mixt3SedFOAM: improved sediment transport prediction via wall-free Low-Re turbulence modeling

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Abstract

Accurate sediment transport modeling requires high-fidelity numerical tools capable of capturing both large- and small-scale flow phenomena. Mixt3SedFOAM, developed by Ouda and Toorman [1], is a three-phase mixture-theory-based solver for sediment transport in free-surface flows. In this framework, interphase momentum transfer is modeled through a slip-velocity closure accounting for drag force, turbulent dispersion, and shear-induced diffusion. However, the original turbulence modeling approach relies on wall functions, which limits the accurate prediction of bed-load transport and bed shear stress. Moreover, the presence of a sediment bed with varying height restricts the applicability of conventional wall-dependent low-Reynolds-number (LRN) turbulence models.

Recently, a new wall-free LRN *k-ε* model was developed by Raesi and Toorman [2], employing damping functions based on the dimensionless eddy viscosity normalized by the effective viscosity. The developed model was validated for several turbulent benchmark flows, including channel flow, backward-facing step flow, and flow over a periodic hill. Comparisons with available DNS and experimental data demonstrated that the proposed model effectively captures the flow dynamics and turbulence quantities across these cases. Therefore, in the present study, this LRN model is integrated into Mixt3SedFOAM to accurately resolve the inner boundary layer and improve sediment transport predictions. Channel flows with both low and high sediment concentrations are selected for model validation. In summary, the combination of a wall-free LRN *k-ε* model and appropriate additional dissipation mechanisms due to the presence of sediments is essential for accurately predicting sediment-laden channel flows.

Governing Equations

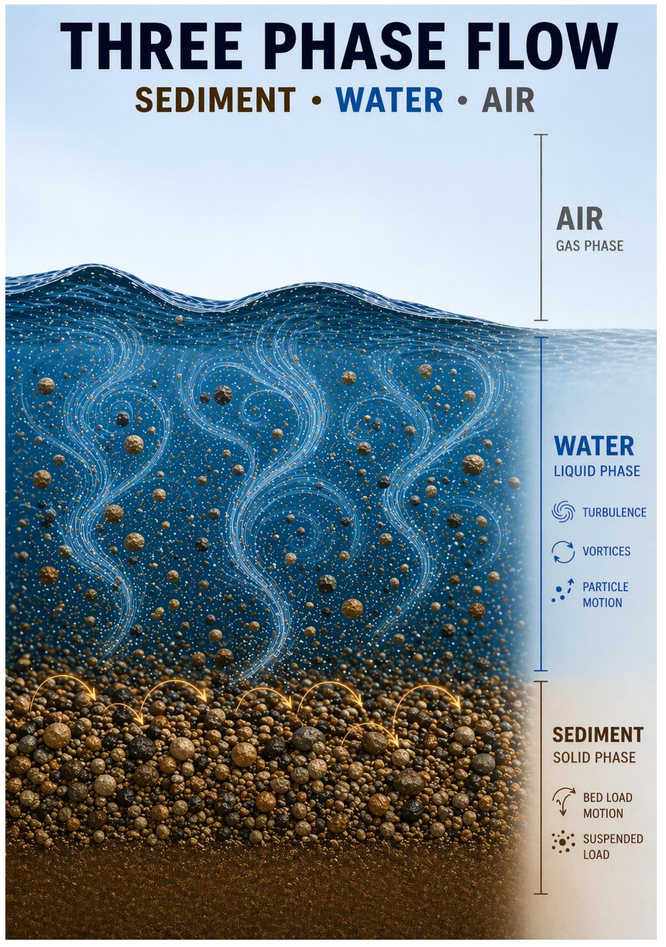
➤Sediment Mass Balance Eq: $$\frac{\partial \alpha_s}{\partial t} + \nabla \cdot (\alpha_s v) + \nabla . \left[\alpha_s \left(\frac{\alpha_w}{\gamma} - \frac{\alpha_s \alpha_w (\rho_s - \rho_w)}{\rho} + \frac{\alpha_s \alpha_w \alpha_a (1-S)}{\gamma(\alpha_s S + \alpha_w)} \right) w \right] = 0$$

➤Fluid Mass Balance Eq: $$\frac{\partial \alpha_w}{\partial t} + \nabla \cdot (\alpha_w v) + \nabla . \left[\alpha_w \left(-\frac{\alpha_s}{\gamma} - \frac{\alpha_s \alpha_w (\rho_s - \rho_w)}{\rho} + \frac{\alpha_s \alpha_w \alpha_a (1-S)}{\gamma(\alpha_s S + \alpha_w)} \right) w \right] + \nabla . (\alpha_w \alpha_a U_c) = 0$$

➤3-phase Momentum Conservation Eq: $$\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho v v) = -\nabla (p_{rgh} + p_s) + \nabla . [\bar{\bar{\tau}} + \tau^T + \tau^D_{s-w} + \tau^D_{m-a}] - gh\nabla(\rho) + 2\sigma H \nabla(\gamma)$$

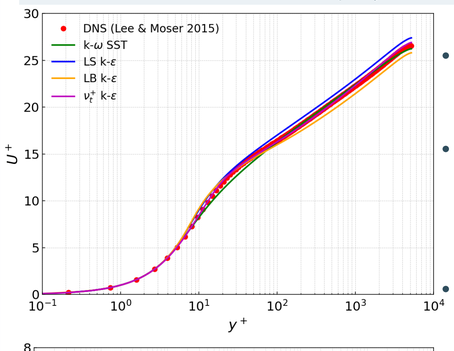
➤LRN mixture *k-ε* model:

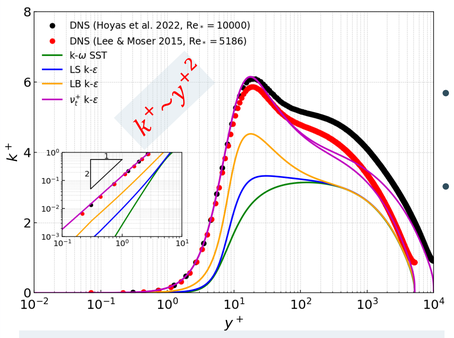
$$\frac{\partial \rho k}{\partial t} + \nabla \cdot (\rho v k) = \nabla \cdot \left[\left(\mu_m + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + 2\mu_m D : D - \rho\varepsilon - G_k - D_k \qquad \frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho v \varepsilon) = \nabla \cdot \left[\left(\mu_m + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + f_1 C_{1\varepsilon} \frac{\varepsilon}{k} 2\mu_m D : D - f_2 C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - G_\varepsilon - D_\varepsilon$$



Clear-**Water** Flow

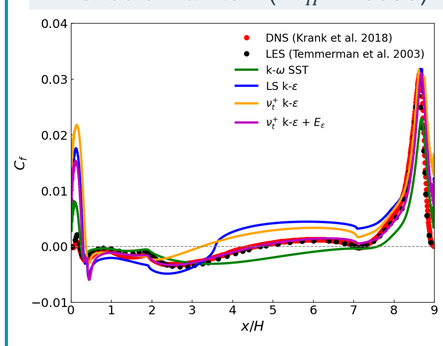
➤Turbulent Channel Flow ($Re_\tau = 5186$):

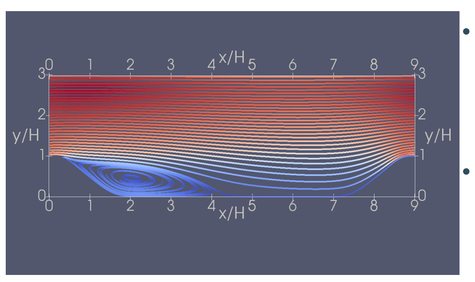




- Accurate mean velocity prediction.
- Good agreement with DNS data of turbulence parameters.
- Correct near-wall asymptotic behavior achieved without wall-distance dependence.
- Stable wall-free low-Re turbulence modeling.
- Inner boundary layer resolved directly with $y^+ < 1$

➤Periodic Hill Flow (Re_H =10595):





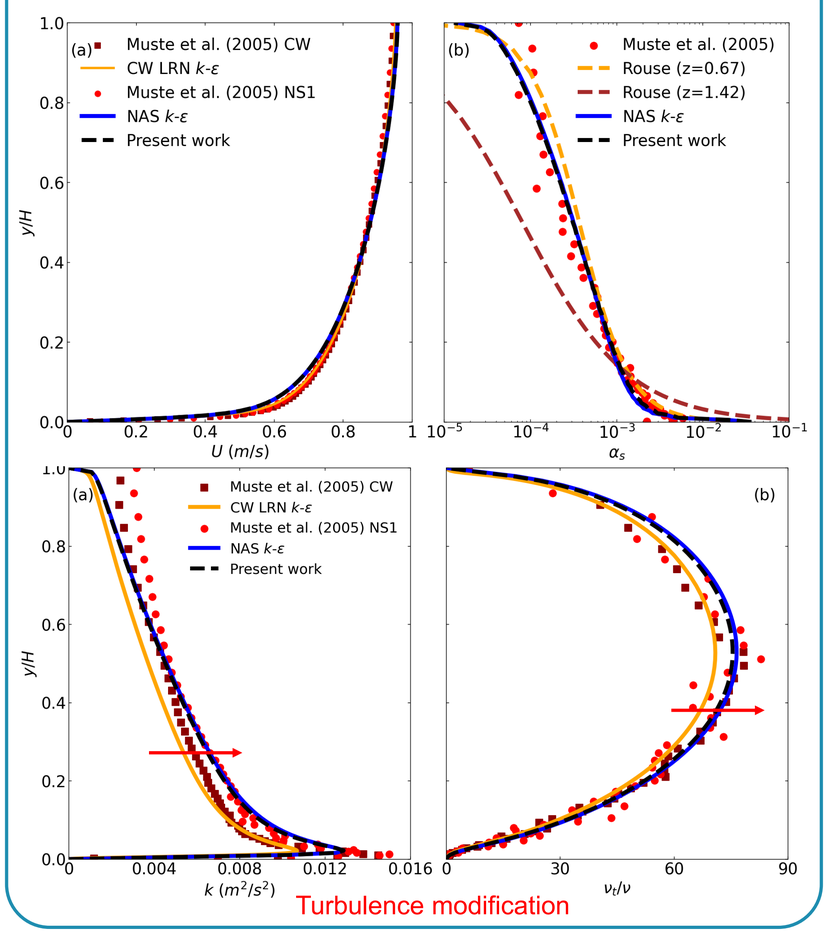
- Accurate prediction of separation and reattachment regions.
- Good agreement with reference C_f profiles.
- Captures recirculation bubble and shear-layer development.
- Enhanced prediction of separated shear-layer recovery using E_ε
- Demonstrates robustness of the model for complex separated turbulent flows.

✓ Accurate prediction of both equilibrium and separated turbulent flows

Low Concentration **Sediment** Flow

➤Dilute sediment-laden flow (Muste et al. (2005)):

- Accurate prediction of the flow field using the wall-free LRN mixture *k-ε* model.
- Steeper velocity gradients in dilute sediment-laden flow.
- "Enhanced turbulence levels even at low sediment concentrations.
- Flow modifications are primarily governed by altered velocity gradients rather than additional sediment dissipation terms.



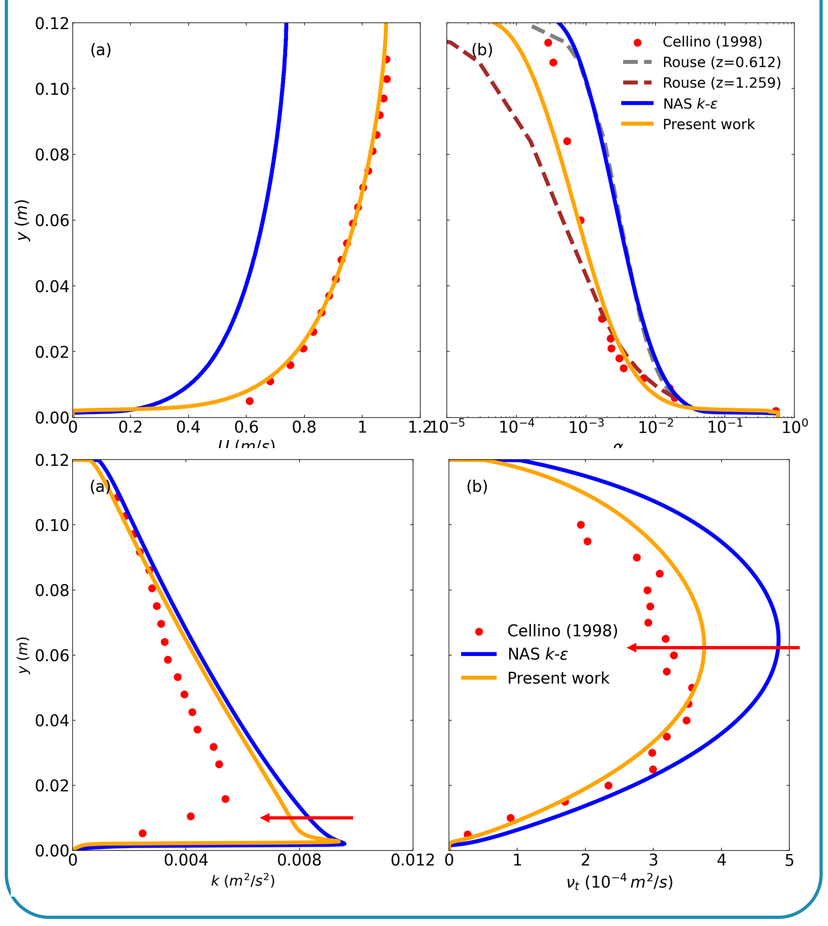
Turbulence modification

✓ Even dilute sediment concentrations modify near-wall turbulence

High Concentration **Sediment** Flow

➤Non-Dilute sediment-laden flow (Cellino (1998) Q70S025):

- Accurate prediction of dense sediment-laden flow behavior using the wall-free LRN mixture *k-ε* model.
- Strong sediment stratification significantly modifies turbulence structure.
- Improved prediction of flow behavior compared with the standard NAS *k-ε* model.
- Turbulence modulation becomes dominated by sediment-induced dissipation effects at high concentrations.



✓ Dense sediment concentrations strongly alter flow structure

References

[1] Ouda, M., Toorman, E.A., 2019. Development of a new multiphase sediment transport model for free surface flows. International Journal of Multiphase Flow 117, 81–102.
[2] Raesi, R., Toorman, E.A., 2026. Development and assessment of a new wall-free low-Reynolds-number k–ε turbulence model. International Journal of Heat and Fluid Flow 950120, 110382.
[3] Cellino, M., 1998. Experimental study of suspension flow in open channels. Ph.D. thesis. EPFL.854.
[4] Muste, M., Yu, K., Fujita, I., Ettema, R., 2005. Two-phase versus mixed-flow perspective on suspended sediment transport in turbulent channel flows. Water resources research 41

❑ The wall-free Low-Re turbulence framework enables accurate prediction of turbulence modulation from clear-water to dense sediment-laden transport flows.

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