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Influence of swirl number on jet noise reduction using flat vane swirlers

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ABSTRACT

In this work, jet noise reduction using a swirling flow surrounding a circular free jet has been demonstrated. The passive control scheme induces swirl from six flat vanes fixed in an annular passage with vane angles from 0 to 50°, with the corresponding swirl numbers ranging from 0 to 0.91. Noise measurements in terms of overall sound pressure levels, directivity patterns, acoustic spectra; and flow measurements in terms of centerline pitot survey and flow visualization have been carried out to evaluate the efficacy of the passive control scheme. The co-axial swirl jets always reduce the low frequency noise, irrespective of the nozzle pressure ratio. The screech tone is entirely eliminated and broadband shock associated noise mitigated by the co-axial swirl jets. The results of highly under expanded supersonic cases, show that, the weak swirl generates higher noise and high swirl generates lower noise for the same nozzle pressure ratio. The centerline pitot pressure measurements reveal that the co-axial swirl jets decrease the core lengths and the number of shock cells compared to the free jet. The flow visualization study shows that Mach disks are generated at lower pressure ratios for the co-axial swirl jets compared to free jet. The present work proposes swirl as an excellent passive tool for jet noise suppression.

1. Introduction

Swirling flows provide several advantages from subsonic to supersonic ranges in reacting flows (gas turbine combustion and furnaces), non-reacting flows (vortex amplifiers and reactors, cyclone separators) [1], jet engine noise reduction [2], combustion in an incinerator [3], heat transfer in pipes to enhance convective heat transfer [4], and so on. Swirling flows are also observed in atmospheric flows such as vortex shedding from aircraft wings and typhoons. Generally the swirl effects are sometimes favorable, as in combustion systems, and sometimes undesirable as in delta wings at high angle of attack when it leads to drop of lift. Co-axial jets are generally used for mixing of different fluids, aircraft engine combustion, rocket injectors and aircraft by-pass jet engine nozzles. However, the measurement of acoustic characteristics of the co-axial jets assumed importance when by-pass jet engines were introduced as an alternative to overcome the turbo jet engine noise [5]. Hence, understanding the flow and acoustic features of co-axial swirling jet is necessary.

1.1. Swirl flow and its characterizations

Swirl flow needs a tangential velocity component which is superimposed on the axial flow [4] and swirl flows are vortical structure in nature [6]. The methods to create the swirl flows are swirl vanes, axial-plus tangential injection and pipe rotation.

The co-axial jet is a single jet surrounded by an annular jet, which does not extend to infinity [7]. The schematic of co-axial vane swirl jet flow structure is shown in Fig. 1. It consists of a primary potential core (primary PC), a secondary potential core (secondary PC), and inner and outer shear layers. The presence of two shear layers is a significant feature in co-axial jet and strongly influences the near field [8]. According to Ko and Kwan [9], for a co-axial jet initial merging zone (Zone 1), contains the two potential core regions and ends roughly at the place where the secondary or outer potential core disappears. In the intermediate zone (Zone 2) the primary potential core still exists and the mixing of the primary and secondary flows occurs. This zone may extend about two to three primary diameters from the initial merging zone. The two jets have merged completely and the co-axial jet develops like a single jet the fully merged zone (Zone 3).

Swirl number (S), is a non-dimensional number used to define the degree of swirl imparted to the flow. It is the ratio of the axial flux of swirl momentum (G_θ) to the product of axial flux of axial

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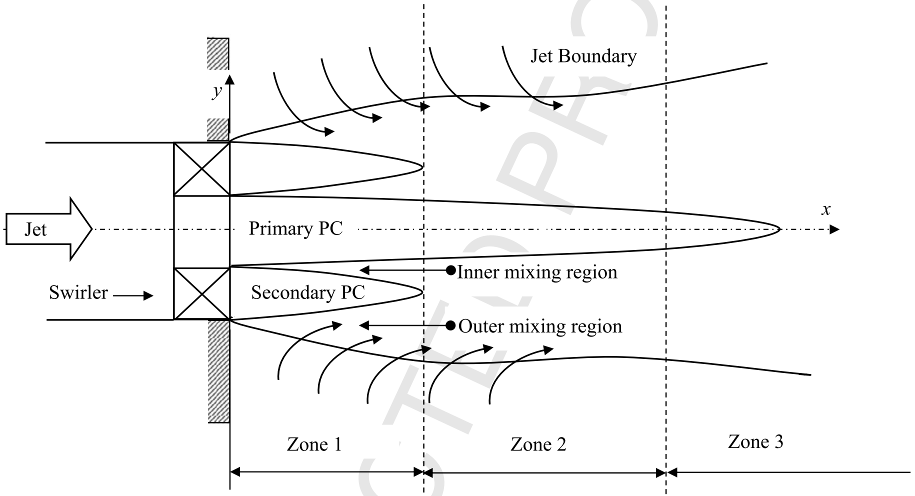
Nomenclature

D	Non-swirl jet exit diameter	mm
D_h	Hub internal diameter	mm
D_s	Swirl diameter	mm
L_s	Shock cell length	mm
M	Mach number	
n	Number of vanes	
P_0	Settling chamber pressure	Pa
P_t	Pitot pressure	Pa
S	Swirl Number	
St	Strouhal number	
t_b	Blade thickness	mm
t_h	Hub thickness	mm
w	Width of the swirler	mm
θ	Vane angles, degrees	

Abbreviations

BSAN	Broadband shock associated noise
EA	Emission angle
ER	Entrainment rate
OASPL	Overall sound pressure level
SFV	Swirler – flat vane
SPL	Sound pressure level
VB	Vortex breakdown



Zone 1: Initial Merging Region, Zone **2:** Intermediate Region, Zone **3:** Fully Merged Region

Fig. 1. Flow characteristics of co-axial vane swirl flow.

momentum (G_x), and the equivalent nozzle radius (R), as shown in Eq. (1):

$$S = \frac{G_\theta}{G_x R} \tag{1}$$

where, G_θ is the axial flux of swirl momentum, including the x–θ direction turbulent shear stress term (Eq. (2)); G_x is the axial flux of axial momentum, including the x direction turbulent normal stress term and pressure term (Eq. (3)); u, v, w are the velocity components in (x, r, θ) cylindrical polar coordinates directions [1,10].

$$G_\theta = \int_0^\infty (\rho u w + \overline{\rho u' w'}) r^2 dr \tag{2}$$

$$G_x = \int_0^\infty (\rho u^2 + \overline{\rho u'^2} + (p - p_\infty)) r dr \tag{3}$$

It can be expressed in terms of geometric parameter of the annular swirl jet by considering a constant vane angle and nozzle radius [1,10].

$$S = \frac{2}{3}\left(\frac{1-(D_h/D_s)^3}{1-(D_h/D_s)^2}\right)\tan\theta \tag{4}$$

where, D_s is the swirl jet diameter in mm, D_h is the hub internal diameter in mm, and θ is the vane angle in degrees (refer Fig. 3). Further, the equation (4), is used to calculate the swirl number for the present study.

Effect of hub ratio (D_h/D_s) on the swirl number is less, however, the vane angle is strongly influences the swirl number. The swirl number can be classified as Weak swirl $S \leq 0.4$, Medium swirl $S \leq 0.6$ (when the streamline start diverging considerably, but no recirculation) and High swirl ($S > 0.6$).

Free jet ($S = 0$): For free jets, theoretically no static pressure gradient in the axial or radial direction is observed [11] for subsonic conditions; further no appreciable tangential velocity component exists and swirl number is zero.

Weak swirl ($S \leq 0.4$): Radial pressure gradients may be observed in an axial location due to the co-axial swirling flow, thereby increasing the pressure along the axis. Due to this, the width of the jet slightly increases. However, no recirculation region is found in the flow field because the adverse pressure gradient is not sufficient enough to create a recirculation or in other words, the forward momentum is large enough to overcome the axial pressure gradients.

High swirl ($S \geq 0.6$): A strong axial and radial pressure gradients are dominant just downstream of a nozzle exit. Axial recirculation in the form of a Central Recirculation Zone (CRZ) is observed in this region because the axial pressure gradient exceeds the forward kinetic forces and the flow reverses its direction to center of the jet [12].

Many previous researchers have studied vane swirl jet for mixing and combustion applications. For instance, Kilik and Raj [13,14]

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