Applied Acoustics 126 (2017) 149–161

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Jet noise reduction using co-axial swirl flow with curved vanes

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ARTICLE INFO

Article history:
Received 18 November 2016
Received in revised form 4 May 2017
Accepted 5 May 2017

Keywords:
Jet noise
Curved vanes
Swirl jets
Co-axial swirl jet

ABSTRACT

Experimental studies are carried out to reduce the jet noise using co-axial swirlers in the form of curved vanes fixed in an annular passage. The swirl numbers considered for the present work ranged from 0 to 1.31, and the corresponding swirl vane angles ranged from 0 to 60°. The nozzle pressure ratios studied ranged from 1.8 to 6. The acoustic far field study at subsonic conditions revealed the presence of transonic tones for the non-swirl jet. However, swirl eliminates the transonic tones and a weak swirl is most efficient for noise reduction at subsonic conditions. The centerline total pressure measurements indicate the reduced core length for the swirl jets compared to the non-swirl jets. At supersonic conditions, the non-swirl jet emits the highest noise at all the emission angles compared to the swirl jets. The swirl jets are free from screech tones, and have lower amounts of shock associated noise, even at high nozzle pressure ratios. The centerline total pressure measurements and schlieren visualization studies show that shock cell spacing and the number of shock cells are reduced in the swirl jets compared to the non-swirl jet.

1. Introduction

Jet noise reduction and mixing enhancement in free or co-axial jets have been perennial challenges to the fluid dynamics community. Jet flow systems are ubiquitous in engineering applications such as aircraft/rocket combustions and nozzles, gas laser cutting and industrial welding. The high speed free jets generate an immense amount of noise, posing a threat to the health of humans/animals as well as health and safety of structures.

Swirling flows have received a lot of attention in combustion chambers [1], suppression of jet noise [2], augmentation of heat transfer [3], reducing pressure loss in pipe flows [4], and so on. This is because, the swirling flows exhibit high rates of entrainment, higher mixing rate, improved flame holder properties in combustion chamber [5].

However, past research studies on jet noise reduction using swirl are very limited. More common than swirl is the use of vanes [6] or tabs [7] that are employed at the exit of the nozzle for mixing enhancement and noise reduction. However, there has been very minimal attempt to calculate the swirl number and using swirl as a tool for noise suppression. Thus, the present work reports the effect of swirl number/vane angle on flow and noise from free jets at various nozzle pressure ratios (NPRs).

1.1. Flow field characteristics of free jet or non-swirl jet

The free jet expands in a quiescent or moving ambient fluid without any restriction. The spreading jet generates vortices due to the shear, and its evolution can be demarcated into the potential core region, transition region, and self-similarity region. Potential Core (PC) is a region where the centerline velocity is equal to the jet exit velocity and usually extends up to 4–6 diameters for subsonic turbulent jets. In the transition region, the centerline velocity starts to decrease and extends up to 6–20 diameters. Further, in this region different sizes of eddies are observed and the flow is completely dominated by turbulent and viscous action. In the self-similarity regions, the radial velocity profiles are similar at any axial location. In the acoustic point of view, all the three regions are responsible for the noise generation. However, the end of the potential core is a significant noise source due to strong vortical action and turbulence production [8].

At supersonic imperfectly expanded conditions, the shock/expansion fans are generated due to the pressure difference between the jet and the ambient. The repeated shock system is responsible for producing high amplitude of a shock noise and screech tones, which are discussed in the next section.

1.2. Flow field characteristics of swirl and co-axial swirl jet

The swirl jet is defined as a jet flow with tangential velocity components imposed upon axial velocity components. The basic

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http://dx.doi.org/10.1016/j.apacoust.2017.05.009

swirl generation methods are swirl vanes, tangential injection and pipe rotation. For fixed flat or curved vanes the swirl number can be calculated from Eq. (1), by considering the constant vane angle and nozzle radius [9],

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

where D_h and D_s are hub and swirler diameters in mm. θ is the vane angle in deg relative to the swirler longitudinal axis.

Eq. (1) is used in the present work to calculate the swirl number. The swirl number can be classified as weak, medium and high swirl. When $S \leq 0.4$, it is termed as weak swirl; only slight axial pressure gradients are observed, which are not enough to create any recirculation. When $S \leq 0.6$, it is called as medium swirl, and the streamline starts diverging considerably and no recirculation zone is observed. When $S > 0.6$, the flow may be called high swirl, and at this condition strong axial and radial pressure gradients are observed and this leads to recirculation in the central portion of the jet [9]. The vortical structures in the shear layers of the swirl jets are different from those of non-swirl jets, and result in enhancement of the entrainment rate and higher turbulence production [10]. In addition, the high swirl is responsible for high entrainment rates and mixing rates compared to weak and non-swirl jets [11,5].

From the literature, we may grade the entrainment rate (ER) of jets as follows:

$$ER_{\text{High Swirl}} > ER_{\text{Weak Swirl}} > ER_{\text{Non-Swirl}}$$

At high swirl numbers, the formation of intense reverse flows generates a Vortex Breakdown (VB) [9,5]. During the vortex break down phenomenon, the velocity profile transforms into a wake-like velocity profile. This causes abrupt structural changes in the vortex core, resulting in the formation of a stagnation point and a strong reverse flow. Vortex breakdown has both merits and demerits; for example, it acts as a flame holder and enhances the mixing, which in turn, may reduce the NO_x emissions in the combustion chamber. One of the demerits is, it affects the lift distribution in delta wings of aircraft [12].

The co-axial swirl jet consists of a primary potential core, secondary potential core and inner and outer mixing layers. The co-axial jet flow regions can be divided into three zones according to Ko and Kwan [13] and the same regions can be extended for co-axial swirl jets. The primary and secondary potential cores exist and the secondary potential core almost disappears in the initial merging zone (Zone 1 in Fig. 1). Primary and secondary core shear layers merge together in the intermediate region (Zone 2 in Fig. 1), the primary potential core still exists in this zone. Further downstream, the co-axial jet develops like a single jet, and this zone is called as the fully merged region (Zone 3 in Fig. 1).

It is generally observed that compared to the single free jet, the co-axial non-swirl or swirl jet, has significantly different flow structures. A few past findings on co-axial jets are discussed briefly. Ribeirio and Whitelaw [14] conducted experiments on co-axial jets with and without swirl. It was observed that when the swirl is introduced in the outer stream, the near field becomes complicated and swirling flows show higher spread rates. Baek et al. [15] conducted experiments on the supersonic dual co-axial free jet for various pressure ratios of inner and outer nozzles and outer nozzle ejection angles. It was observed that at highly under expanded conditions the outer jet produced new oblique shock waves. Further, the Mach disk diameters become smaller with an increase in inner jet pressure ratios. Lee et al. [16] investigated an under expanded dual co-axial swirling jet for different pressure ratios. They observed that the outer secondary co-swirling jet considerably changes the primary and center swirling jet features such as shock cell structures and the recirculation regions.

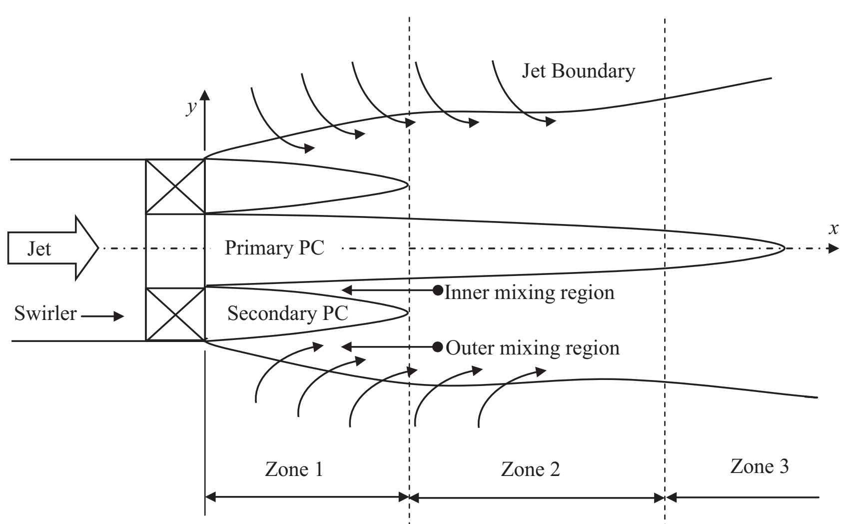
1.3. Acoustic characteristics

When the jet fluid mixes with the ambient fluid, the interaction between the jet fluid and ambient fluid generates various types of noise with a multitude of spectral features. The noise characteristics of free and swirl jets are introduced in this section.

1.3.1. Free jet noise

The main noise sources in the jet flow field can be classified into three forms: turbulent mixing noise, which exists in both subsonic and supersonic jets, broadband shock associated noise (BBSAN) and screech tone which may emanate from supersonic imperfectly expanded jets. Fig. 2 shows major noise sources of supersonic jet noise and their locations in the frequency spectra.

The turbulent mixing noise is generated from the mixing between the jet and the ambient fluids, and it consists of two components, one due to fine scale turbulence structures and the other due to large scale turbulence structures [17]. When the large scale



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

Fig. 1. Flow structures of a co-axial vane swirl jet.