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Quantum lattice Boltzmann method with probability encoding for simulating nonlinear fluid dynamics

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Quantum computing shows remarkable promise for accelerating computational fluid dynamics [1]. Although various quantum algorithms have been proposed for linear flows, developing the quantum algorithms for nonlinear problems remains a significant challenge[2]. We introduce a novel node-level description of lattice gas for simulating nonlinear fluid dynamics on a quantum computer. This approach leverages the advantages of the lattice Boltzmann method[3] (LBM) and lattice gas cellular automata[4] (LGCA) on low-dimensional representation and linear collision, respectively. Building on this framework, we propose a quantum lattice Boltzmann method (QLBM) algorithm. The proposed QLBM algorithm exhibits linearity, L1-norm conservation, and positivity preservation. In the quantum implementation of QLBM, we define a trace-preserving and completely positive mapping for the quantum system and construct a corresponding quantum gate circuit to realize the algorithm. We validated QLBM through simulations of Taylor-Green flow, vortex-pair merging, and two-dimensional turbulence, agreeing well with direct numerical simulation (DNS). Fig. 1 compares QLBM and DNS results for vortex-pair merging, demonstrating QLBM's capability to capture nonlinear fluid dynamics. This algorithm holds the potential for exponential speed-up in large-scale flow simulations, advancing quantum computing applications for further fluid dynamics simulation.

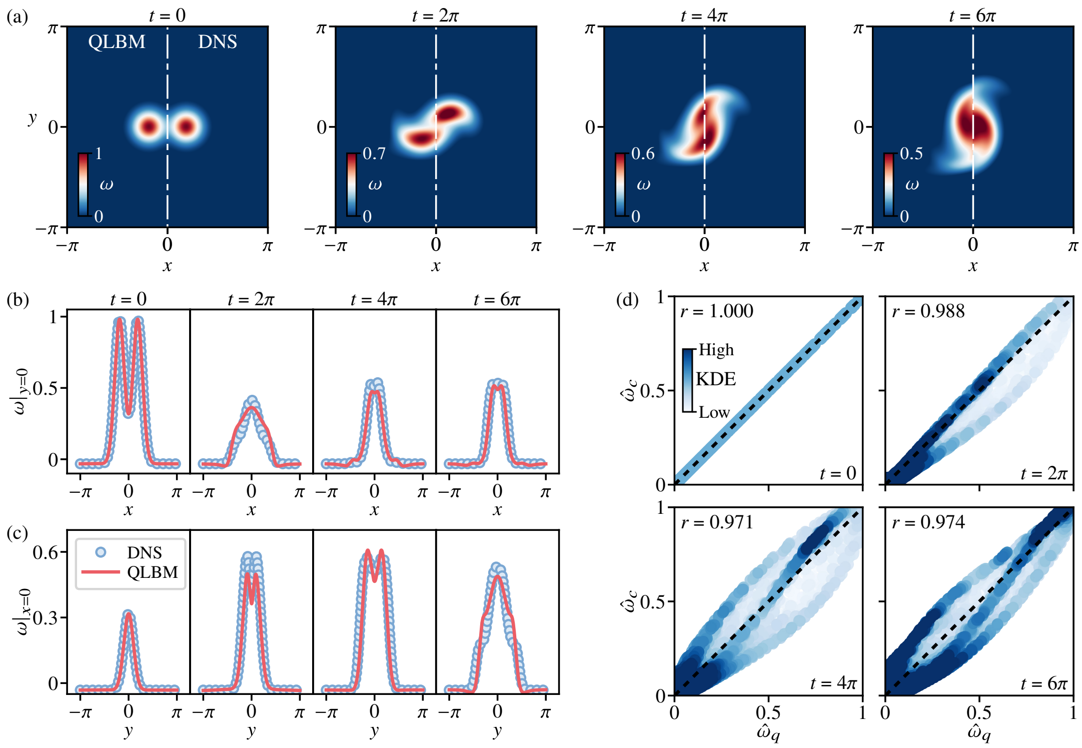

Figure 1: Comparison of QLBM with the the D2Q9 model and DNS with the pseudo-spectral method for simulating merging of a 2D Gaussian vortex pair: (a) vorticity contours, vorticity distributions along (b) $y = 0$, (c) $x = 0$, and (d) kernel density estimation distributions at $t = 0$, 2π, 4π, and 6π with viscosity $\nu = 0.0018$.

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