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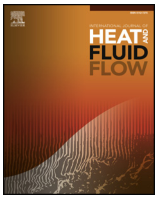

Effect of nozzle inlet geometry in high temperature hydrocarbon liquid jets

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ABSTRACT

An experimental study was conducted to investigate the effect of orifice inlet geometry on discharge and cavitation characteristics of high-temperature hydrocarbon liquid jets. The fuel was heated to 553 K (280 °C) using an induction heater, at an upstream pressure of up to 1.0 MPa, and injected to atmospheric pressure conditions through variously chamfered plain orifices of diameter 0.7 mm and length 4.3 mm. Hydraulic characterization in terms of fuel temperature was carried out by introducing the discharge coefficient, and the macroscopic internal flow characteristics were correlated with Reynolds number and cavitation numbers. The variation of C_d with respect to T_{inj} in the non-cavitating region below the boiling point shows that C_d increases with increasing chamfer depth C, but the C_d trend nearly converges to a maximum value when the relative chamfer depth reaches 20% of the orifice diameter. In the cavitating region, on the other hand, the effect of chamfer depth on the mass flow rate or C_d diminishes as the cavitation becomes stronger with increasing T_{inj}. The plot of C_d with respect to Re shows laminar to turbulent transition in high chamfer depth cases at $\Delta P = 0.3$ MPa, and this reveals that the internal flow in the current orifice configuration at relatively low velocity conditions remains laminar even at high Re for higher chamfer depths. Furthermore, the curves of C_d with respect to Re for various chamfer depths at each ΔP condition merge when T_{inj} is very high, implying that the trend of C_d with respect to Re at high T_{inj} conditions becomes independent of chamfer depth. The variation of C_d with respect to cavitation number for various chamfer depths converges gradually under cavitating conditions, and this suggests that the degree of cavitation (as quantified by the cavitation number) inside fuel injectors of different chamfer depths becomes closer as T_{inj} reaches very high values. It can, therefore, be concluded that because of mass flow choking the hydraulic characteristics represented by the discharge coefficient of high temperature hydrocarbon liquid jets become independent of chamfer depth in strong cavitation conditions as T_{inj} increases beyond the boiling point, and are determined only by the pressure difference between P_{inj} and P_{sat} at T_{inj}.

1. Introduction

Hydrocarbon-fueled supersonic combustion ramjets (scramjets) offer excellent performance characteristics, including high specific impulse and operational flexibility, and they have been studied as practical hypersonic alternatives to solid and liquid rockets for use within the atmosphere (Van Wie et al., 2005). There are still, however, many technical barriers to realization of operational air-breathing hypersonic systems; one of the most serious but inevitable problems arising from hypersonic flight is aero-thermodynamic heating (National Research Council, 1998). The immense heat on the surface of a vehicle and the engine wall requires not only special materials that can resist and block the heat but also active heat-sink cooling systems (Van Wie et al., 2005). Fortunately, heat-absorbing chemical reactions such as thermal and catalytic cracking give liquid hydrocarbons excellent cooling capacity, and this means that they can be circulated as coolants in active cooling systems before they are injected into the engine for use as fuel (Sobel and Spadaccini, 1997; Rao and Kunzru, 2006). At the exit of such a cooling system, however, the fuel has reached a very high temperature, depending on overall heat load and heat sink capacities (Gasner et al., 1992), and the heated fuel must be pressurized for injection into the combustor. At these high temperatures and pressures the fuel may reach supercritical conditions (Edwards, 1993).

It is known that the internal flow conditions in a fuel injector have a strong influence on injection and spray patterns (Soteriou et al., 1995; Tamaki et al., 1998; Aleiferis et al., 2010), and therefore the injection and spray characteristics of high-pressure, high-temperature fuel may differ from those at near-ambient temperature conditions. The process of phase change in a liquid caused by a decrease of static pressure at constant ambient temperature is known as cavitation (Aleiferis et al., 2010), and when fuel is supplied to an injector at high temperature, the

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Nomenclature

A_o	outlet (orifice) area of the injector (m^2)
C	chamfer depth (mm)
Ca	cavitation number, $Ca = \frac{P_\infty - P_{sat}}{\rho_l V^2 / 2}$
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_B	pressure inside the bubble (Pa)
P_∞	ambient pressure (MPa)
P_{inj}	injection pressure (MPa)
P_L	local liquid pressure (Pa)
P_{sat}	saturation vapor pressure (MPa)
R	bubble radius (m)
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 injector (Pa), $\Delta P = P_{inj}$ - P_∞
μ_l	liquid viscosity (Pa·s)
ρ_l	liquid density (kg/m^3)
σ	liquid surface tension (N/m)

internal fuel flow is very susceptible to cavitation because the saturated vapor pressure of a liquid rises rapidly with increasing temperature. In some extreme cases, cavitation may result in mass flow choking or the development of critical cavitation conditions (Nurick, 1976; Payri et al., 2009; Cioncolini et al., 2016; Lee et al., 2017b), as well as hydraulic flip (Soteriou et al., 1995; Tamaki et al., 1998; Tafreshi and Pourdeyhimi, 2004; Suh and Lee, 2008). Along with the cavitation inside the injector, the high temperature liquid fuel will experience flash boiling when it is injected into the atmosphere, where the saturation vapor pressure is higher than the ambient pressure. Flash boiling is the phase change associated with the depressurization of a liquid jet outside the injector (Sher et al., 2008), and it usually accompanies compressible flow phenomena such as shock waves and flow choking (Vieira and Simoes-Moreira, 2007; Lamanna et al., 2014).

The behaviors of injection and spray characteristics under cavitating and/or flashing conditions have been studied extensively over the past decade, using not only water (Nurick, 1976; Tamaki et al., 1998; Ramamurthi and Patnaik, 2002; Cioncolini et al., 2016) but also diesel-like fuel (Soteriou et al., 1995; Payri et al., 2004, 2009; Sou et al., 2007; Suh and Lee, 2008; Lamanna et al., 2014) as the working fluid. Few studies, however, have been concerned with cavitation and flash boiling in aviation fuel, as induced by increased saturation vapor pressure under very high injection temperature conditions. Under these conditions, the effects of cavitation, including decreasing flow rate and discharge coefficient (Payri et al., 2009; Cioncolini et al., 2016), can be adverse because they may significantly reduce the precision of fuel control in hypersonic air-breathing engines. At the same time, the unique jet breakup of the flashing liquid is known to be conducive to atomization because the spray formed by flash boiling has a wide cone angle, small mean droplet diameter with higher homogeneity, and short penetration depth relative to non-flashing spray at a specified operating pressure (Vieira and Simoes-Moreira, 2007; Sher et al., 2008; Lamanna et al., 2014).

Recently, Lee et al. (2017a, 2017b) have investigated the internal flow characteristics of heated liquid jets of an aviation fuel both experimentally and numerically, and found that high fuel temperature induces cavitation, which ultimately results in mass flow choking, and choked cavitation is the main cause of the sharp decrease in discharge coefficient, regardless of the injection pressure, when the fuel injection temperature exceeds the saturation temperature at ambient pressure of the fuel jets. In addition, Jin et al. (2018) considered the flash boiling spray and atomization characteristics of superheated hydrocarbon liquid jets injected to atmospheric pressure, and observed that the superheated fuel spray clearly shows the typical features of flashing atomization, including wide spray angle and homogeneous droplet distribution. They also found that the breakup regime of high temperature hydrocarbon liquid jets can be broken down into four modes - a turbulent primary breakup mode, an aerodynamic bag/shear breakup mode, a transitional flashing mode, and a fully flashing mode. The aforementioned studies, however, were limited to the effects of cavitation and flash boiling on hydraulic and spray characteristics of high temperature liquid fuel jets injected through a sharp-edged plain orifice injector, in order to exclude any effects of orifice geometry.

The details of the nozzle geometry, however, such as the orifice inlet roundness and length-to-diameter ratio, are known to be important to the generation of cavitation and turbulence inside the nozzle (Reitz and Bracco, 1979; Kent and Brown, 1983; Lefebvre, 1989). For example, in nozzles with small length-to-diameter ratios, cavitated fuel vapor can reach the nozzle exit, in a phenomenon referred to as “super-cavitation” (Sou et al., 2007) or hydraulic flip (Soteriou et al., 1995; Tamaki et al., 1998; Tafreshi and Pourdeyhimi, 2004; Suh and Lee, 2008). When the nozzle is long enough, the liquid flow can re-attach to the downstream walls of the vena-contracta (Nurick, 1976; Lee et al., 2017b). In addition, if the inlet corner is rounded sufficiently, the liquid fuel flows through the nozzle without detaching from the walls, and thus neither the vena-contracta nor cavitation bubbles may be present, and this enables the discharge coefficient to remain relatively high (Nurick, 1976). It is also known that a square-edged inlet nozzle requires a greater pressure drop for operation with equal mass flow rates, and the higher turbulence intensity level produced in the square-edged nozzle correlates with wider spray dispersion angles (Reitz and Bracco, 1979; Kent and Brown, 1983). Thus, the issue of nozzle geometry effects on flow phenomena related to liquid fuel cavitation and atomization is of great importance for combustion systems that employ fuel injection into the combustor (Kent and Brown, 1983). From a practical point of view, furthermore, there are many types of fuel nozzles having a variety of geometries. As a result, an in-depth investigation is needed on the effect of injector geometry on high temperature hydrocarbon liquid jet injection and atomization characteristics, in order to ensure precise fuel control and facilitate effective fuel injection, mixing, and combustion in scramjet combustors for hypersonic air-breathing engines.

In the current paper, therefore, an experimental study investigating the effect of orifice inlet geometry on the discharge and hydrodynamic characteristics of high-temperature liquid jets is presented; here we focus on the single parameter of chamfer depth, as chamfer may be imposed on a plain-orifice injector either intentionally or as an artifact of manufacturing. Pressurized heated liquid hydrocarbon, simulating aviation fuel used as coolant in the active cooling system of a hypersonic flight vehicle, is injected through plain orifice nozzles having different chamfer depths at the orifice inlet. The fuel is heated to close to 573 K (300 °C) using an induction heater, at an upstream pressure of up to 1.0 MPa, and discharged to atmospheric pressure conditions. Following the analysis of Lee et al.’s study (2017a), hydraulic characterization in terms of fuel temperature is carried out by introducing the discharge coefficient, and the macroscopic internal flow