Turbulence Meets Ice: Decoding the Equilibrium of Scalloped Geometries

Ali Tavakoli, Ruo-Qian Wang, Department of Civil and Environmental Engineering, Rutgers, the State University of New Jersey

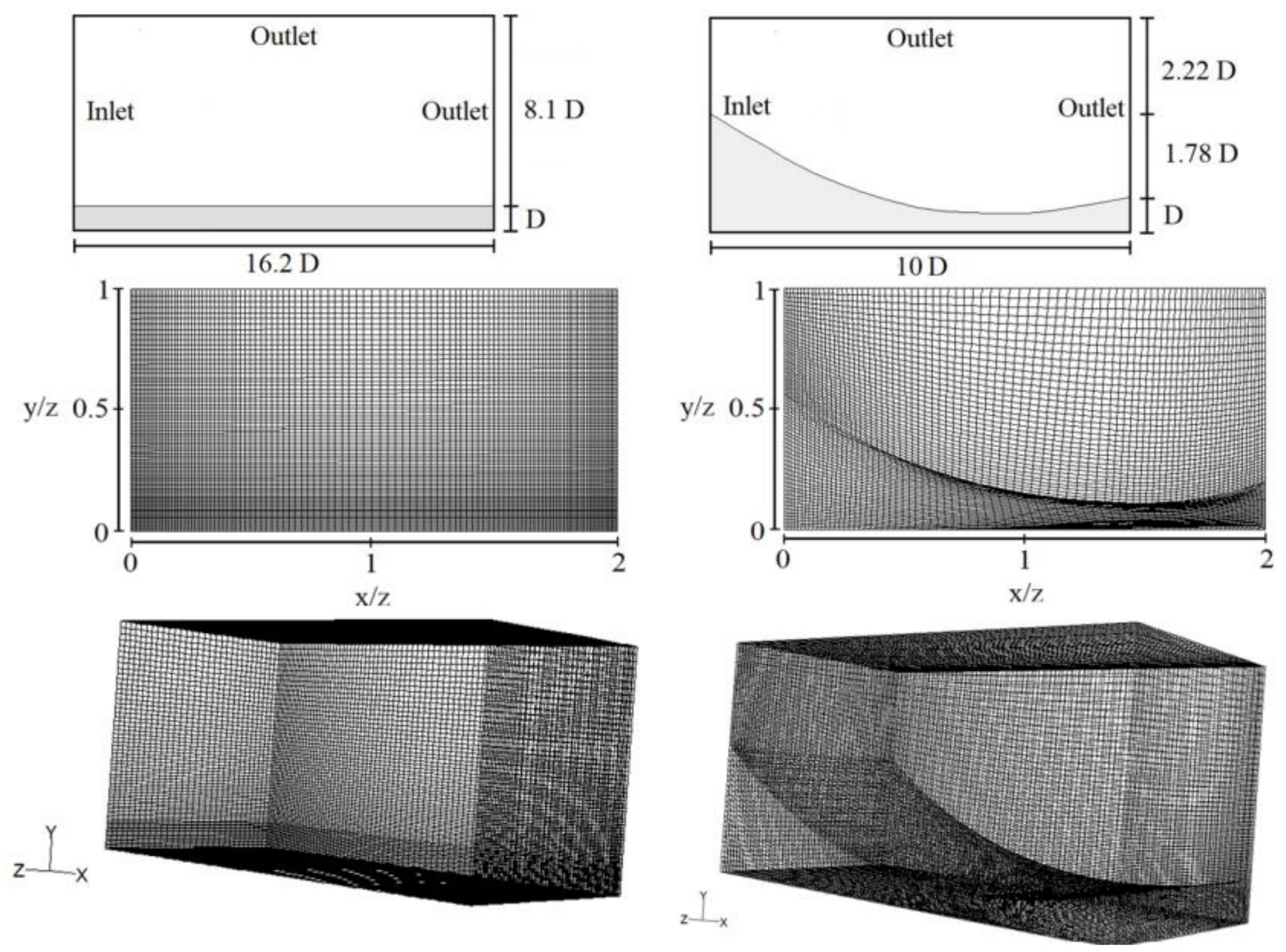
Introduction

Patterns such as ripples and scallops emerge spontaneously on surfaces exposed to fluid flow, from **sand dunes and riverbeds** to **glacial ice** and even **industrial pipelines**. These self-organized structures arise from a feedback between **flow turbulence** and **surface topography**, shaping landscapes and influencing melting, erosion, and transport processes. Despite their widespread occurrence in nature and engineering, the physical mechanisms behind their formation and equilibrium geometry remain elusive. Understanding these processes provides new insights into **ice–ocean interactions**, **climate change impacts**, and **flow–surface coupling** in geophysical and industrial settings.

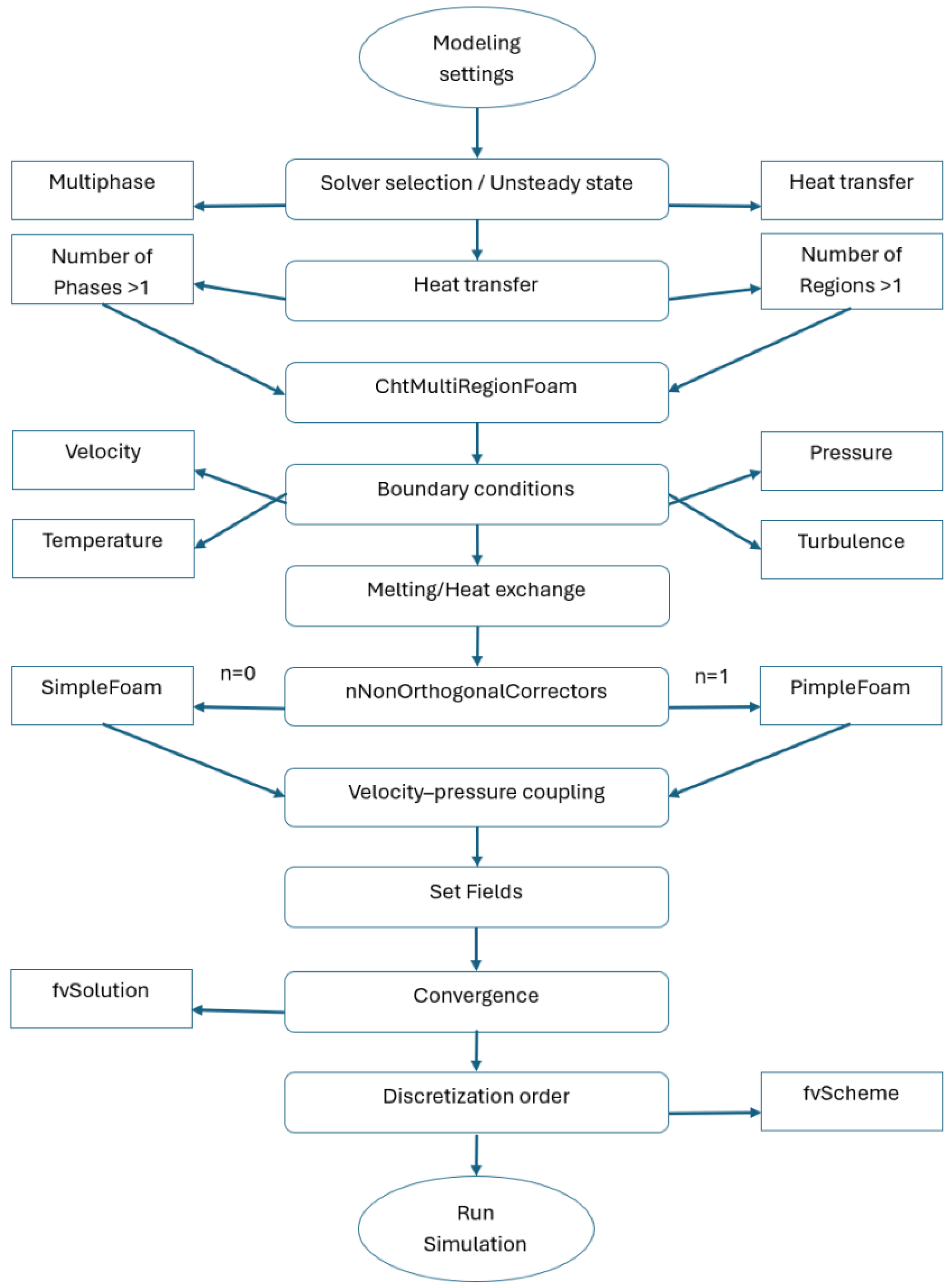
Rose's Pass, Mammoth Cave, Kentucky, USA; Ice caves under Mount Rainier's crater; Ripples inside failed pipes; Sand Ripples; Riverbed Ripples; Snow Ripples; Ripples of River Ice

Methodology

We simulated both flat and scalloped ice–water interfaces using 3D structured meshes (54k–640k cells). The scalloped geometry reproduces laboratory experiments with asymmetric crests and troughs. The Navier–Stokes equations with heat transfer were solved using the **finite volume method** in OpenFOAM. Turbulence was modeled with LES to resolve vortical structures near the interface. **Boundary Conditions**: Inlet: fixed velocity & temperature, Outlet & top: atmospheric pressure, Bottom & walls: no-slip condition, Mesh sensitivity tests confirmed convergence and physical accuracy. **Algorithm**: The **PIMPLE/SIMPLE** algorithm ensured stable velocity–pressure coupling with adaptive time-stepping. **Simulation Goals**: Compare flat vs. scalloped melt rates, Identify vortex formation mechanisms, Quantify phase lag between, turbulence production and melting peaks The flowchart and mesh diagrams below summarize the numerical setup and solution workflow.

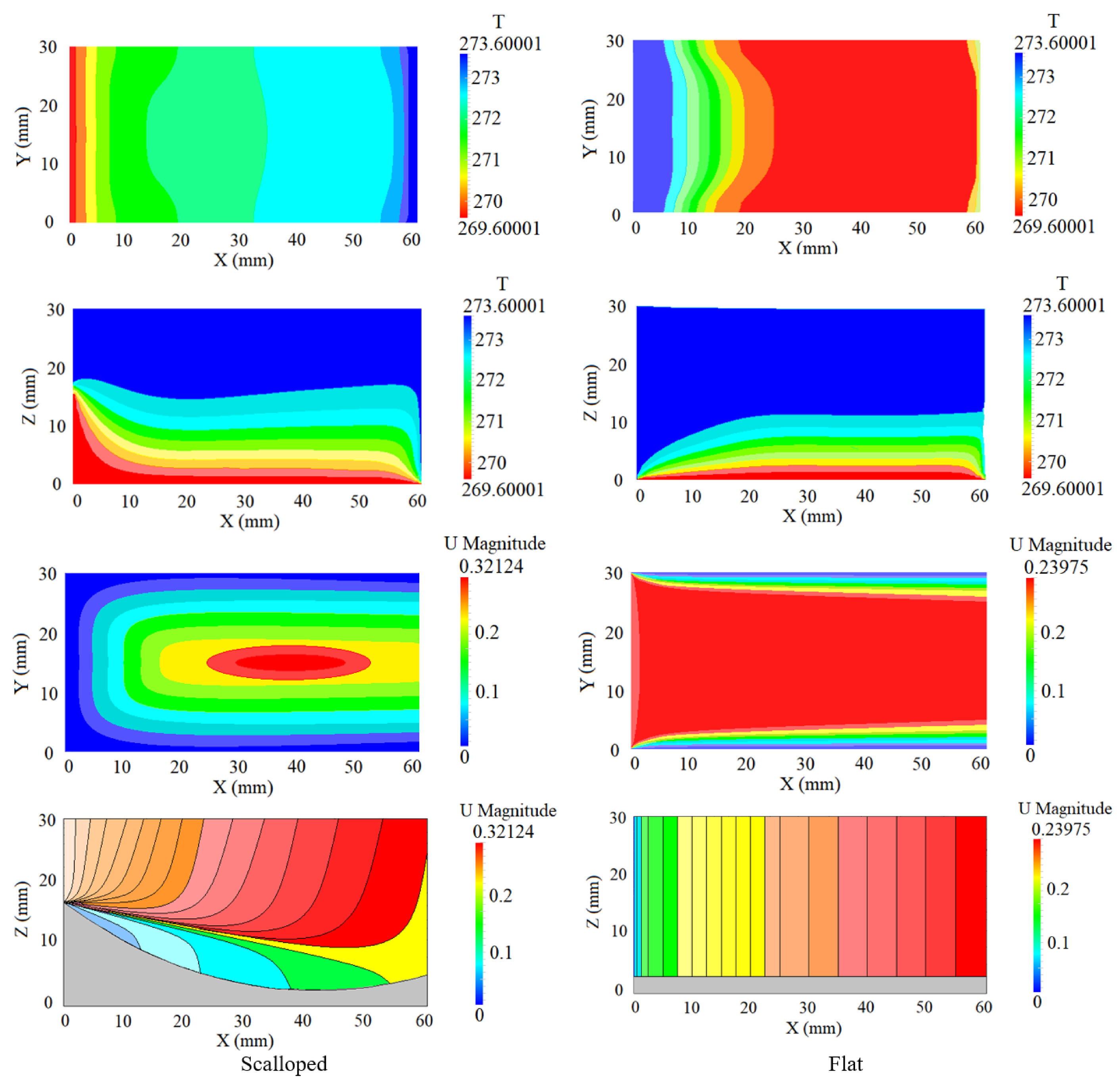


Methodology (cont.)



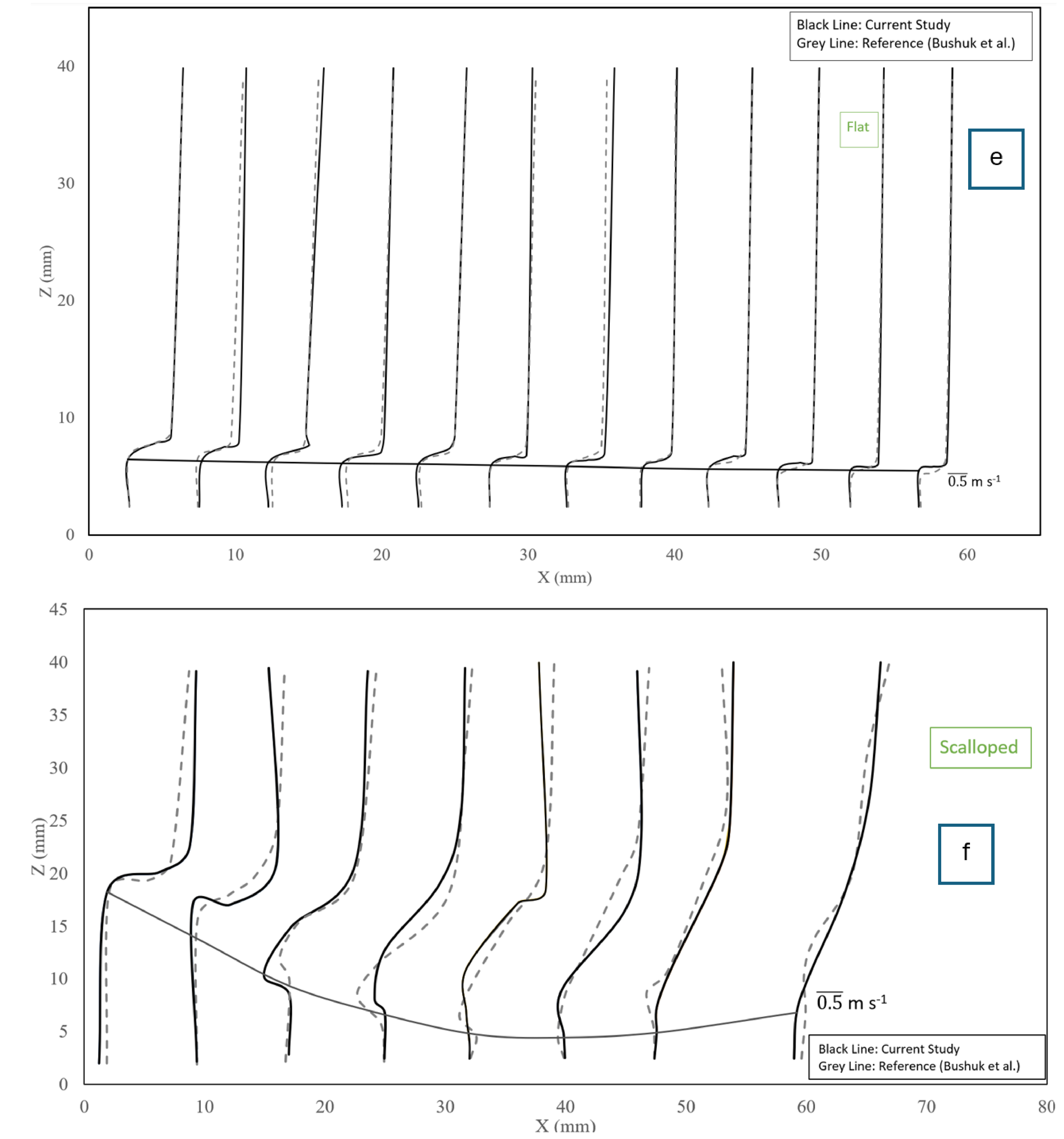
Results

Temperature contours reveal **stronger thermal gradients** above scalloped surfaces. Velocity magnitude plots show **higher near-wall shear** and **reverse flow zones** absent in flat cases.

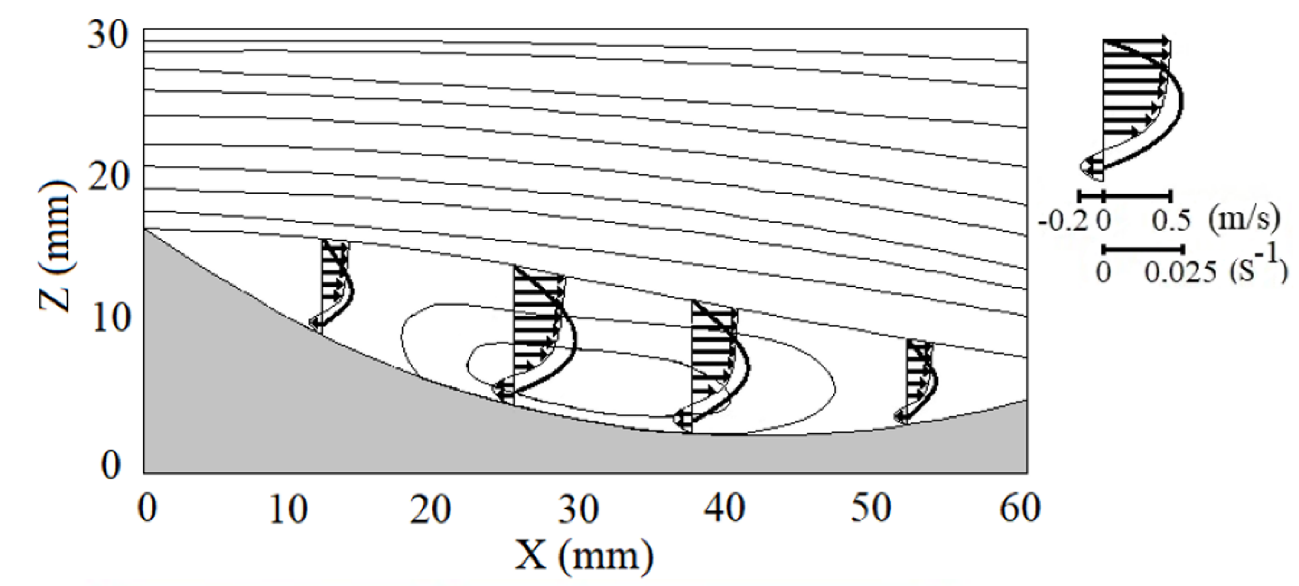


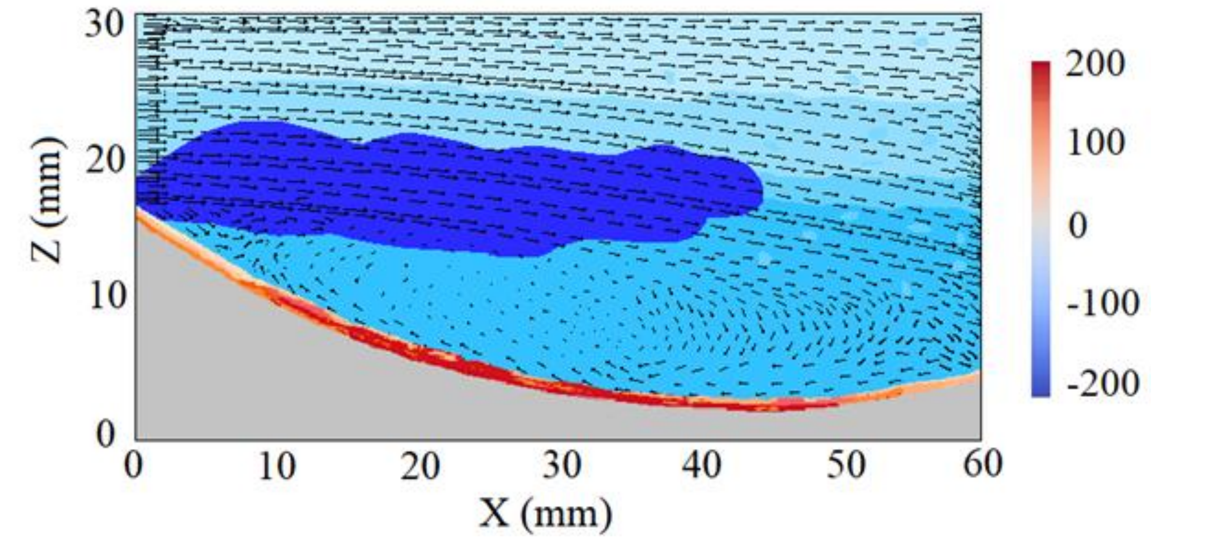
Results (cont.)

LES velocity profiles align with **Bushuk et al. (2019)** lab data. Figure panels confirm accurate reproduction of **flow separation** and **vortex dynamics** seen in experiments.



Formation of recirculating dipole vortices inside troughs. Strong near-wall shear and secondary circulation zones enhancing mixing. Vorticity generation and its spatial expansion above scalloped surfaces reveal intensified shear layers driving enhanced turbulence melt coupling.





Acknowledgement

This research was supported by the National Science Foundation under Grant No. 2322222. The authors gratefully acknowledge the NSF's support in enabling this work.