International Journal of Heat and Fluid Flow 65 (2017) 166–176

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Hydraulic characterization of high temperature hydrocarbon liquid jets

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ARTICLE INFO

Article history:
Received 22 May 2016
Revised 3 December 2016
Accepted 20 April 2017

Keywords:
Orifice injector
Fuel temperature
Discharge coefficient
Cavitation
Mass flow choking

ABSTRACT

An experimental study has been conducted to investigate the hydraulic characteristics of a plain orifice nozzle issuing pressurized high-temperature liquid hydrocarbon, in order to simulate injection of aviation fuel after being used as coolant in an active cooling system in a hypersonic flight vehicle. 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 a sharp-edged orifice of diameter 0.7 mm and length 4.3 mm. It has been observed that the isothermal lines on the plane of the mass flow rate versus the square root of the pressure drop (ΔP) were clearly affected by increased fuel temperatures, and the discharge coefficient (C_d) decreased sharply with increasing fuel injection temperature (T_{inj}) above the fuel boiling point of 460 K. The Reynolds number (Re) for three ΔPs with respect to T_{inj} reached maxima and then began to decrease as T_{inj} increased for each ΔP case, and the fuel temperature of maximum Re at a given pressure condition increased as ΔP increased. The effects of cavitation on the hydraulic characteristics of the high temperature fuel were explored by representing C_d with respect to three cavitation numbers and dissipation efficiency. The behaviors of C_d showed a clear dependency on cavitation number, and all of the results collapsed to a single curve, regardless of ΔP. In addition, the curve indicated that the C_d characteristics was divided into non-cavitating and cavitating regions by the critical cavitation numbers near the fuel boiling point, and a sharp decrease in C_d was found to be typical in the cavitating region. The relationship between C_d and Re showed that when T_{inj} exceeded the boiling point the high temperature liquid jets experienced a sharp decrease in C_d at a determined Reynolds number, due to the collapse of the mass flow rate induced by the choked cavitaiton.

1. Introduction

Supersonic Combustion Ramjets (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 from supersonic to hypersonic flights (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 problems arising from hypersonic flight is aero-thermodynamic heating (National Research Council, 1998). It is known, for example, that the air total temperature and the surface temperature of a hypersonic vehicle flying at Mach 5 are 980 °C and 550 °C, respectively, and the wall temperature of a scramjet engine exceeds 2000 °C (National Research Council, 1998). The tremendous heat on the surface of a vehicle and the engine wall requires not only high-temperature/insulation materials that can resist and block the heat, but also active cooling systems, which can operate as a heat sink (Van Wie et al., 2005). Even though these regenerative cooling structures increase system cost and complexity, efficient system operation is possible when the loaded fuel is used as the coolant in a volume- (and weight-) limited hypersonic vehicle (Van Wie et al., 2005).

Another important issue for hypersonic flight is the selection of appropriate fuels. When a hypersonic vehicle travels at speeds over Mach 5, the air flow inside the engine is supersonic, and the residence time of the fuel/air mixture is very short – usually less than a millisecond (Pace, 2007). In addition, a series of shock waves makes the air flow in the combustor very complicated. For such an adverse environment, hydrogen is thought to be the most promising fuel, due to its superb ignition characteristics and very high flame propagation speed (Van Wie et al., 2005; Pace, 2007). However, hydrogen presents challenges for practical scramjet use of its low density in gaseous form and the need for complex and bulky cryogenic fuel systems to allow use in the liquid state. Hydrocarbons, on the other hand, are sufficiently dense and usually in liquid state at ambient conditions, which eventually reduces takeoff weight and increases payload by keeping storage tanks simple and compact (Pike, 1999). As a result, hydrocarbon-fueled

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.04.007
0142-727X/

Nomenclature

A_i	inlet area of the injector (m^2)
A_o	outlet (orifice) area of the injector (m^2)
Ca	cavitation number, $Ca = \frac{P_\infty - P_{sat}}{\rho V^2/2}$
C_c	area contraction coefficient
C_d	discharge coefficient, $C_d = \frac{\dot{m}_f}{A_o\sqrt{2\rho_l \Delta P}}$
CN	cavitation number, $CN = \frac{P_\infty - P_{sat}}{P_{inj} - P_\infty}$
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)
R	specific gas constant (kJ/kg·K)
Re	Reynolds number, $Re = \frac{\rho_l V D}{\mu_l}$
T_{inj}	fuel injection temperature (K)
T_{sat}	saturation temperature (K)
V	average injection velocity (m/s)
Greek symbols	
ΔH_{fg}	enthalpy of evaporation (kJ/kg)
ΔP	pressure drop across the injector, $\Delta P = P_{inj}$ - P_∞
μ_l	liquid viscosity (Pa·s)
$\Pi_{\Delta P}$	dissipation efficiency, $\Pi_{\Delta P} = \frac{P_{inj} - P_\infty}{\rho V^2/2}$
ρ_l	liquid density (kg/m^3)

scramjets have been intensively studied, in order to find efficient methods of fuel injection, mixing, ignition, and flame holding capable of overcoming the short residence time and the complicated flow environment (Van Wie et al., 2005; Pace, 2007).

Liquid hydrocarbon fuels have been in use as an aviation fuel for air-breathing propulsion systems for decades. Two kinds of jet fuel – JP-8 (or equivalently, Jet A-1) and JP-10 – are currently widely available in the U.S. for aircraft and missiles, respectively, due to their stability, ease of handling, and appropriate physical properties for aviation applications (Edwards, 2003). These liquid hydrocarbons are known also to have excellent cooling capacity, through heat-absorbing chemical reactions such as thermal and catalytic cracking (Edwards, 1993; Cooper and Shepherd, 2002), and thus can be used as coolant in active cooling systems (Sobel and Spadaccini, 1997; Rao and Kunzru, 2006). The fuel at the exit of a cooling system, however, is inevitably heated to 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 a scramjet combustor. At these high temperatures and pressures, the fuel may reach supercritical conditions (Edwards, 1993).

The injection and spray characteristics of high-pressure, high-temperature fuel may differ from those near ambient temperature conditions, possibly including physical phenomena such as cavitation (Nurick, 1976; Soteriou et al., 1995; Tamaki et al., 1998; Arcoumanis et al., 2001; Tafreshi and Pourdeyhimi, 2004; Strotos et al., 2015) and flash boiling (Oza, 1984; Vieira and Simoes-Moreira, 2007; Sher et al., 2008; Neroorkar, 2011). Cavitation is the process of phase change in the flowing 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 cavitation 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 may form, grow, move, and collapse inside the injector. Once cavitation is present, 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., 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 injection characteristics under cavitating 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 fuel (Soteriou et al., 1995; Arcoumanis et al., 2001; Payri et al., 2004, 2009; Sou et al., 2007; Suh and Lee, 2008; Strotos et al., 2015) as the working fluid.

Though there have been extensive studies of cavitation inside fuel injectors and its effect on spray and atomization characteristics, most of these studies have dealt with cavitation induced by increasing either injection pressure or flow velocity at ambient temperature conditions. In fact, they have mainly focused on the beneficial effects of cavitation in diesel fuel injection, including increased spray angle and more uniform droplet distribution (Soteriou et al., 1995). Few of these studies have been concerned with cavitation in aviation fuel, as induced by increased saturation vapor pressure in very high temperature conditions. Nevertheless, the adverse effects of cavitation under these conditions, including decreasing flow rate and discharge coefficient, may significantly reduce the precision of fuel control in hypersonic air-breathing engines, and warrant investigation.

The current paper, therefore, presents an experimental study of discharge and hydrodynamic characteristics in a plain orifice nozzle issuing pressurized high-temperature liquid hydrocarbon, in order to simulate injection of aviation fuel used as coolant in the active cooling system of a hypersonic flight vehicle. The fuel is heated to nearly 573 K (300 °C) using an induction heater at an upstream pressure of up to 1.0 MPa and injected to atmospheric pressure conditions. Hydraulic characterization in terms of fuel temperature is carried out by introducing the discharge coefficient, and the macroscopic internal flow characteristics are correlated to Reynolds number and various cavitation numbers. First, in Section 2, the experimental setup for the high-temperature fuel injection is described, and methods and parameters for analyzing the experimental data are introduced. In Section 3, the operating conditions considered in this study and the data set of results obtained from the experiment are presented, and the behaviors of the discharge coefficient and Reynolds number with respect to fuel injection temperature are analyzed. In addition, the effects of cavitation in high temperature fuel on the hydraulic characteristics are explored by representing the discharge coefficient with respect to several cavitation numbers. Also shown is the correlation between the discharge coefficient and Reynolds number to discuss the evidence of the choked cavitation of the high temperature liquid jets. Finally, conclusions are presented in Section 4.

2. Experiment and analysis

2.1. Experimental setup and procedures

Fig. 1 shows a schematic diagram of the high-temperature fuel injection test rig designed and manufactured for the current study. The fuel is initially stored in the fuel tank for a few days to remove any dissolved gas. When the experiment begins, the fuel is pressurized by the high pressure air tank and then supplied from the