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Transverse jet-cavity interactions with the influence of an impinging shock

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ABSTRACT

For high-speed air breathing engines, fuel injection and subsequent mixing with air is paramount for combustion. The high freestream velocity poses a great challenge to efficient mixing both in macroscale and microscale. Utilising cavities downstream of fuel injection locations, as a means to hold the flow and stabilise the combustion, is one mechanism which has attracted much attention, requiring further research to study the unsteady flow features and interactions occurring within the cavity. In this study we combine the transverse jet injection upstream of a cavity with an impinging shock to see how this interaction influences the cavity flow, since impinging shocks have been shown to enhance mixing of transverse jets. Utilising qualitative and quantitative methods: schlieren, oilflow, PIV, and PSP the induced flowfield is analysed. The impinging shock lifts the shear layer over the cavity and combined with the instabilities generated by the transverse jet creates a highly complicated flowfield with numerous vertical structures. The interaction between the oblique shock and the jet leads to a relatively uniform velocity distribution within the cavity.

1. Introduction

The introduction of this paper is focused on two different flow phenomena, namely, transverse jets and cavities in supersonic flow. Although these two topics may seem disconnected at first, they are brought together through this research.

Transverse jet injection into supersonic/hypersonic flows has several engineering applications ranging from flow control and attitude control, by creating forces and moments, to fuel injection in scramjets and thrust vector control (Ferri and Nucci, 1951; Sullins, 1993; Ali et al., 2000; Gruber et al., 2000; Kontis, 2004; Lee, 2006a,b; Erdem and Kontis, 2010; Cecere et al., 2011). Such flows are extremely complicated and unsteady, making the numerical and experimental studies of such phenomena very difficult and challenging.

For the application in scramjet combustion, due to the millisecond residence times of the flow, efficient mixing is key (Tomioka et al., 2003; Burtschell and Zeitoun, 2004; Huang et al., 2001). Mai et al. (2011) showed that by having an incident shock impinge close to the transverse jet injection location, an enhanced mixing level can be achieved with an increased residence time that would lead to a more efficient combustion. Similar findings were reported by Schetz et al. (2010) regarding the increased mixing levels during shock-jet interactions and also the location of the impinging shock which results in the best mixing, that is, when the shock impinges immediately downstream of the jet. The enhancing combustion properties of impinging shocks is also documented by Huh and Driscoll (1996) where the authors believe that it is the adverse pressure gradient caused by shock that is responsible for altering the recirculation zones and leading to flame stability.

According to Lazar et al. (2008) cavities represent a fundamental fluid dynamic configuration, with applications ranging from supersonic aircraft weapon bays and the problems associated with aerodynamic drag and heating to high-speed combustion. Employing cavities inside scramjets is a mechanism to improve combustion by decelerating the breathing air from supersonic to subsonic speeds in order for combustion to occur. Supersonic flows over cavities lead to extremely unsteady flows, requiring detailed analysis and design consideration. As evident from the schlieren photograph of Fig. 1, in all flows over a cavity a shear layer is present, which develops out of the boundary layer behind the leading edge of the cavity and is sustained by the velocity difference between the freestream and the flow inside the cavity. In supersonic flows an oblique shock forms at the leading edge of the cavity due to the separation of the boundary layer and an expansion or compression wave is similarly seen at the trailing edge. As the

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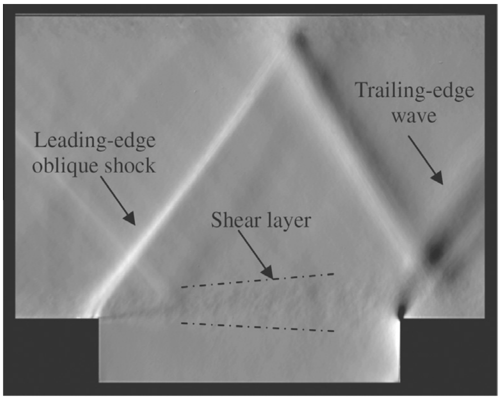

Fig. 1. Schlieren image of a typical supersonic flow over cavity (Lazar et al., 2008).

shear layer separates from the leading edge of the cavity, it starts to roll up into large-scale vortical structures due to the KelvinHelmholtz instability. When these structures impinge on the trailing edge of the cavity, acoustic waves are generated. These waves propagate to the leading edge within the cavity, because the free-stream flow is supersonic, to further excite the shear layer (Zhuang et al., 2006).

Gruber et al. (2001) looked at how changes in the aft wall of an open cavity can lead to changes in the shear layer and hence the drag and residence time within the cavity. Sakamoto et al. (1995) revealed the complex three-dimensional nature of two-dimensional cavity flows, and the oscillatory nature of the leading edge cavity shock. When introducing an impinging shock over the cavity, they found that the shear layer angle, separation lines, and the features of the bow shock at the rear corner of the cavity depend strongly on the impinging shock location. Ukai et al. (2013) showed that if an injector is positioned close to the cavity leading edge, not only is the mixing enhanced within the cavity, but a stable mixing can be achieved independent on the jet-to-freestream momentum flux ratio.

According to Ben-Yakar and Hanson (2001) flame holding is achieved by: (1) organisation of a recirculation area where the fuel and air can be mixed partially at low velocities and (2) interaction of a shock wave with partially or fully mixed fuel and oxidizer; both of these methods can be found in the present study. It is therefore the goal of this study to examine the flow physics when combining an impinging shock wave with a transverse jet located upstream of a cavity. It is believed that combining the merits of enhanced jet mixing due to an impinging shock together with placing a cavity downstream, higher levels of mixing and flow stability can be achieved. It is believed that the results will not only shed light on the fundamental flow characteristics but also help in the development and verification of advanced turbulence modelling tools.

2. Experimental setup

2.1. Wind tunnel and model

The wind tunnel, identical to that used by Ukai et al. (2013) is an intermittent indraft tunnel with test section dimensions of 150 × 215 × 485 mm (width × height × length). Desiccant particles are present at the tunnel inlet to absorb the moisture in the air, a heater is used to dry the desiccants and relieve them of any moisture content. For a Mach number of 1.9, the tunnel has a stable run time of approximately 5 s and a Mach number variation of ±0.01 for different runs. The Reynolds number for the current experiments is 8.4×10^6/m. Although previous studies examining scramjet flow physics have covered higher Mach numbers and Reynolds numbers in the 10^6 regime (Holland, 1992), the flow inside the combustion chamber of a scramjet would be travelling at a much lower Mach number due to the various compression waves encountered upstream (Che Idris et al., 2014).

As shown in Fig. 2, a shock generator with a wedge angle of 10° is mounted on the top wall of the test section to generate an oblique shock wave. The location of the shock generator can be varied in the streamwise sense. Two locations are chosen, Case 1 immediately downstream of the jet location, and Case 2 where the shock wave impinges 7.5 mm downstream of the cavity leading edge.

A rectangular open cavity, 100 mm in length (L) and 20 mm deep (D), was designed into the bottom wall of the test section. An axisymmetric conical jet hole with an orifice diameter of di = 2.2 mm was placed 10 mm (0.1L) upstream of the cavity along the centreline, with air as the jet medium. A jet to freestream momentum flux ratio, measure of the jet penetration into the freestream, of 5.3 was chosen, identical to the work of Ukai et al. (2013, 2014) which is defined in Eq. (1),

$$J = \frac{\gamma_{\text{jet}} p_{\text{jet}} M_{\text{jet}}^2}{\gamma_o p_o M_o^2} \tag{1}$$

where γ denotes specific heat ratio, p pressure, M Mach number, and the subscripts “o” and “jet” refer to the freestream and jet conditions, respectively (Huang et al., 2001).

2.2. Measurement techniques

A standard Z-type schlieren system was utilised, identical to that used by Zare-Behtash et al. (2009, 2011) The light source was a 450 W continuous Xenon lamp and a Photron SA-1 high-speed camera was used to capture images at a frame rate of 10 kfps with an exposure time of 1 μs.

Oil flow visualisation is a simple and effective method for visualising surface flow patterns (Lada and Kontis, 2010). Here, a mixture of fluorescent powder, paraffin, oleic acid, and silicon oil was used to map the flow. Before each run, the oil is deposited inside the cavity near the rear wall and illuminated with a pair of UV LED panels, 390 nm wavelength, from both sides of the test section. Images are acquired using a Canon SLR camera, model EOS-450D, with a 12 M pixel resolution. The recipe was optimised through trial and error to ensures that the oil does not dry too quickly, allowing sufficient time for the flow to establish, but at the same time it is not too viscous to obstruct the flow.

For particle image velocimetry, a Litron Nano L series, ND:YAG Q-switched laser, 532 nm wavelength, 4 ns pulse duration,

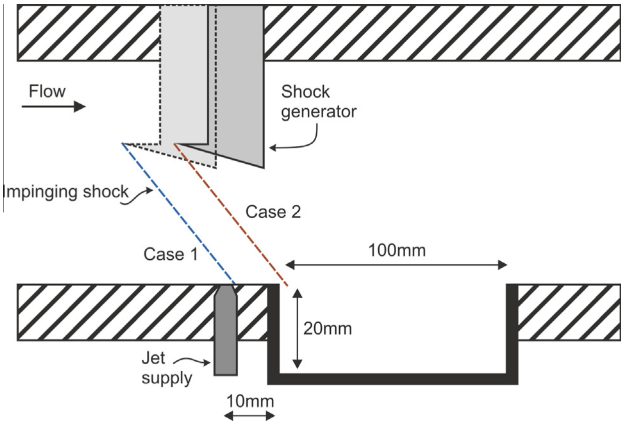

Fig. 2. Model arrangement and test cases for shock impingement.