Control of sonic jets by fluidic injection

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Abstract. The present experimental study aims at investigating the effect of fluidic injection by means of air tabs on the core of circular and square sonic jets issuing from orifice at different levels of underexpansion. The experiments were conducted by varying the injection pressure ratio (IPR) from 3 to 5 for a fixed nozzle pressure ratio (NPR) 3, 4 or 5. Shadowgraph visualization was used to quantify core length of jet with and without fluidic injection. The injection in both circular and square sonic jets resulted in reduction of core length at all the NPRs. For each NPR, the maximum and minimum core length reductions occurred at IPRs 5 and 3, respectively, showing that the mixing promotion in circular or noncircular sonic jets is influenced by momentum of the injected jet. Among the NPRs, the reduction in core length was maximum at NPR 3 and minimum at NPR 5 for both circular and square jets at all the IPRs. The injection caused a highest reduction in the core of square jet than the circular jet all NPRs except NPR 5. A highest reduction of about 50% was achieved at NPR 3 and IPR 5 for square jet.

1. Introduction
Control of jets by fluidic injection is considered an effective active jet control technique for mixing enhancement as well as jet noise reduction. Compared to other jet control methods, use of mini jet for jet control imparts minimal or almost no thrust loss. Due to its tremendous application potential of jet control, substantial amount of work has been done in the past few decades. Fluidic injection was found efficient in controlling the subsonic, sonic and supersonic jets.

The concept of air tabs was first studied by Davis [1]. for Mach 0.8 circular jet. He showed that two air tabs at the exit of nozzle caused a significant increase of jet mixing. The air tab study of Yu et al. [2], for subsonic jet proved that the air tab can enhance mixing without causing any thrust loss. The use of air tab for supersonic Mach number of 1.3 by Wan and Yu [3], showed that the air tab resulted in faster jet centerline velocity decay thus increasing the jet mass flux entrainment. For Mach 1.56 jet, Cuppoletti et. al. [4], demonstrated that the injected fluid can penetrate deep into the main jet shear layer causing a faster potential core reduction. Chauvet et. al. [5], investigated underexpanded supersonic jets subjected to radial secondary injections to test the efficiency of fluidic injector. They concluded that the number of injectors should be less than or equal to four for efficient mixing. They also showed that the mixing process in the distorted jet by radial injections is strongly actuated by longitudinal vortices. The analysis of shock patterns in a highly underexpanded jet controlled by radial injections by Chauvet et. al. [6], confirmed the evolution of shock-wave structure to a pattern resembling a Mach disk due to transverse mass flows.

Arun Kumar et. al. [7], experimentally studied the control of sonic circular jets using air tabs. They found that the distortion due to air tab increases with increase in Mach number and mass flow rate, and decrease in diameter of air tab. The core length reduction of about 76% and 82% was achieved when
the Mach number of the control jet was increased to 1.56 and 1.71, respectively. Arun Kumar et. al. [8] manipulated Mach 2 jet using convergent and convergent-divergent injectors. They found that the mass flow rate ratio of the mini jets to the main jet, the expansion ratio and the injector type had a profound effect on the core length of the controlled jet. Maximum core length reduction was achieved at the design condition than at the off-design condition of the manipulated jet. Arun Kumar et. al. [9] performed an empirical scaling analysis of Mach 2 jet control using steady fluidic injection to establish the relationship between supersonic core length and mass flow ratio, expansion ratio, nozzle exit diameter, injector exit diameter. A monotonic decrease in core length with an increase in mass flow ratio of the mini jet to the main jet was observed for all pressure ratios. Also, the injection caused upstream movement of shock crossover point thus reducing the core length and hence higher mixing.

From the literature, it can be noticed that the fluidic injection by mini jet or air tab as an active control method was used mostly for circular jets. The effect of injection on noncircular jets is yet to be investigated. It is well known that the noncircular jets exhibit increased entrainment and enhanced mixing than the equivalent circular jets [10]. The use of noncircular geometries as a passive control technique can enhance both large- and small-scale mixing due to their azimuthal asymmetry. It would be interesting to study the mixing characteristics of noncircular jets in the presence of fluidic injection. Therefore, the present experimental work aims at investigating the effect of fluidic injection on the mixing characteristics of sonic square jet issuing from an orifice. The main control parameters in the present study are nozzle pressure ratio (NPR) and injection pressure ratio (IPR). Both the parameters are varied from 3 to 5, insteps of 1 corresponding to the underexpanded levels of sonic jets. For comparison, an equivalent circular sonic jet from an orifice is studied under identical conditions. Shadowgraph visualization is used to quantify the core length and hence mixing for both circular and square sonic jets, with and without injection.

2. Experimental Setup
The present experimental work was carried out using open jet setup in High Speed Aerodynamics Lab at Department of Aerospace Engineering, SRMIST. The schematic layout of the setup is shown in Figure 1. The models used for the study were circular and square orifices (Figure 2). The equivalent diameter \((D_{eq})\) of the square orifice is 10 mm, which is equal to the circular orifice diameter. A constant area circular tube of 1 mm diameter was used to inject air into the main jet. The constant area tubes were placed opposite to each other at the exit of the orifices with an offset distance of 2 mm from the orifice exit as shown in Figure 2. The injection pressure and nozzle pressure ratios were controlled by separate valves in the present study.

![Figure 1. Schematic of open jet setup available at SRMIST.](image-url)
3. Shadowgraph Visualization
The waves present in the sonic jets were visualized using shadowgraph system available at SRMIST. The images projected on the screen were captured using a still camera. The visualization was done perpendicular to the direction of fluidic injection which corresponds to the plane of visualization as shown in Figure 3.

4. Results and Discussions
The shadowgraph visualization was done for pressure ratios (both NPR and IPR) 3 to 5, insteps of 1. For a fixed NPR, the IPR was changed from 3 to 5. The pressure ratios 3 to 5 correspond to underexpanded levels of sonic jet. The supersonic core captured using shadowgraph is used to quantify the core lengths of sonic jets with and without injection. The length of supersonic core is defined as the axial extent up to which the supersonic flow prevails in the jet field [11]. In this study, the axial extent of waves in the shadowgraph image was taken as the supersonic core length for
circular and square sonic jets. Therefore, it has to be noted that the measured core lengths using shadowgraph are only approximate.

It was noticed that the core length of circular and square jets increased with increase of NPR from 3 to 5. For all the NPRs, the core length of sonic square jet was shorter than the equivalent circular jet which was due to the better mixing characteristics of square jet compared to its circular counterpart. The core lengths of square jet at NPRs 3, 4 and 5 are $6.1D_{eq}$, $5.6D_{eq}$, and $4.6D_{eq}$ compared to $9D_{eq}$, $8D_{eq}$ and $5D_{eq}$ of circular jet, respectively. The shadowgraph of circular and square jets at NPRs 3 and 5 are shown in Figure 4. At highly underexpanded NPR 5, the strong expansion waves at the orifice exit resulted in Mach disk formation in both circular and square jets (Figure 4(b) & (d)).

For all the NPRs studied, the injection in both circular and square sonic jets resulted in reduction of core length, with maximum and minimum reduction at IPRs 5 and 3, respectively. The shadowgraph results of circular and square jets at NPR 3 and IPRs 3 and 5 are shown in Figure 5. For both the jets, the core length reduction is maximum at IPR 5 for all the NPRs, because at highest studied IPR of 5, the injection mass flow rate is maximum which leads to increased penetration of main jet and subsequently increased mixing due to streamwise vorticity generation by the penetrated mini jet. The increased mixing of main jet due to the better penetration of injected mini jet is the reason for reduced core length at IPR 5 than at IPRs 3 and 4 in all the NPR’s. Therefore, the maximum core length reduction for circular and square sonic jets at NPRs 3 to 5 occurs at the maximum IPR of 5 followed by IPR 4 and minimum at IPR 3. Thus, it can be concluded that the mixing promotion in circular or noncircular sonic jets is dependent on the momentum of the injected jet. Among the NPRs, the reduction in core length was maximum at NPR 3 (Figure 6) and minimum at NPR 5 for both circular and square jets at all the IPRs. For all the IPRs, square jet showed higher reduction than the circular jet at NPRs 3 and 4 except NPR 5 where the circular jet showed slightly higher reduction than square jet. The highest reduction of about 50% was achieved at NPR 3 and IPR 5 for square sonic jet (Figure 6).

The present study shows that the mini jet injection not only enhances the mixing of circular and square sonic jets but also makes the waves weaker which is beneficial from the aeroacoustic point of view.

![Shadowgraph of circular and square jets at NPRs 3 and 5 without injection.](image)

**Figure 4.** Shadowgraph of circular and square jets at NPRs 3 and 5 without injection.
5. Conclusions
The present experimental study of fluidic injection in square and circular sonic jets shows that the injection in both circular and square sonic jets resulted in reduction of core length at all the NPRs, with maximum and minimum reduction at each NPR occurred at IPRs 5 and 3. This proves that the mixing promotion in circular or noncircular sonic jets depends on the momentum of the injected jet. At all IPRs, square jet showed higher reduction than the circular jet at NPRs 3 and 4 except NPR 5 where the circular jet showed slightly higher reduction than square jet. The highest reduction of about 50% was achieved at NPR 3 and IPR 5 for square sonic jet.

6. References
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