Transcritical droplets: An experimental and numerical analysis

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Abstract

Numerous research efforts in the field of combustion technologies, e.g., gas-turbines, liquid propellant rockets or diesel engines, have the goal to increase the overall efficiency of the deployed facilities. A standard approach is the rise of system temperature and pressure, in modern devices even beyond the critical point of the injected fuel. The injection and disintegration of the liquid fuel is a crucial aspect in this context as it defines the mixing behaviour inside the combustion chamber. A liquid droplet, injected at a subcritical temperature and embedded in a supercritical environment, undergoes two simultaneous processes: 1) warming up due to the heat transfer from the gas phase towards the droplet; 2) cooling down due to the rapid evaporation in the unsaturated surroundings. For injection temperatures approaching the critical value (e.g. $T_d \approx 0.9\,T_c$), the drop might experience a transition to a supercritical state if the heat transfer from the surroundings prevails over the cooling effect of the vaporisation process. These characteristics strongly influence the evaporation and mixing process of the fuel and change it distinctively, compared to that of a subcritical combustion. For a better understanding of the fundamental phenomena and disintegration processes in a supercritical environment a detailed experimental and numerical study is undertaken in the framework of the SFB TRR75 collaborative research project.

A test facility for the experimental investigation of droplet evaporation in the vicinity of the critical point has been set up. It consists of a drop on demand droplet generator that is enclosed in a heatable pressure chamber. The drop detachment process is triggered by means of electric field forces. The temperature of the droplet liquid can be controlled independently of the surrounding gas temperature. Optical access to the process is provided by four fused silica windows allowing the coupling in and out of laser light and the observation by optical detectors. The functionality and reproducibility of the drop detachment process has been tested and quantified by high-speed shadowgraphy imaging. These images showed typical ligaments in the wake of the droplet, as already observed by different authors. Preliminary investigations with glare points and diffuse light indicate that these ligaments consist of an optically dense, gaseous mixture of the droplet fluid and the surrounding gas. The vapour layer is rapidly convected away due to the relative motion between the drop and the gas. In order to confirm these findings, a detailed experimental study will be undertaken incorporating advanced measurement techniques, e.g. Raman spectroscopy and Planar Laser Induced Fluorescence and Phosphorescence (PLIFP).

For the numerical investigation, a multiphase solver was created using the open source CFD toolbox OpenFOAM. The solver utilizes a Volume of Fluid (VOF) based approach for capturing the liquid-gas interface, allowing to account for significant interface deformations. It is capable to obtain solutions on general unstructured meshes, to adaptively increase the resolution of the interfacial regions and boundary layers using mesh refinement and to carry out parallel calculations on multiple CPUs. Species and energy transport in both phases as well as phase change is considered. Due to the strong dependence of material properties on temperature, pressure and mixture composition near the critical point, variable properties, including density fluctuations, are considered. Since focus is first put on free falling droplets in resting isobaric environment, low Mach number assumptions are made to reduce the complexity. An important objective of this project is the validation of the numerical method for simulation of droplet dynamics and evaporation based on the experimental database.

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