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Experimental study of co-annular jet subjected to transverse disturbances

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A B S T R A C T

The results of an investigation of the flow field of two coaxially aligned jets consisting of an inner primary jet and a co-annular outer jet issuing from a nozzle with convex sidewalls are reported. A transverse flow injection into the co-annular jet was used to shape the co-annular jet flow. In the region between the exits of the two jets, a recirculating toroidal eddy is formed due to opposing pressure gradients. In the presence of transverse injection, the eddy bifurcates into two lobes with radially emanating flow structures that substantially increase the decay of axial velocity and the spread rate to twice the values when compared to the characteristics of the primary jet alone. Measurements of mean velocities and Reynolds stresses were made at the jet Reynolds number of 16,000 with the help of a specially designed two-component Laser-Doppler-Velocimetry system. Topology of the resulting complex flow in view of the measurements is presented and discussed.

1. Introduction

High noise levels experienced by residential communities living in close proximity to air bases as well as the ground crew of aircraft carriers has been the topic of pertinent jet noise reduction research in the last few decades. Although the crew noise problem is reduced to a large extent by personal protection equipment, the noise intensity level exceeds desired standards by high margins ([28]. Studies on jet mixing and interaction in the past have shown that the noise generated by a jet varies with the eight power of the jet velocity for subsonic flows, and it varies with the third power for the supersonic flows [30]. It is hence highly desirable to reduce the velocity of the jet, in order to reduce the noise generated by the jet engines. Since the thrust generated by a jet engine is directly related to the exit velocity of the jet, reducing the exhaust jet velocity is not considered as a viable approach for propulsion. However, research on rapid decay of jet momentum by enhanced mixing continues to be of interest for noise abatement.

A number of methods have been proposed by researchers to overcome jet noise using mixing techniques over the last 50 years. These techniques can be broadly categorized as passive control by geometric modifications, and active control that includes plasma/heat discharge techniques. The main objective of all the methods tested is to increase mixing of the exhaust jet with surrounding ambient air in the shortest distance possible. Jet mixing has been observed to redistribute the noise energy, thereby decreasing the energy content in the low frequency ranges and increasing energy at higher frequencies. The fact that there are two distinct sources of jet noise: the fine-scale turbulence, and the large turbulence structures of the jet flow was reestablished by Tam [30]. It was acknowledged that, these structures generated near the nozzle exit quickly grow as they move downstream, and are often larger than the jet diameter in the axial direction.

A summary of the existing methods on mixing enhancement by Nedungadi et al. [23] shows that generating streamwise vortices is a generally accepted way to enhance mixing. Research done in the past decade includes NASA's investigation of noise sources using experimental and computational methods on chosen configurations. Bridges et al. [11] investigated forty three different mixing configurations. PIV technique has been used by Bridges et al. [12] to measure the mean flow and turbulence characteristics, and two-point velocity correlations to identify noise sources.

The spreading characteristic of compressible jets with various nozzle geometries and use of various tab configurations has been summarized by Zaman [32] who showed that triangular tabs inserted into the core flow and inclined away from the nozzle exit perform very well in increasing the mixing of compressible flows including supersonic jets. The spreading rate of the jet doubled for all of the configurations he studied. He also showed that the noise levels for both circular and rectangular jets reduced with

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Nomenclature

d	outer diameter of the primary flow tube, 6.35 mm
r	radial distance measured from centerline of jet
Re	Reynolds number, $Re = \frac{\rho U_j d}{\mu} = 16{,}000$
u	time-dependent axial fluctuating velocity
u'	axial root mean square fluctuating velocity, $u' = \sqrt{\overline{u^2}}$
$\overline{u^2}$	axial stress
U	mean axial velocity
U_c	centerline velocity at an axial location
U_j	primary jet exit velocity, 40 m/s
U_s	co-annular jet velocity, 35 m/s
v	time-dependent radial fluctuating velocity
v'	radial root mean square fluctuating velocity, $v' = \sqrt{\overline{v^2}}$
$\overline{v^2}$	radial stress
V	mean radial velocity
$\overline{uv}$	Reynolds shear stress
x	axial distance from the exit

the use of tabs on the order of 10 dB at frequencies below 20 kHz. This was attributed to the different vortical structures formed by tabs. In general it was observed that mixing enhancement redistributed the acoustic energy; while the noise levels at frequencies below 20 kHz were reduced, the noise levels above this frequency increased. Shifting the noise to higher frequencies is welcomed since attenuation of high-frequency noise is readily accomplished by the atmosphere [29].

Another technique studied is the use of pulsed synthetic jets with the zero net mass flow and 1.5% of the core mass flow rate to generate a flapping effect at the exit of the jet. Large-scale oscillations were generated in the jet resulting in drastic reduction of the potential core (Nedungadi et al. [23]). Results show that low-frequency forcing (250 Hz) resulted in better mixing enhancement compared to high frequency forcing. However, the technique reduced the noise levels below 4 kHz on the order of 2 dB at a jet exit Mach number of $M = 0.6$. A novel technique studied by Anderson et al. [3] and Callender et al. [13] made use of a filament attached to the jet centreline for supersonic-jet noise reduction and several filaments attached to the circumference of the nozzle for improved mixing. The filament placed at the centreline was observed to reduce the noise levels on the order of 10 dB overall by extracting the acoustic energy and converting it to vibrational energy thereby enhancing the mixing of the large-scale eddies.

The effect of microjets on noise reduction was investigated using eighteen 400 μm diameter microjets oriented at 45° to the jet axis around the lip of a $M = 0.9$ jet [5]. Sound pressure level and PIV flow field measurements were made to identify the effect of the microjets. Surprisingly, the axial and the radial turbulence intensities reduced by 15% and 20% respectively and the near field noise level also reduced by 2 dB. The influence of microjets on noise levels of an unheated jet at Mach numbers ranging 0.7–0.9 were investigated by Castelain et al. [14] using different size, velocity, number of microjets at multiple orientations. Their results indicated that as many microjets as feasible should be used to render the most noise reduction. In addition, the preferred location of the microjets was found to be close to the nozzle exit. Behrouzi et al. [6] studied the effect of two jet vortex generator tabs on the centerline velocity decay rate both in low and high subsonic flows. The vortex generators were placed at the edge of the jet, opposing each other on the circumference of the jet. With only 1% of the main jet mass flow rate for the vortex generators, they showed that a pulsating injection at 2 Hz resulted in larger velocity decay in comparison to steady jets. The velocity reduction achieved at different downstream locations without the pulsed jets was 5% but increased to 14% with pulsed jets when operated 180° out of phase.

Large body of literature exists about the round-free jets both issuing from a long pipe resulting in a fully developed flow discharge or issuing from a nozzle with a large contraction ratio resulting in a top-hat velocity profile. Research focusing on different aspects of the flow field, such as the effect of the initial conditions on the potential core development and its effect on the self-similarity, can be found in experimental studies by, for example, Boguslawski and Popiel [10], Antonia and Zhao [4], Ferdman et al. [18], George [19], Burattini et al. [8], Burratini and Djenidi [9], and computational study by Boersma et al. [7]. Experimental work by Panchapakesan and Lumley [24], Hussein et al. [20] and references therein describe the development of the flow characteristics in the self-similar region. Previous research findings allude to the self similarity of the mean and the fluctuating velocities beyond $x/d = 20$ and $x/d = 35$, respectively [26].

Previous research indicates that there are several mechanisms that can efficiently increase the velocity decay rate with enhanced mixing. However, additional requirements dictated by the application, coupled with difficulty in understanding the noise generation mechanism are issues that need to be carefully considered. A configuration that utilizes axisymmetric Coanda effect that causes the primary jet to attach itself to the surrounding surfaces has shown promise in increasing the velocity decay rate. Experiments based on such configurations have been previously utilized in flow control and jet vectoring applications [2,25]. The research work presented in this paper was focused on the investigation of the flow physics of a round jet subjected to lateral strain under the influence of Coanda effect and manipulated with transverse fluid injection. Measurements were made using both one and two simultaneous velocity component Laser Doppler Velocimetry (LDV) system.

2. Experimental set-up

The schematic drawing of the jet apparatus shown in Fig. 1 consisted of a stereolitographically printed outer nozzle placed on top of an acrylic settling chamber. The key feature of the outer nozzle is the convex sidewalls formed using 12.7 mm radius half-circular arcs resulting in the minimum aperture of 8.43 mm. The primary jet emanates at $U = 40$ m/s from a 72 cm long straight stainless steel tube of 6 mm inside diameter (6.35 mm outside diameter) that is axially aligned with the outside nozzle and is supplied from a separate regulated source. Presence of primary jet tube passing through the outer nozzle results in 1.05 mm annulus, where the velocity is 35 m/s. This interaction between the two co-annular jets is pinched by the flow through a pair of 1.68 mm orifices located on the diametrically opposite sides of the outside nozzle and results in the bifurcation of the co-annular jet into two lobes diverging in a plane that is perpendicular to the axis of the two orifices.

During the tests, the exit of the primary jet was kept at the same elevation as that of the plane of the outer nozzle to simulate a free jet. This was considered to be important to ensure that the momentum rate at the exit of the primary jet was not modified by the secondary jets prior to exiting the nozzle. During the single jet experiments only the inner tube flow was seeded. During the