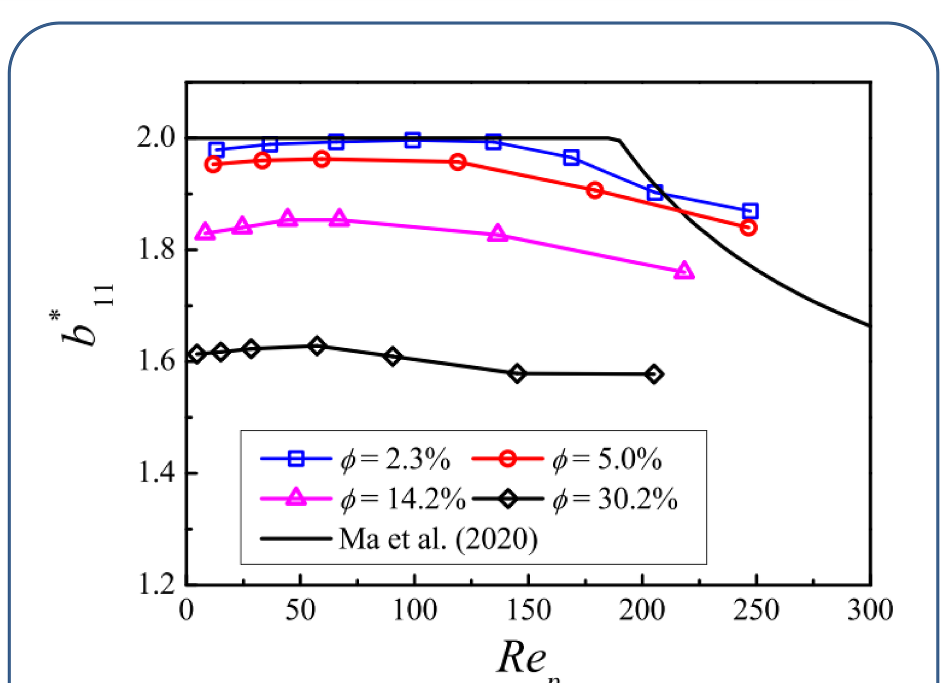
$$I_\varepsilon = C_{\varepsilon2}\phi_f\rho_f\frac{\varepsilon^2}{k}, \frac{C_{\varepsilon3}}{C_{\varepsilon2}} = Re_p\frac{d_pF_D}{(1-\phi)\rho_f\left(k/u_r^2\right)u_r^2}$$



雷诺应力各向异性分量



伪湍动能



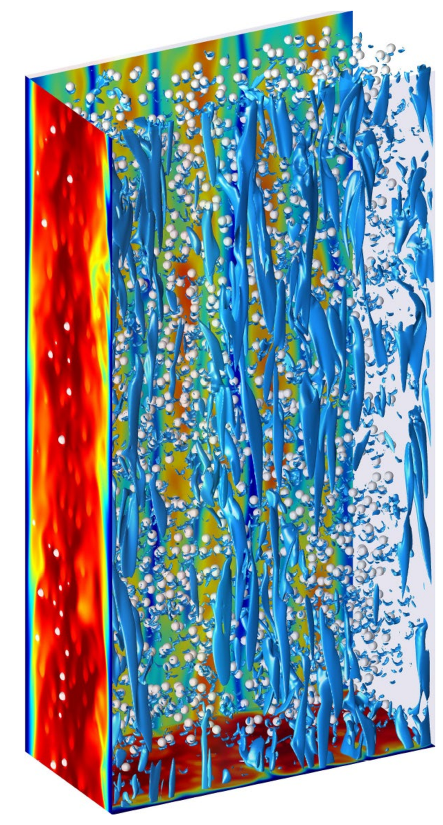
等效雷诺应力界面项系数

$$k/u_r^2 = 0.92\rho_r^{-0.02}\phi^{0.78} + 0.05\phi^{0.3}(1-\phi)\left(Re_p/200\right)^{1.1} + 25\phi^2\left(\rho_r+0.5\right)^{-0.15}(1-\phi)^3\exp\left(-\phi^{1/2}(1-\phi)^{1/2}Re_p^{1/2}\right)$$

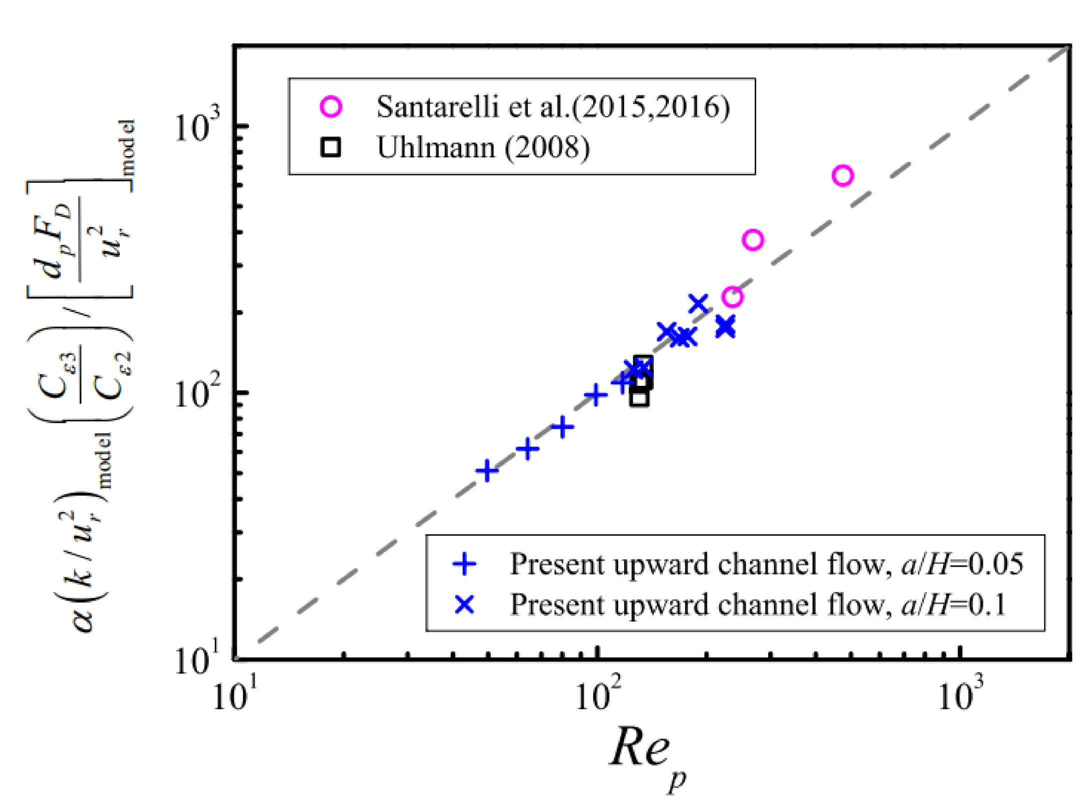
$$I_{ij}^* = b_{ij}I_k - C_3\left(I_{ij} - \delta_{ij}I_{kk}/3\right)$$

$$b_{ij}^* = \left(1-C_3\right)b_{ij} + 2C_3\delta_{ij}/3$$

竖直颗粒悬浮湍槽流

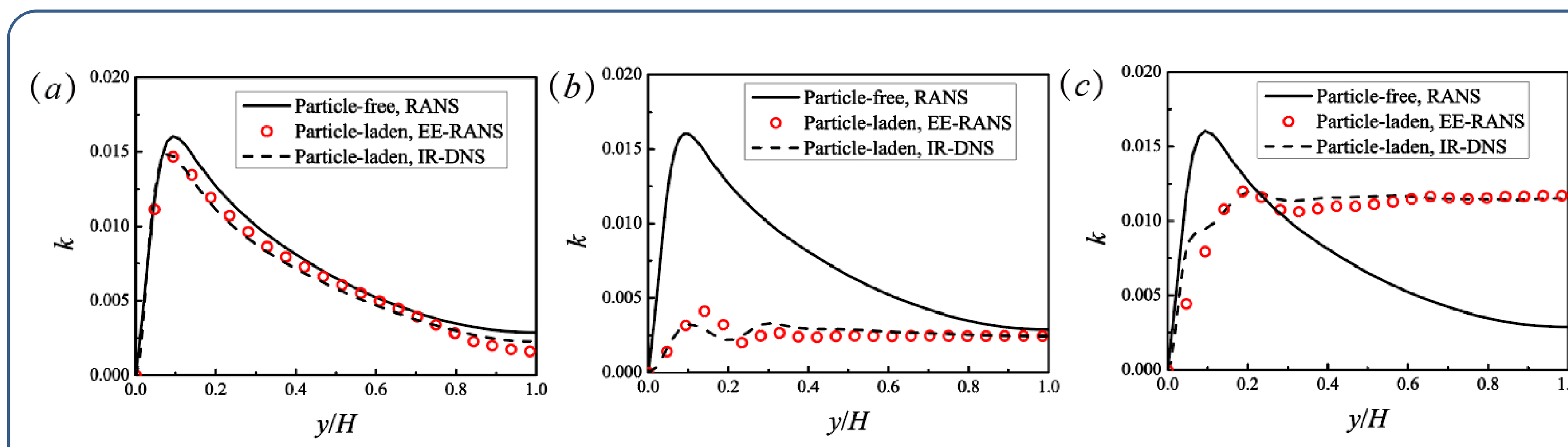


颗粒悬浮竖直湍槽流示意图

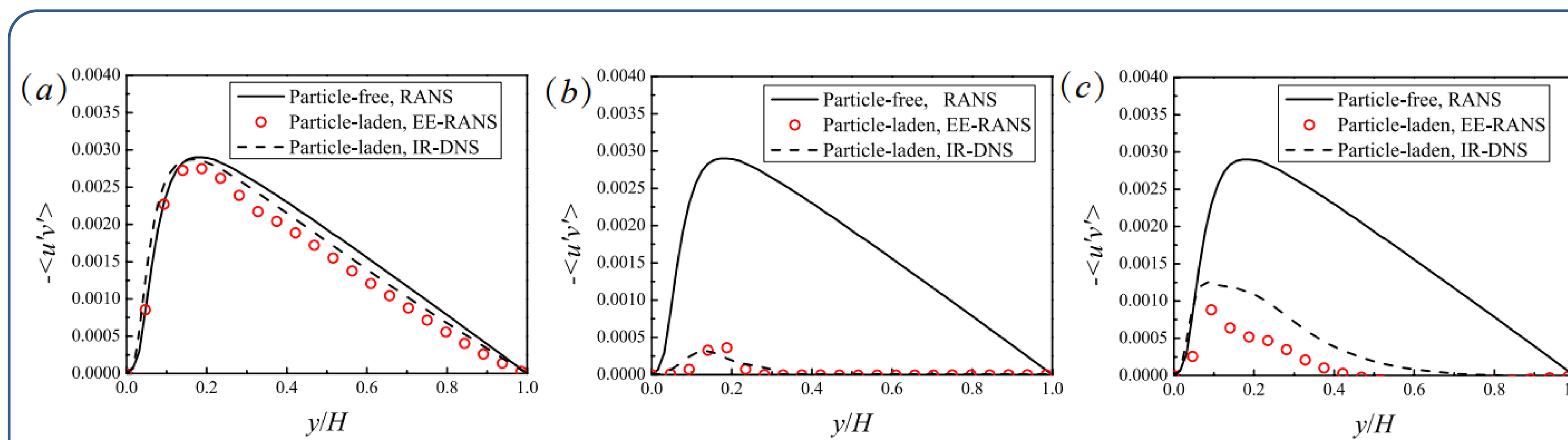


此前直接数值模拟中槽道中心处的结果

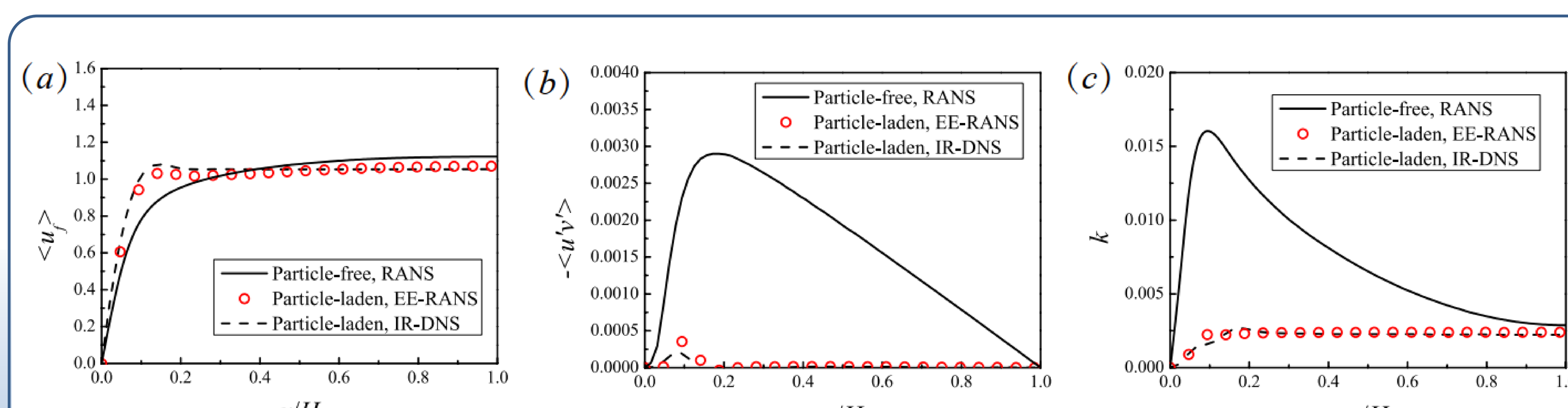
$$\begin{cases}
\frac{\partial \phi_f\langle u_1\rangle}{\partial t} = -\phi_f\frac{d\langle p\rangle}{dx_1} + \frac{1}{Re}\frac{\partial}{\partial x_2}\left(\phi_f\frac{\partial\langle u_1\rangle}{\partial x_2}\right) - \frac{\partial\left(\phi_f\langle u_1'u_2'\rangle\right)}{\partial x_2} - F_D \\
\frac{\partial\phi_f\langle u_1'u_1'\rangle}{\partial t} = -2\phi_f\langle u_1'u_2'\rangle\frac{\partial\langle u_1\rangle}{\partial x_2} + D_{11} + \Phi_{11} + \varepsilon_{11} + I_{11} \\
\frac{\partial\phi_f\langle u_2'u_2'\rangle}{\partial t} = D_{22} + \Phi_{22} + \varepsilon_{22} + I_{22} \\
\frac{\partial\phi_f\langle u_3'u_3'\rangle}{\partial t} = D_{33} + \Phi_{33} + \varepsilon_{33} + I_{33} \\
\frac{\partial\phi_f\langle u_1'u_2'\rangle}{\partial t} = -\phi_f\langle u_2'u_2'\rangle\frac{\partial\langle u_1\rangle}{\partial x_2} + D_{12} + \Phi_{12} + \varepsilon_{12} + I_{12} \\
\frac{\partial\phi_f\varepsilon}{\partial t} = P_\varepsilon + D_\varepsilon + \varepsilon_\varepsilon + I_\varepsilon
\end{cases}$$



模型预测的槽道内的湍动能



模型预测的槽道内的雷诺剪切应力



较高浓度：模型预测的槽道内的平均流体速度、雷诺剪切应力和湍动能