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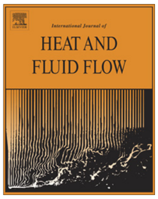

Effects of dual jets distance on mixing characteristics and flow path within a cavity in supersonic crossflow

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ABSTRACT

A rectangular open cavity with upstream dual injectors at a freestream Mach number of 1.9 was investigated experimentally. To evaluate the effect of the distance between the jets, the flow characteristics were investigated using the high-speed schlieren photography, particle image velocimetry, and surface oil flow techniques. The dual jet distances of 18 and 54 mm were used. Unstable flow occurs over the cavity in all cases and is not improved by changing the distance between the dual jets. Although the distance between the dual jets does not influence the flow stability, the flow field varies decidedly depending on the dual jets distance. The enhancement of air mixing depends on the distance between the jets. A long dual jets distance was found to yield better mixing characteristics within the cavity than a short one. When the jets are further apart, the mainstream between two counter-rotating vortex pairs behind the jets flows strongly into the cavity because of the increased blow-down occurring between the vortex pairs. Additionally, a counterflow with a low velocity magnitude occurs behind the jets. Hence, mixing is enhanced within the cavity by effects of the opposed flow. When the jet pairs are closer to each other, the counter-rotating vortex pairs are in contact; as a result, the blow-down effect does not occur between them. The flow drawn into the cavity from the mainstream is supplied from the sides of the test section into the cavity.

1. Introduction

Supersonic combustion ramjet (scramjet) engines require an optimized injection system that produces higher performance due to enhanced fuel–air mixing and improved flame stabilization. Additionally, a low profile drag is a key component that will increase the net power. Designing the optimum injection system having all of these capabilities is challenging. Because a scramjet engine is mounted on hypersonic vehicles working at Mach numbers ranging from 4 to 8 (Drummond et al., 2006), the residence time of the supersonic freestream within the combustion chamber of a scramjet is extremely short, typically on the order of milliseconds. It is not easy to design the optimum injector because of the high-speed flow and short residence time.

Having a flush-mounted multiple injection system is an effective means of combining the benefits of low profile drag injection with improved mixing characteristics. Flush-mounted multiple injection systems have been shown to enhance the fuel–air mixing characteristics (Lee, 2006; Jacobsen et al., 2000; Cox-Stouffer and Gruber, 1999). Pudsey and Boyce (Pudsey and Boyce, 2010) has shown that the multiport jet arrays are more effective for mixing in the near field around the injection location, although the mixing is not improved in the far field compared to that in a single injection system. Ming-bo et al. (2011) investigated the effect of the distance between the injection ports on the mixing characteristics in a parallel multiple injection model. When the distance between the multiple ports in parallel injection is short, an adequate the mainstream is not supplied between them, and the mixing effect is decreased. This is because of the interaction between the bow shocks in front of the injected jets. To obtain optimum mixing characteristics, it is necessary to investigate the mixing phenomena in a simplified multiple injection model. In multiple injection systems, a complex flow field behind the injectors is induced by many shock wave interactions generated around the multiple injections, making it difficult to fully understand the mixing characteristics. For a tandem dual injection system, Lee (2006) has shown that the mixing characteristics of the dual injection system are enhanced compared to those of a single injection system. A rear injection flow possesses higher penetration and diffusion because the mainstream is blocked in front injection. An optimal distance

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between the front and rear jets exists at which better mixing is obtained.

A cavity model enhances the fuel–air mixing and flame holding properties of scramjet engines (Yang et al., 2013; Yu et al., 1998; Gruber et al., 2004; Sakamoto et al., 1995; Kang et al., 2012; Yeom et al., 2013; Ghodke et al., 2011; Tatman et al., 2013; Rasmussen et al., 2005; Lada and Kontis, 2010, 2011). Yu et al. (2001) has shown that a cavity model can induce faster mixing and a high combustion pressure, although the combustion performance depends on the cavity configuration. Cavity models are classified as open cavity or closed cavity depending on the cavity geometry: length-to-depth ratio (L/D). In general, an open cavity ($L/D < 7$–10) is often used as a flame stabilizer because of its low drag properties compared to a closed cavity ($L/D < 10$–13). The surface pressure on the aft wall of the closed cavity increases because the shear layer over the cavity impinges strongly on the aft wall (Gruber et al., 2001). Although high drag also occurs in cavities with an aft ramp, even if the cavity geometry is an open one, such cavities exhibit high performance as a flame holder (Gruber et al., 2004).

Although an open cavity enhances the flame stabilization and fuel–air mixing, this performance decreases if unstable flow occurs over the cavity. The shear layer usually impinges on the rear edge of the cavity and generates an acoustic wave. When pressure oscillations occur inside the cavity by the successive compression waves, the flow becomes unsteady over the cavity (Lawson and Barakos, 2011; Li et al., 2013). Although stable flow can be obtained around a cavity when an aft ramp is adopted, the profile drag increases (Gruber et al., 2001). A shock-jet impingement system could be effective for unstable flow over the cavity. If a shock wave impinges on the shear layer near the rear edge of the cavity, the flow over the cavity might become steady because the shear layer is lifted up by the shock interaction (Sakamoto et al., 1995).

The mixing and flame holding capability varies depending on the injector position. For open cavities containing a fuel injector within the cavity, the presence of an aft ramp provides high performance as a flame holder, although the performance varies with the injector position (Gruber et al., 2004; Rasmussen et al., 2005). Even for a cavity with an upstream injector and a straight aft wall, which possesses lower drag than a cavity with an aft ramp, the mixing characteristics depend on the injector position. Ukai et al. (2014) have shown that if an injector is positioned farther from the cavity front edge, the mixing is decreased. For an injection position close to the cavity, the mixing is enhanced within the cavity, and stable mixing performance can be obtained independent of the jet-to-free stream momentum flux ratio.

It is necessary to design an optimum injection system for the development of scramjet engines. The cavity model exhibits higher fuel–air mixing and flame stabilization performance, although these characteristics depend on the cavity configuration and injector position. Additionally, a flush-mounted multiple injection system can enhance the mixing. An open cavity with a flush-mounted multiple injection system could be the solution for higher combustion performance. However, it is difficult to accurately understand the flow field around a cavity with multiple injection ports because many shock interactions occur around the injections. In this study, to understand the flow physics around a cavity with injections, in particular the air mixing and flow stability, an experimental investigation was performed in a wind tunnel at a Mach number of 1.9. To simplify the study, a dual injector with a rectangular open cavity was adopted. The dual jets distance was varied, and the flow field was investigated using the high-speed schlieren photography, particle image velocimetry (PIV), and surface oil flow techniques.

2. Experimental setup

2.1. Experimental conditions

The experimental investigation was performed at a Mach number of 1.9 in the Aero-Physics Laboratory trisonic wind tunnel at The University of Manchester (Ukai et al., 2014). A schematic diagram of the cavity geometry is shown in Fig. 1. A rectangular open cavity with $L/D = 5$ [100 mm in length (L) and 20 mm in depth (D)] was adopted and embedded into the lower wall of the test section. A converging round jet orifice with an exit diameter of 2.2 mm was vertically machined upstream of the cavity. The jet orifices were located 10 mm from the front edge of the cavity. Ukai et al. (2014) showed that the air mixing is enhanced within the rectangular open cavity with $L/D = 5$ when the jet is positioned 10 mm from the front edge of the cavity. The distance between the dual jets was 3BL (18 mm, Case 1) or 9BL (54 mm, Case 2), where BL is the boundary layer thickness at the jet hole location. A test case with no jet (Case 0) was also considered.

Different distances between the jet injections were used to investigate the flow physics, especially the flow mixing characteristic, flow stability, and flow pattern within the cavity. High-pressure air supplied through a pressure regulator and flexible tubing was used as the jet gas. Flexible tubes separated from the outlet of a pressure regulator supplied high pressure air for each jet. Only one pair of jet holes was operated at a time, either the jets that are 3BL apart or the pair that is 9BL apart. The jet pressure was adjusted to provide a jet-to-free stream momentum flux ratio of $J = 5.3$; J is defined as Eq. (1),

$$J = \frac{Y_{jet} p_{jet} M_{jet}^2}{Y_0 p_0 M_0^2} \tag{1}$$

where γ is the specific heat ratio, p is the static pressure, and M is the Mach number, and subscripts “0” and “jet” refer to the free-stream and jet conditions, respectively.

2.2. High-speed schlieren photography

High-speed schlieren photography (Kontis et al., 2008a,b; Zare-Behtash et al., 2011; Erfani et al., 2012) with a standard Z-type optical arrangement was employed to visualize the flow field around the cavity. The optical arrangement consists of a pair of 203.3 mm diameter parabolic mirrors with 1016 mm in focal length and a 450 W Xenon continuous light source (Newport). The light generated from the light source is cut off by a slit and collimated by a parabolic mirror. The collimated light passes through the test section and is reflected by the second parabolic mirror. The offset angle between the collimated light beam and the light source was set to 10° to prevent coma. A knife edge is located at the focal point of the second mirror to adjust the sensitivity. High-speed schlieren images were recorded using a high-speed video camera (Fastcam SA-1, Photron Corp.) with a maximum resolution of 1024 × 1024 pixels. A frame rate of 8.0 kfps with an exposure time of 1 μs was used.

2.3. Particle image velocimetry

PIV was used to evaluate the flow velocity and other properties inside the cavity. The PIV system has been successfully applied in previous studies (Erdem et al., 2012; Erfani et al., 2012; Zare-Behtash et al., 2008). A Nd:YAG Q-switched laser (Litron Nano PIV series, LPU550) having a pulse energy of 200 mJ at a repetition rate of 15 Hz and wavelength of 532 nm with a pulse duration of 4 ns was used for the PIV illumination. A laser illuminator was located at the side of the test section, and a planar laser sheet

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