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Numerical study of choked cavitation in high temperature hydrocarbon liquid jets

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ABSTRACT

A numerical study was conducted on a practical plain orifice injector issuing pressurized high-temperature aviation fuel, in order to simulate injection of fuel after use as a coolant in the active cooling system of a hypersonic vehicle. A three-dimensional unstructured mesh inside the orifice was created using ICEMCFD™ S/W, and the CFD analysis was performed using FLUENT™ S/W. A multiphase mixture model was used to simulate cavitating two-phase flow, and the full cavitation model was activated to predict the mechanism and effects of cavitation induced by the high fuel vapor pressures at elevated temperature conditions. The simulation was performed for fuel heated up to 553 K (280 °C) at an upstream pressure (P_{inj}) of up to 1.0 MPa, and various ambient pressures (P_∞). The results were compared with experimental data, and the simulation was found to predict the discharge coefficient (C_d) with respect to the fuel injection temperature (T_{inj}) quite well at the given conditions. The CFD analyses for high fuel temperature conditions revealed that the mainstream flow inside the injector separates from the orifice wall at the vena contracta due to the generated fuel vapor cavity, and the attached flow at the end of the cavity separates again to produce a very small recirculation zone. In addition, for a given pressure drop, the sharply decreasing trend of the mass flow rate (or C_d) with increasing T_{inj} varies depending on P_∞, because the mass flow choking is determined by the relationship between P_∞ and the vapor pressure (P_{sat}) at T_{inj}. Finally, C_d with respect to cavitation number was found to follow an almost identical line, even at different P_∞. This confirms that choked cavitation at high fuel temperature conditions depends on the downstream pressure of the orifice, and the effect of cavitation on C_d at high T_{inj} is well represented by the cavitation numbers, regardless of P_{inj}, P_∞, and T_{inj}.

1. Introduction

Hydrocarbon-fueled scramjets have been studied as hypersonic alternatives to solid and liquid rockets for use within the atmosphere because of their excellent performance characteristics, including high specific impulse and operational flexibility in the supersonic to hypersonic regimes (Van Wie et al., 2005). Hypersonic flight is challenged, however, by the inevitability of aero-thermodynamic heating (National Research Council, 1998); the tremendous heat on the surface of a vehicle and the engine wall requires not only materials that can resist and block very high temperatures, but also active heat-sink cooling systems (Van Wie et al., 2005). Fortunately, liquid hydrocarbons have excellent cooling capacity through heat-absorbing chemical reactions such as thermal and catalytic cracking, and thus can be circulated as coolants in active cooling systems before injection into the engine for use as fuel (Sobel and Spadaccini, 1997; Rao and Kunzru, 2006). In such a system, however, the fuel at the injector exit reaches a very high temperature, depending on overall heat load and heat sink capacities (Gasner et al., 1992), and the heated fuel must be highly pressurized for injection into a scramjet combustor. At such high temperatures and pressures the fuel could reach supercritical conditions (Edwards, 1993).

Internal flow conditions in the injector are known to have a strong influence on injection and spray patterns (Soteriou et al., 1995; Tamaki et al., 1998; Aleiferis et al., 2010). Furthermore, the injection and spray characteristics of high-pressure, high-temperature fuel may differ from the characteristics at near-ambient pressure and temperature conditions, and may include physical phenomena such as cavitation (Nurick, 1976; Soteriou et al., 1995; Tamaki et al., 1998; Arcoumanis et al., 2001; Tafreshi and Pourdeyhimi, 2004; Giannadakis et al., 2008; Cioncolini et al., 2016; Mitroglou et al., 2017) and flash boiling (Oza, 1984; Vieira and Simoes-Moreira, 2007; Sher et al., 2008; Karathanassis et al., 2017). Cavitation is known as the process of phase change in a liquid caused by a decrease of static pressure at constant ambient temperature (Aleiferis et al., 2010); when fuel is supplied to an injector at high temperature, the internal fuel flow is very susceptible to

Abbreviations: CFD, Computational Fluid Dynamics; DES, Detached eddy simulation; LES, Large-eddy simulation; RANS, Reynolds averaged Navier–Stokes

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Nomenclature

A_o	outlet (orifice) area of the injector (m^2)
Ca	cavitation number, $Ca = \frac{P_\infty - P_{sat}}{\rho V^2/2}$
C_d	discharge coefficient, $C_d = \frac{\dot{m}_f}{A_o\sqrt{2\rho_l \Delta P}}$
D	diameter of orifice (m)
K	cavitation number, $K = \frac{P_{inj} - P_{sat}}{P_{inj} - P_\infty}$
$\dot{m}_f$	fuel mass flow rate (kg/s)
P_∞	ambient pressure (MPa)
P_{inj}	injection pressure (MPa)
P_{sat}	saturation vapor pressure (MPa)
Re	Reynolds number, $Re = \frac{\rho_l VD}{\mu_l}$
T_{inj}	fuel injection temperature (K)
T_{sat}	saturation temperature (K)
V	average injection velocity (m/s)

Greek symbols

ΔP	pressure drop across the injector, $\Delta P = P_{inj} - P_\infty$
μ_l	liquid viscosity (Pa·s)
ρ_l	liquid density (kg/m^3)
σ	liquid surface tension (N/m)

cavitation. Cavitation may, in fact, occur even when the injection pressure is relatively low, because the saturated vapor pressure of a liquid rises rapidly with increasing temperature. As high temperature fuel accelerates near the nozzle throat and then flows downstream to the nozzle exit, cavitation bubbles are present inside the injector. As a result, very steep density variation occurs in the low-pressure region of the flow, and the formation of vapor cavities in the liquid-filled injector has strong influence on the injection characteristics (Soteriou et al., 1995; Tamaki et al., 1998; Aleiferis et al., 2010); in some extreme cases, cavitation may result in mass flow choking or critical conditions (Nurick, 1976; Wallis, 1980; Payri et al., 2004, 2009; Cioncolini et al., 2016), as well as hydraulic flip (Soteriou et al., 1995; Tamaki et al., 1998; Tafreshi and Pourdeyhimi, 2004; Suh and Lee, 2008).

The behaviors of sprays and the characteristics of injection under cavitating conditions have been studied extensively in recent decades, with water as the working fluid (Nurick, 1976; Tamaki et al., 1998; Sou et al., 2014; Cioncolini et al., 2016). There have also been numerous studies of the effects of cavitation on injection and the characteristics of sprays and atomization in plain orifice nozzles, using diesel fuel as the working fluid (Soteriou et al., 1995; Arcoumanis et al., 2001; Payri et al., 2004, 2009; Suh and Lee, 2008). Though there have been a variety of studies of cavitation inside fuel injectors, and its effects on injection and atomization characteristics, most of these studies have dealt with cavitation induced by increasing either injection pressure or flow velocity at ambient temperature conditions. Furthermore, even though there have been a few studies on high fuel temperature conditions (Aleiferis et al., 2010), those studies have focused mainly on the beneficial effects of cavitation in diesel fuel injection, including more uniform droplet distribution and increased spray angle (Soteriou et al., 1995). Few studies, however, have been concerned with cavitation in aviation fuel, as induced by increased saturation vapor pressure under very high temperature conditions. In these conditions, the effects of cavitation can be adverse, and may result in decreasing flow rate and discharge coefficient (Lee et al., 2017). Cavitation can thus significantly reduce the precision of fuel control in hypersonic air-breathing engines, and this warrants in-depth, systematic investigation of high temperature cavitating flow.

There have been numerous experimental studies investigating in-nozzle cavitating flow using flow visualization techniques (Arcoumanis et al., 2001; Suh and Lee, 2008; Payri et al., 2009; Aleiferis et al., 2010; Sou et al., 2014; Bicer and Sou, 2016; Mitroglou et al., 2017). It is still very difficult, however, to visualize the inside of a practical fuel injector, because of limited optical accessibility, especially at extreme flow conditions. In addition, visualization data cannot provide microscopic details of the local two phase flow field. Further understanding of the underlying physics and its application to engineering design should therefore be aided by CFD (Tafreshi and Pourdeyhimi, 2004; Giannadakis et al., 2008; Sou et al., 2014; Wang et al., 2014; Bicer and Sou, 2016; Karathanassis et al., 2017; Koukouvinis et al., 2017; Orley et al., 2017; Torelli et al., 2017).

In a real fuel nozzle discharging high temperature hydrocarbon liquid jets, it has been observed that when the fuel injection temperature exceeds the fuel boiling point, the high fuel temperature induces cavitation, which ultimately results in a sharp decrease in the discharge coefficient caused by mass flow choking (Lee et al., 2017). At the same time, flash boiling occurs outside the injector and affects the spray structure and atomization of the liquid fuel jets (Jin et al., 2018). However, the coupling between the internal and external nozzle flow simulations is known to be still inherently weak, and a rigorous and realistic method to simulate both the internal and near nozzle flows is yet to be reported (Wang et al., 2014). Therefore, a numerical study on high temperature fuel inside a plain orifice injector has been initiated,

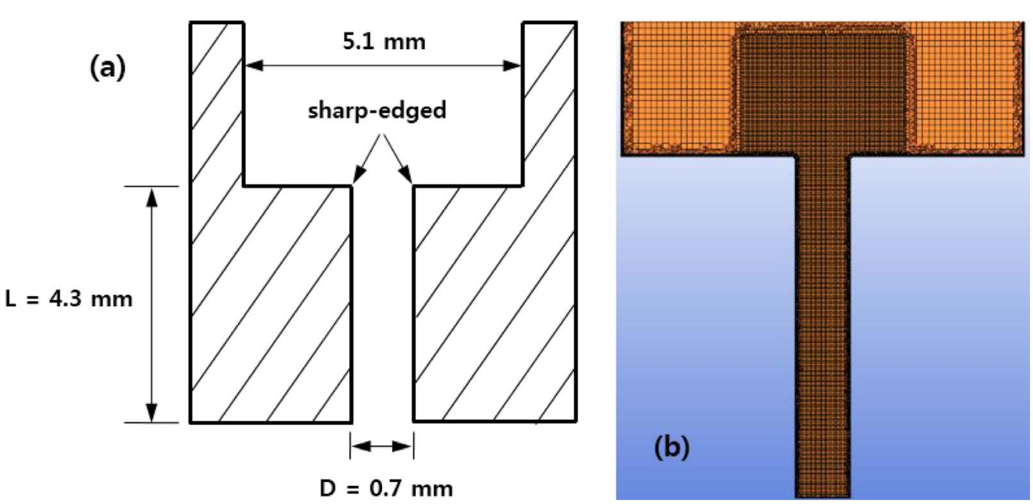

Fig. 1. Plain orifice injector; (a) Schematic of center plane and (b) mesh system.