Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

Comparative Evaluation of Incompressible and Density-Varied Approaches for Turbulence Analysis in Hydraulic Jumps

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ABSTRACT

Hydraulic jumps, defined by the abrupt transition from supercritical to subcritical flow regimes, are recognized as critical phenomena in engineered systems, such as spillways, stilling basins, and energy dissipators, and in natural environments, where oxygenation and nutrient distribution are enhanced by turbulent mixing. Turbulence in hydraulic jumps is conventionally analyzed using incompressible Reynolds averaging formulations that assume constant density, an assumption that results in the oversight of significant density perturbations induced by air entrainment. Consequently, inaccuracies in the prediction of turbulence metrics are introduced, particularly in interfacial regions characterized by steep density gradients. In the present study, turbulence characteristics derived from traditional incompressible Reynolds averaging are compared with those obtained from density-varied formulations, with a focus on key parameters such as the production and dissipation rates of turbulent kinetic energy and turbulence mass fluxes, in order to demonstrate the impact of density perturbations on turbulence behavior and overall energy distribution. To achieve this, a high-resolution Large Eddy Simulation (LES) model is employed in conjunction with the Volume of Fluid (VOF) method, by which the intricate turbulent structures inherent to hydraulic jumps are resolved, and the multi-scale interactions between water and entrained air are captured. The insights derived from the present study establish a robust foundation for modeling and analyzing hydraulic jumps. Moreover, enhanced turbulence metrics are expected to reduce uncertainties in numerical simulations and facilitate the development of advanced turbulence closure models that incorporate density perturbations, ultimately yielding a more accurate representation of turbulent mixing processes.

Keywords: Density-Varied Reynolds Averaging, Hydraulic Jump, Turbulence, Large Eddy Simulation, Turbulent Kinetic Energy