Control of mach 2 jet using sonic coflow

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Abstract. An experimental investigation was done to understand the effect of sonic coflow jet on the core length of Mach 2 jet at different levels of expansion. The sonic jet surrounding the primary Mach 2 jet was produced using a sonic nozzle, whereas a convergent-divergent nozzle was used for Mach 2 jet. The annular gap between the sonic and supersonic nozzles was 1mm. For a fixed main jet NPR, the NPR of the sonic jet was varied from 4 to 6 (in steps of 1), which correspond to underexpanded levels of the sonic jet. The NPR of Mach 2 jet was varied from 4 to 6, which correspond to overexpanded states of Mach 2 jet. Without sonic coflow, the core length of Mach 2 jet was found to increase with the increase of NPR which was quantified using shadowgraph visualization. For all the main jet NPRs, the increase in coflow NPR resulted in the increase of core length. For each NPR of Mach 2 jet, the core length increases with the increase of coflow NPR. The maximum core length for NPRs 4 to 6 was at coflow NPR of 6 and minimum was at coflow NPR 4. The sonic coflow was found to retard the mixing of Mach 2 jet at all the pressure ratios, but it resulted in weakening the strength of waves present in the core of Mach 2 jet.

1. Introduction
The coflow jets are used in many devices where two fluids are mixed together and are widely present in aircraft exhaust systems, fuel injectors, and combustion chambers to improve the mixing of fuel and oxidiser. On the other hand, they are also utilized in various applications such as dispersion of flames from the industrial exhausts to a greater height and to increase the flame length in welding equipment. Most of the modern high-speed aircrafts use coflow jets in order to suppress the noise produced by the supersonic jets. The jet noise may cause irreversible damage to auditory organs and fragile structures. One of the common methods to suppress the noise level is to introduce an annular coflow surrounding the main supersonic core.

Sharma et al. [1]. experimentally studied the overexpanded coflowing jets using centreline pitot pressure distribution plot. They observed that the presence of sonic coflow reduces the shock cell strength of Mach 2 supersonic core. Papamoschou [2]. found that at suitable conditions, the coflow removes a strong source of noise and eliminates the Mach wave radiation. Murakami et al. [3]. conducted coflow supersonic jet experiments and reported that at higher Mach number, the greater diameter of the secondary stream will increase the primary stream potential core length. Srinivasarao et al. [4]. found that by introducing the coflow at all under-expansion levels of the primary jet resulted in increase core length and decrease in shock strength. Lee et al. [5]. performed shadowgraph visualization to reveal near field flow structure of a co-axial free jet. The effect of the secondary stream was prominent only when the primary jet is overexpanded or moderately underexpanded. Lovaraju et al. [6]. performed experimental work on subsonic and sonic
coflowing jets. The coflow was found to modify primary jet mixing characteristics and shock strength. The core length of the sonic underexpanded jet was found to increase with increase of NPR. Srinivasarao et al. [7] reported the effect of thin and thick lip thickness of subsonic and underexpanded sonic coflow core nozzles. Their result reveals that a higher lip thickness nozzle leads to greater mixing and shorter core length of primary jet.

From the coflow jet literature, it is seen that the coflow nozzle pressure ratio (NPR) was maintained the same as the nozzle pressure ratio of main jet / primary jet. In other words, the coflow NPR was not controlled for a fixed nozzle pressure ratio of main jet. Also, the effect of sonic coflow on supersonic jet was not completely studied. Therefore, the present experimental work aims at understanding the effect of sonic coflow on Mach 2 jet at different levels of expansion. The main jet nozzle pressure ratio and coflow nozzle pressure ratio were controlled separately in the present study which aided in controlling the coflow NPR for a fixed main jet (Mach 2) NPR. For every main jet NPR of 4, 5 and 6, the sonic coflow NPR was increased from 4 to 6, insteps of 1. The mixing characteristics of coflowing jets were studied by quantifying the core length of jets using shadowgraph visualization.

2. Experimental Setup and Model Details
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 coflow nozzle model used for the study consists of sonic and convergent divergent (Mach 2) nozzles. The sonic jet surrounding the primary Mach 2 jet was produced using a sonic nozzle, whereas a convergent-divergent nozzle was used for Mach 2 jet. The annular gap between the sonic and supersonic nozzles was 1mm. The main jet nozzle pressure ratio and coflow nozzle pressure ratio were controlled separately using separate settling chambers with control valves as shown in Figure 1. A photograph of coflow nozzle is shown in Figure 2.

![Figure 1. Schematic of open jet setup available at SRMIST.](image-url)
3. Shadowgraph Visualization
The waves present in the jet were visualized with shadowgraph system available at SRMIST. The images projected on the screen were captured using a still camera. The visualization was done with and without coflow to understand the effect of sonic coflow on the Mach 2 jet.

4. Results and Discussions
The present investigation was done for different nozzle pressure ratios (NPRs) of main jet (Mach 2) and coflow (sonic) jets. For a fixed main jet NPR, the NPR of the coflow sonic jet was varied from 4 to 6, which correspond to underexpanded levels of the sonic jet. The NPR of Mach 2 jet was varied from 3 to 6, which correspond to overexpanded states of Mach 2 jet. The supersonic core of Mach 2 jet with and without sonic coflow captured using shadowgraph was used to quantify the core length in the present study. The length of supersonic core is defined as the axial extent up to which the supersonic flow prevails in the jet field [8]. In this work, the axial extent of waves in the shadowgraph image was taken as the supersonic core length controlled and uncontrolled jets. Therefore it has to be noted that the measured core lengths using shadowgraph are only approximate.

Without sonic coflow, it was found that the core length of Mach 2 jet increased with increase of NPR. The core length of Mach 2 jet at NPRs 4, 5 and 6 are about 5.8D, 8.6D and 13.6D, respectively. With increasing NPR, the strength of the waves in the supersonic core of Mach 2 jet was also found to be increasing. The shadowgraph results of Mach 2 jet without coflow are shown in Figure 3. In the presence of coflow, the core length of Mach 2 jet increases for the all the coflow NPRs. The increase of core length of Mach 2 jet due to sonic coflow was noticed at all main jet NPRs. For every main jet NPR, the core length increased with increase of coflow NPR. For main jet NPR 4, the core lengths corresponding to coflow NPRs 4, 5 and 6 are 9.6D, 11.8D and 13.6D, respectively. The core length elongations for NPRs 5 and 6 at coflow NPRs 4, 5, 6 are 9.4D, 11.4D, 13.6D and 16.4D, 18.6D, 19.2D, respectively. The shadowgraph results of Mach 2 jet at NPRs 5 and 6, with coflow at NPRs 5 and 6 are shown in Figure 4. The increase in core length due to sonic coflow indicates reduced mixing of Mach 2 jet with the ambient fluid. This is because the sonic coflow jet envelops the Mach 2 jet from the ambient fluid, thereby reducing the mixing of Mach 2 jet with the ambient fluid. The shock structure of Mach 2 jet was drastically altered by the sonic coflow at all the pressure ratios. Even though the sonic coflow resulted in reduced mixing of Mach 2 jet, the sonic coflow was found to be reducing the strength of waves in the Mach 2 jet at all the test conditions. The reduced wave strength is advantageous from the aeroacoustic point of view.
Figure 3. Shadowgraph of Mach 2 jet without coflow at NPRs 4, 5 and 6.

(a) NPR 4
(b) NPR 5
(c) NPR 6

Figure 4. Shadowgraph of Mach 2 jet with coflow at NPRs 5 and 6.

(a) NPR 5 and coflow NPR 5
(b) NPR 5 and coflow NPR 6
(c) NPR 6 and coflow NPR 5
(d) NPR 6 and coflow NPR 6

5. Conclusion
The present experimental investigation shows that the core length of Mach 2 jet increases in the presence of sonic coflow. The core length of Mach 2 jet increased with increase of coflow NPR at all
the NPRs. The maximum core length for NPRs 4 to 6 was at coflow NPR of 6 and minimum was at coflow NPR 4. The increase in core length indicates reduction in mixing of Mach 2 jet due to sonic coflow. For each NPR studied, the mixing reduction was found to increase with increase of coflow NPR. Even though the sonic coflow had resulted in core length increase and hence mixing reduction of Mach 2 jet, the sonic coflow was found to weaken the waves in the Mach 2 jet at all the pressure ratios.

6. References

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