Shock Wave Interaction Characteristics produced by Liquid Jet Injection in a Supersonic Crossflow

Srinivas M V V[1] and Arun Kumar R[1,*]
1: Dept. of Mechanical Engineering, Indian Institute of Technology Jodhpur, Jodhpur-342030, India
* Corresponding author: arunkr@iitj.ac.in

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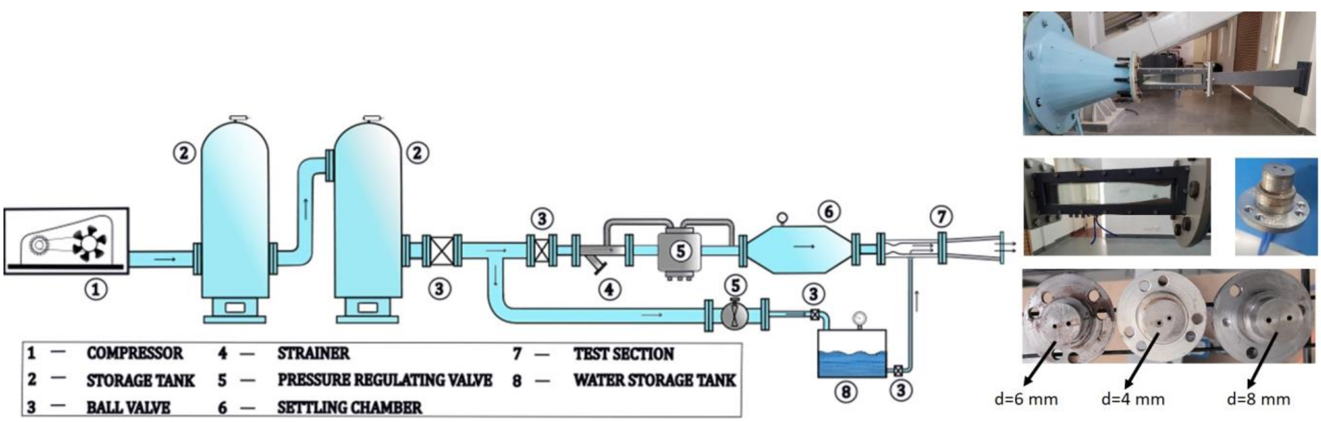
ABSTRACT This study experimentally investigates the shock wave interaction characteristics produced by transverse liquid injection in a supersonic crossflow of Mach 2.2. Time-resolved Schlieren imaging technique was used to capture the flow dynamics of the liquid jet as well as the shock characteristics in the crossflow. Various injectors like single circular liquid injectors, and tandem liquid injectors with different injector spacings (4mm, 6mm, and 8mm) are connected to the test section to investigate the liquid injection in supersonic crossflow. The diameter of each liquid injector is fixed such that the single injector and tandem injectors maintain the same ratio of liquid-gas momentum flux. It was noted that when the liquid jet is injected through a single circular injector, it results in the formation of a bow shock and a separation shock just upstream of the injection location. Additionally, it was noted that higher injection pressure of the liquid jet led to increased penetration, causing the core flow to deflect more around the liquid jet, thus forming a stronger bow shock wave upstream to the injector. The experiments were further performed with tandem injectors (one placed behind the other) with different injector spacing. Initial experiments conducted using the tandem injector demonstrated the presence of two bow shock waves, each resulting from the two separate liquid injectors. These two shock waves interact with each other leading to complicated shock reflections. The bow shock wave produced by the single injector reflects from the top wall with a regular reflection structure. For the tandem injection configuration with the same pressure ratio as that of circular injection, the reflection of the bow shock wave from the top wall produced a Mach reflection structure. The shock reflection structure is found to be varying with changes in injector spacing. Additionally, it has been noted that the surface waves on the liquid jet led to the formation of micro shocks that interact with the primary bow shock.

1 INTRODUCTION

The investigation of liquid jets in crossflow is a subject of extensive research, owing to its importance and the wide range of practical applications it encompasses. Liquid jets experience either supersonic or subsonic crossflow, depending on the specific application (Eslamian et al., Broumand & Birouk). Over the past few decades, researchers have been working on the development of air-breathing engines capable of achieving hypersonic speeds and one such engine is a scramjet engine. In contrast to traditional gas turbine engines, the combustion process within a scramjet engine takes place at supersonic speeds leading to a very short residence time (in the order of milliseconds) for air-fuel mixing. For efficient combustion, the liquid fuel must break up into smaller droplets, followed by atomization, and subsequent uniform mixing with the crossflow. Due to the complexity of processes that must be accomplished within a few milliseconds, this might lead to inefficient combustion. Furthermore, the injection of a liquid jet into supersonic cross-flow leads to compressible flow phenomena such as shock waves and expansion fans, which might have an additional effect on the combustion process. Developing a comprehensive understanding of the intricate flow physics such as shock interactions, liquid break up, etc. is thus essential for the development of scramjet combustor. Less & Schetz conducted a series of investigations to analyze the temporal behavior of liquid jets injected perpendicular to the flow with various flow Mach values ranging from 0.48 to 3. The droplet size changes were seen to occur throughout the frequency range of 1-14kHz. In addition, they observed that the frequency of the liquid jet breakup was linked to the frequency of the surface waves propagating through the liquid jet column. Sebastian & Muruganandam conducted an experimental study on the dynamic characteristics of the interactions between two shock waves: an oblique shock generated by a shock generator, and the bow shock developed as a result of liquid injection. The incidence of Edney shock interactions is shown to be dependent on the local bow shock angle, which is in turn influenced by the momentum flux ratio. Sebastian et al. experimentally investigated the effect of shock interaction with a liquid jet to study the liquid jet penetration characteristics. They observed an increase in the jet penetration when the shock interacts with the strong part of the bow shock. Sathiyamoorthy et al. conducted tests to investigate the penetration of jets and the combustion characteristics of liquid jets in tandem configuration in a supersonic crossflow. It was noted that the tandem liquid jets exhibited higher jet penetration in comparison to the single liquid injection. With the tandem liquid injection, it was noted that increasing the momentum flux ratio and the inter-jet spacing between the injectors led to greater penetration. Previous literature was mainly focused on understanding the fundamentals of liquid break-up characteristics and determining the height of liquid jet penetration for a single liquid injector. However, there have been limited investigations on the shock characteristics produced by tandem liquid jet injection into a supersonic cross flow. Therefore, the objective of this study is to examine the impact of tandem liquid injection on shock structures and to compare the characteristics of shock waves with both single and tandem liquid injection. Additionally, this study also investigates the effect of variation of the liquid injection mass flow rate on the jet penetration.

2 EXPERIMENTAL METHODOLOGY

The experiments were carried out using the supersonic wind tunnel facility (Mach 2.2) at IIT Jodhpur, India. The schematic of the wind tunnel is depicted in Fig. 1(a). The compressed air necessary for the experiment was sourced from a reciprocating compressor capable of operating at a maximum pressure of 30 bar and delivering 40 CFM. This compressor feeds two storage tanks, each with a capacity of $3m^3$, ensuring a continuous air supply throughout the experiment. A pressure regulating valve (PRV) in the wind tunnel maintains a consistent air supply by adjusting the pressure in the supply line. The flow of air is controlled by a ball valve. Downstream of the PRV, a settling chamber equipped with a pressure gauge and a port for measuring the stagnation pressure of the fluid flow is connected. The test section, attached to the settling chamber, features a convergent-divergent nozzle capable of producing a steady supersonic flow with a designed Mach number of 2.2. Various injectors, including single liquid injectors and tandem liquid injectors with different hole spacings, are attached to the test section to investigate liquid injection in supersonic crossflows, as shown in Fig.2(b). The liquid is injected into the wind tunnel test area through a pressure feed system. A smaller pressure regulating valve placed upstream of the water storage tank allows for variation in injection pressure. The mass flow rate of the injected liquid jet is controlled by varying the pressure of the feed system.



a) Schematic of the liquid injection experimental setup

b) Various injector geometries

Figure 1: Schematic of the liquid injection experimental setup

3 RESULTS

This section presents the findings from the initial tests conducted using a single and tandem liquid injector. The Schlieren imaging technique was employed to visualize the shock structures that arise from the injection of a liquid jet into a supersonic crossflow. The preliminary experiments were conducted by injecting the liquid into the supersonic crossflow at an injection pressure of 3 bar. The diameter of a single injector is 2.83mm, whereas the diameter of each injector in the tandem injector is 2mm. The diameter of the tandem injector has been determined such that the momentum flux ratio remains constant for both single and tandem injector cases. Figure 2 displays the comparison of Schlieren images for single and tandem injection cases. It can be seen from Fig. 2(a) (single injector case) that the introduction of a liquid jet into the crossflow generates a single bow shock, denoted as BS. However, for the tandem injection case through two circular ports, two bow shocks upstream to both injector locations can be seen as shown in Fig.2(b). Additionally, the formation of micro shocks due to the surface instabilities can also be observed in Fig. 2. It can also be observed from Fig.2 that the incident bow shock from the injector location reflects from the top wall. For the single injector case, a regular reflection can be observed from the top wall. However, for the tandem injection case, the reflected wave from the top wall originates at a much upstream location compared to the single injection case. The upstream movement of the reflected shock from the top wall can be attributed to the thickening of the boundary layer. This indicates that the incident shock strength increases with a tandem injection configuration compared to a single injection configuration leading to an enhancement in the boundary layer thickness. It is also observed that a further increase in injection pressure leads to the formation of a Mach reflection shock structure at the top wall for the tandem injection configuration compared to the single injector case. Further experiments are planned to be conducted to attain a deeper understanding of the formation of shock structures with the tandem injector.

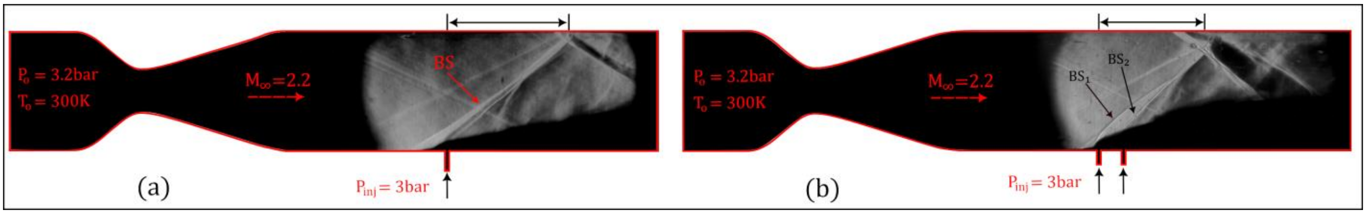


Figure 2: Comparison of shclieren images taken at a particular time instant for the injection pressure of 3bar (a) Single Injection (b) Tandem Injection (BS- Bow Shock, BS_1- Bow Shock due to 1st injector, BS_2- Bow Shock due to 2nd injector)

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