



Full Length Article

Injection characteristics of near critical and supercritical kerosene into quiescent atmospheric environment

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ABSTRACT

The injection of RP-3 aviation kerosene at near and above critical conditions into a quiescent atmospheric environment is experimentally investigated with special emphasis on the effects of injection temperature and pressure on the jet characteristics of shock structure and phase transition. Visualization of the near-field shock/jet structure is performed using Schlieren imaging. Results show that fuel condensation occurs when supercritical RP-3 is injected at near critical temperature. At the supercritical injection conditions investigated, ideal-gas-like expansion and internal shock structures are observed. A RP-3 surrogate is used to determine the thermodynamic phase diagram to reveal the phase transition during the injection processes. The characteristics of the Mach disk are further presented and discussed. It is found that the location and size of the Mach disk as well as jet expansion angle increase with increasing injection pressure. Furthermore, specific heat ratios and compressibility factors of RP-3 surrogate and N₂ are evaluated to analyze their differences in Mach disk diameter and jet expansion angle; it is shown that the compressibility factor is the primary factor that deviates the jet structure of RP-3 from that of ideal-gas N₂.

1. Introduction

In advanced gas turbine engines, as well as in the supersonic combustion ramjet engines and pulsed detonation engines, the use of endothermic hydrocarbon fuels as primary coolant for airframe and engine components can result in the fuel being heated to supercritical state before injected into the combustion chamber [1–4]. The thermodynamic and transport properties of the supercritical fuels have been shown to differ drastically from those of liquid or gaseous fuels [5–7]. Specifically, supercritical fuels have liquid-like density, gas-like diffusivity, zero surface tension, and large compressibility. In addition, the specific heat, viscosity, and thermal conductivity of supercritical fuels exhibit complex temperature dependence, especially near the critical point where a small change in temperature can change the fuel thermodynamic properties significantly [8,9]. The different supercritical fuel properties will inevitably affect the injection process and subsequent combustion. Previous studies [10–13] have suggested that the injection and the fuel/air mixing processes are not only dominated by the fluid dynamics, the anomalies in the fuel thermodynamic properties near the critical point also play an important role. Therefore, the supercritical injection of hydrocarbon fuels has become an increasingly important research topic for the development of advanced propulsion

systems.

Challenged by the complex injection process, considerable amount of work has gone into the fundamental understanding of supercritical injection into a quiescent environment. Wu and coworkers [14,15] studied the supercritical ethylene injections into the quiescent nitrogen gas; the results showed that fuel condensation manifested by the opaque region is observed at low injection temperatures, and the Mach disk locations of supercritical ethylene jets match those of ideal-gas jets; however, the size of Mach disk and expansion angle increase as injection temperature approaches the critical point. Star et al. [16] conducted a numerical study of supercritical ethylene injection using compressible Navier-Stokes equations with thermodynamic behavior of ethylene described by Peng-Robinson equation of state; the simulations are in qualitative agreement with experimental results in terms of jet structure, fuel condensation, and effects of back pressure and injection temperature. Lin et al. [17] studied the structure and phase transition of supercritical methane/ethylene mixtures into quiescent nitrogen gas; the visualization of the near field jets and inside the injector showed that fuel condensation can occur inside the injector when injection temperature is near the critical point, when the supercritical injection is away from critical point, the fuel jets undergo ideal-like expansion and exhibit visible internal shock structures; the Mach disk location is

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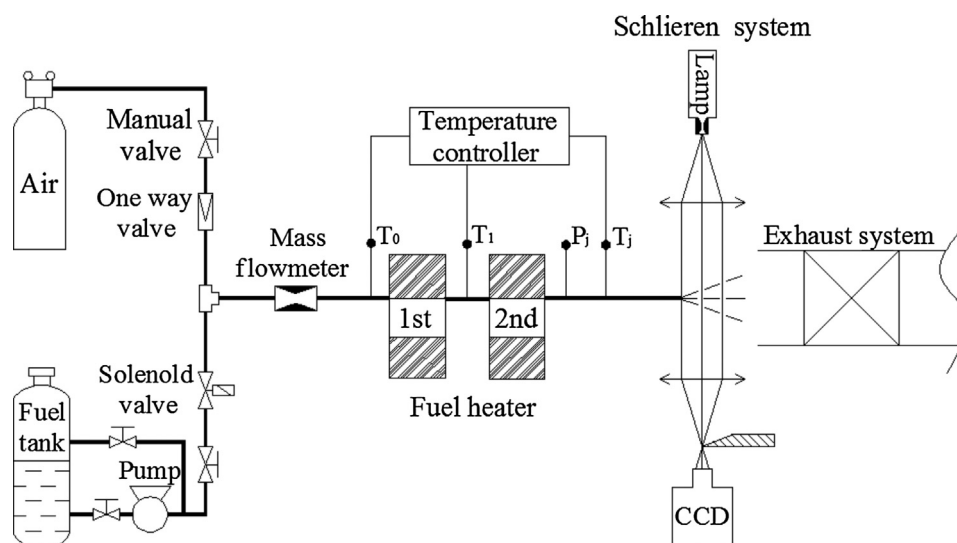


Fig. 1. Schematic of fuel injection setup and Schlieren imaging system.

consistent with observation of supercritical ethylene injection [15] that follows the ideal-gas expansion. Roy et al. [18] studied the disintegration of supercritical fluoroketone injected into subcritical and supercritical chamber conditions, and the evolution of droplet size with distance from the injector was identified; it was concluded that the mixing process is enhanced drastically in the supercritical-to-supercritical injection than the supercritical-to-subcritical injection as the condensed droplets in the latter case need further vaporization before efficient mixing. Qiu et al. [19] subsequently simulated the experiments of Roy et al. [18] to investigate the supercritical injection processes and the accompanying potential phase changes; the simulation results for supercritical-to-subcritical injections are consistent with experimental observations, and reveal that condensation occurs when the temperature difference between the injectant and ambient gas is large enough to promote strong enough heat transfer to send the local mixture into the two-phase state.

Recent studies have focused on the supercritical injections of more complex hydrocarbon species and practical fuels. Lamanna et al. [20] studied the near-critical *n*-hexane injections in a shock tube to investigate the fuel jet disintegration; three different disintegration modes, identified as subcritical, supercritical, and near-critical flashing regimes are determined by initial fuel temperature and expansion ratio. The supercritical regime resembles many features of an ideal-gas jet, e.g., shock structure and Mach disk location, while the thermodynamic anomalies near the critical point can trigger the onset of non-equilibrium fuel condensation. Dounghthip et al. [21] experimentally and numerically studied the supercritical-to-supercritical injections of Jet A; it was found that the supercritical jet structures at supercritical ambient conditions undergo subsonic ideal-gas like expansion, the penetration depth decreases with increasing fuel temperature, and the expansion angle increases with increasing mass flow rate; no shock structure is observed in the supercritical-to-supercritical injection. Falgout et al. [22] studied the injections of superheated butanol, dodecane, hexadecane, and diesel into air at three conditions that span the range from subcritical to supercritical states of the fuel; it showed that the jets of neat hydrocarbons tend to undergo a change in surface morphology that scales with fuel/air critical properties, while the jets of diesel are not strongly affected by the ambient conditions. Liu et al. [23] experimentally studied subcritical and supercritical injections of gasoline into atmospheric conditions; it was found that when injection temperature is near the critical point, spray penetration reaches the minimum, while cone angle reaches maximum; however, due to the large observation field, the shock structure near the nozzle exit is not resolved.

Previous studies of supercritical fuel injections have so far been limited to small and neat hydrocarbons, except for Refs. [21–23] of which emphases are primarily focused on the jet structure and interface morphology. The experimental studies of supercritical injections of simple hydrocarbons [14,15,17,20] have shown an ideal-gas-like expansion with a visible shock structure and indicated fuel condensation when the injection temperature is near critical point. The practical fuels have a more complex composition that could affect the injection process, thus the resulting jet structure. Therefore, the present study aims to provide new experimental observations of supercritical injections of RP-3 kerosene fuel into quiescent air with special emphases on the jet expansion process and phase transition outside and/or inside the injector. Jet structures of ideal-gas N_2 injections are also provided for comparison. Thermodynamic properties of RP-3 are evaluated by using a RP-3 surrogate to identify the dominant factor that affects the jet structure. In the next section, we first describe the experimental specifications, including the experimental setup, methodology, and procedure, followed by the flow visualization results and discussion.

2. Experimental specification

2.1. Experimental apparatus

Fig. 1 shows the fuel injection experimental setup and the Schlieren imaging system. The fuel injection setup consists of a fuel tank, a compressed air bottle, a two-stage fuel heater, an injector nozzle, and an exhaust system. The fuel tank has an internal volume of 1000 L which can sustain long experiment duration and minimize the injectant pressure fluctuation during injection. A Coriolis-type mass flow meter with the range of 1–10 g/s and an uncertainty of less than $\pm 1\%$ is used to measure the fuel mass flow rate. The fuel is heated by a two-stage heater to reach the desired temperature gradually. The first-stage heater consists of a 2 m long stainless-steel tube of 2 mm inner diameter and 0.2 mm wall thickness, it can heat the kerosene flow of 3 g/s up to 520 K with negligible coking deposit. The second-stage heater is similar to the first one, which is capable of rapidly heating the kerosene flow up to 760 K in less than 10 s to minimize the fuel coking. Studies [24,25] have shown that thermal cracking of RP-3 kerosene at 760 K is negligible. A temperature controller is used to control the injection temperature of the injectant fuel by adjusting the heating power of the heater. An exhaust system is used to collect the fuel jet and cool it down to ambient temperature by fuel-water cooler. After each run, air is used to purge the fuel injection system to avoid deposit accumulation caused by the fuel residual. Visualization of the jet structure and phase

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