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Precision Structure Tracking for Understanding the Interplay of Hydro- and Thermodynamic Parameters in Ultrafast Multiphase Micro-Sized Flows

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Liquid microjets have found industrial, commercial, and technological applications such as machining, cooling, printing, and additive manufacturing. In internal combustion engines, high-pressure liquid-fuel injection plays the most crucial role in the energy conversion process to improve combustion efficiency and emission. Despite the importance, the liquid-jet dynamics have not been fully understood due to the dearth of experimental methods for interrogating complex turbulent and multiphase flows. We developed an ultrafast x-ray near-field speckle imaging method ideally suitable for visualizing the multiphase turbulent and cavitating flows emanated from direct-injection nozzles with unprecedented spatiotemporal resolution. The ultrafast liquid-fuel dynamics are dominated by injection pressure as well as fuel temperature through cavitation, an important thermodynamic parameter but often difficult to control in engine combustion. The fast near-nozzle dynamics, measured in wide-range operating conditions and with a realistic injection nozzle, are sensitive to the hydrodynamic parameters, such as injection pressure, and surprisingly, their interplay with the fluid temperature, an important thermodynamic parameter. With the most direct and quantitative measurement, we discovered that the near-nozzle fuel-jet dynamics can be perfectly scaled by a single dimensionless parameter, cavitation number. This universal scaling shows that cavitation can be harnessed to elevate the pneumatic-hydraulic to kinetic energy conversion efficiency, critical for promoting fuel atomization and engine combustion performance. This enhancement effect will have even more impact on engine combustion using alternative low-emission fuels with higher saturated vapor pressure. Conversely, the x-ray imaging based high-precision structure tracking method is also ideally suitable for understanding the turbulence in the multiphase flows by quantifying turbulence fluctuation and intensity. The results bring greater impetus to developing realistic models and simulations of multiphase turbulent and cavitating flows to understand how they affect energy conversion in combustion processes.

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