Contribution ID: **28** Type: **Talk**

Quantum Computational Fluid Dynamics

Wednesday 7 May 2025 09:15 (1 hour)

Variational quantum algorithms are particularly promising early applications of quantum computers since they are comparatively noise tolerant and aim to achieve a quantum advantage with only a few hundred qubits. They are applicable to a wide range of optimization problems arising throughout the natural sciences and industry. To demonstrate the possibilities for the aeroscience community, we describe how variational quantum algorithms can be utilized in computational fluid dynamics.

We discuss how classical fluid dynamics problems are translated into quantum variational algorithms by using matrix product operators as a programming paradigm. The intricate multi-scale nature, describing the coupling between different-sized eddies in space and time, allows us to design an efficient structure-resolving tensor network based description of turbulent flows and compute their dynamics. We show how boundary conditions can be incorporated. We provide estimates for how the runtimes of the resulting quantum algorithms scale with problem size and show that only a logarithmically small number of qubits are required. We then discuss several fundamental examples demonstrating the power of these quantum algorithms.

In addition, we discuss how current practical limitations in size and also imperfections of quantum hardware affect the performance of variational algorithms and determine quantum hardware requirements that might allow gaining a quantum advantage over standard classical approaches to fluid dynamics problems. Finally, we demonstrate the power of tensor network based classical algorithms for computational fluid dynamics that arise as an intermediate step in the translation to fully quantum algorithms.

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