Quantum-Enhanced Computational Fluid Dynamics: Hybrid Quantum–Classical Solvers for High-Fidelity

Simulation of Turbulence and Multiphase Flow in Mechanical System Design

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***Abstract*—Computational Fluid Dynamics (CFD) plays a central role in mechanical system design by enabling the simulation of complex flow phenomena such as turbulence, phase transitions, and fluid–structure interactions. However, high-fidelity CFD simulations—particularly those involving turbulent and multiphase flows—are often limited by the computational cost of solving large-scale, nonlinear, and high-dimensional systems of equations. This study explores the potential of quantum-enhanced computational fluid dynamics, focusing on hybrid quantum–classical solvers as a next-generation approach to overcoming these limitations. By integrating quantum algorithms with classical numerical methods, hybrid frameworks aim to accelerate key CFD tasks such as linear system solving, optimization, and high-dimensional state exploration while preserving the stability and accuracy of established solvers. The paper examines how quantum principles such as superposition and entanglement can be leveraged to improve convergence rates and design-space exploration in turbulence modeling and multiphase flow simulations. Through a conceptual and methodological analysis, this work highlights the opportunities, current constraints, and future implications of quantum-enhanced CFD for mechanical system design, offering a forward-looking perspective on the convergence of quantum computing and fluid mechanics.**

Computational Fluid Dynamics (CFD) has become an indispensable tool in modern mechanical engineering, enabling engineers and researchers to model, analyze, and optimize fluid behavior in complex systems ranging from aerospace structures and energy systems to biomedical devices and industrial machinery [4]. By numerically solving the governing equations of fluid motion—most notably the Navier–Stokes equations—CFD provides insights into flow velocity, pressure distribution, heat transfer, and phase interactions that are often inaccessible through analytical methods or experimental testing alone [7]. As mechanical systems become more sophisticated and performance-driven, the demand for high-fidelity CFD simulations has increased significantly.

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