Computers and Fluids 171 (2018) 122–134

Contents lists available at ScienceDirect

Computers and Fluids

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

Large-eddy simulation of sonic coaxial jets with different total pressure ratios of the inner to outer nozzle

Hai-Tao Shi[a,b], Nan-Sheng Liu[a,*], Pei Wang[c], Xi-Yun Lu[a]

[a] Department of Modern Mechanics, University of Science and Technology of China, Hefei, Anhui 230026, China
[b] No. 38 Research Institute of China Electronics Technology Corporation, Hefei, Anhui, 230088, China
[c] Institute of Applied Physics and Computational Mathematics, Beijing 100088, China

ARTICLE INFO

Article history:
Received 8 March 2018
Revised 30 May 2018
Accepted 1 June 2018

Keywords:
Large-eddy simulation
Sonic coaxial jet
Shock/shear-layer interaction
Jet mixing

ABSTRACT

Large-eddy simulation of sonic coaxial jets issuing into a quiescent environment was carried for two total pressure ratios of the inner to outer nozzle, i.e. 5/3 and 3/5. The effects of the total pressure ratio on the flow characteristics were mainly investigated. Various fundamental mechanisms dictating the complex flow characteristics, including jet shear layer evolution, shock system formation, shock/shear-layer interaction, turbulence behavior, and mixing property, have been studied. It is found that the total pressure ratio has an important influence on the flow evolution of coaxial jets as well as turbulence behavior and jet mixing property. The fluid-dynamic shearing and compressing processes are analyzed based on the Lamb vector curl and divergence. The multi-layer structures of the shear layers and shock waves are reasonably captured and the relevant fluid-dynamic processes are clearly clarified. It is also identified that the turbulence behavior and mixing property of the coaxial jets are mainly associated with the shearing effect in the outer shear layer region and the shearing and compressing coupled effect in the jet core region.

1. Introduction

The coaxial jets have attracted much attention because of the extensive fundamentals and the physical complexity. The coaxial jet flow involves some important and complicated phenomena related to the coupled shearing and compressing processes, such as shock/shear-layer interaction, shock/turbulence interaction, compressible turbulence behavior and jet mixing property. However, the physical mechanisms dictating these phenomena remain unclear well and they are highly desirable topics of study due to their fundamental principles and potential applications.

The flow behaviors of sonic coaxial jet are related to the complicated interaction of shock waves and shear layers. The shock structures for a single jet were visualized including barrel shock, Mach disk and reflected shock [1–3]. On the other hand, there exist more complicated shock structures in the coaxial jets. The Mach disk formation of dual coaxial jets was experimentally investigated, indicating that the inlet condition of coaxial jets has an important influence on the shock formation [4]. The near-field flow structures of an underexpanded sonic coaxial jet were visualized to reveal that the annular jet can significantly affect the shock structures of the inner jet [5]. The flow field was measured for supersonic coaxial jets, which was further used to validate numerical simulation [6]. The relevant numerical simulation is scarce. The Reynolds-averaged and hybrid Reynolds-averaged/large-eddy simulation (LES) were employed to simulate a supersonic coaxial jet flow [7]. The time-dependent flow features of a supersonic jet were investigated using LES approach and the near-field flow dynamics and the far-field noise were analyzed [8]. In particular, the LES of swirling flow in a coaxial-jet combustor was performed and the mean and turbulent quantities were well compared to experimental data [9]. They also confirmed that the LES results are significantly more accurate than the Reynolds-averaged Navier–Stokes equation predictions.

The intricate evolution and interaction of the inner and outer shear layers for low-speed coaxial jets have been studied extensively [10–17]. However, the relevant study for the behaviors of high-speed coaxial jet shear layers is still limited. The development of compressible shear layers is mainly dependent on the compressibility effect in addition to the velocity and density ratios across the shear layer [18]. For axisymmetric compressible shear layers, some works were performed to deal with the shape of turbulent eddies, indicating that the compressible shear layers may lead to the occurrence of a wide range of phenomena [19,20]. An experimental study was done to examine the compressibility effect in the

---

* Corresponding author.
E-mail addresses: lns@ustc.edu.cn (N.-S. Liu), xlu@ustc.edu.cn (X.-Y. Lu).

https://doi.org/10.1016/j.compfluid.2018.06.001

Nomenclature

a_∞	uniform sound speed
D	inner nozzle diameter
$\tilde{D}_k$	scalar diffusion coefficient
$\bar{E}$	total energy with density weighted Favre filter
H_i^{SGS}	subgrid energy flux
$\tilde{k}$	thermal conductivity coefficient
$\tilde{\boldsymbol{L}}$	the Lamb vector
M_c	mean convective Mach number
M_l	mean local Mach number
$\bar{p}$	pressure with spatial filter
p_i	inner nozzle pressure
p_o	outer nozzle pressure
P_d	isotropic component of the TKE production
P_s	anisotropic component of the TKE production
$\tilde{q}_i$	heat flux
Q_i^{SGS}	subgrid heat flux
r	radial distance
r_h	jet half-width
Re	Reynolds number
s	local coordinate along shear layer
$\tilde{S}_{ij}$	strain-rate tensor
St	Strouhal number
t	time
T_i	inner nozzle temperature
T_o	outer nozzle temperature
T_∞	uniform temperature
T_{ij}^{SGS}	subgrid turbulent stress tensor
$\tilde{u}_i$	velocity components with density weighted Favre filter
U_i	inflow speed
W_i^{SGS}	subgrid scalar diffusion
x_i	Cartesian coordinate axes
$\tilde{Y}_k$	outer jet mass fraction
δ_{ij}	delta function
δ_ω	vorticity thickness
θ_0	initial momentum thickness
ϑ	dilatation
Λ	streamwise integral length scale
$\tilde{\mu}$	molecular viscosity coefficient
$\bar{\rho}$	density with spatial filter
ρ'	density fluctuation
ρ_∞	uniform density
σ_i^{SGS}	subgrid viscous diffusion
$\tilde{\tau}_{ij}$	viscous stress tensor
$\tilde{\tau}_{ij}^{SGS}$	subgrid stress tensor
$\tilde{\omega}_\theta$	azimuthal vorticity
$\boldsymbol{\omega}$	vorticity vetcor
$\langle\rangle$	time average
$\{\}$	density weighted time average

annular shear layers of high subsonic and underexpanded round jets [21]. Moreover, a direct numerical simulation of compressible turbulent shear layer was performed to analyze the entrainment of flow into the turbulent region across the turbulent/non-turbulent interface [22].

The mixing property and turbulent behavior are more concerned for jet flows [20–22]. The jet mixing from a shock-containing nozzle was investigated to show that the shear layer plays a significant role in the jet development and turbulence intensity [23]. The mixing properties of coaxial jets were experimentally investigated for different diameters of the inner and outer jet [17] and the flow field measurements of a supersonic turbulent jet were performed for different nozzle pressure ratios [24]. The mixing enhancements of a spatially developing planar mixing layer interacting with an oblique shock wave were examined [25]. Moreover, the turbulence behavior of shock/shear-layer interaction was investigated to indicate that the shock impingement results in an amplification of the local turbulence [26]. Based on the analysis of the turbulent kinetic energy transport equation, the turbulence production is correlated to the dilatation and the deformation strain, [26,27] which further have an intrinsic relation to the local flow structures, such as shocks and shear layers.

There exist complicated shock/shear-layer interactions in the compressible coaxial jets, which are associated with the coupling of the compressing and shearing processes. To characterize these fluid-dynamic processes, the Lamb vector acted as a vortex force is usually employed since its character plays an important role in establishing the nature of the flow and can reasonably reflect the effects of the shearing and compressing processes [28–30]. The Lamb vector curl and divergence are related to the source terms of the transport equations of vorticity and dilatation, respectively, which may provide a methodology for the study of local flow structures in flow field, such as vortices and shock waves [30–32]. The mathematical properties and physical interpretations of the Lamb vector divergence that substantiate its kinematical and dynamical significance have been analyzed [31]. The evolution equation for the dilatation has been derived in terms of the invariants of the velocity gradient tensor and used to deal with the compressible turbulent boundary layers [33].

In this paper, a LES technique is utilized to investigate the underexpanded sonic coaxial jets issuing into a quiescent environment. The effects of the total pressure ratio on the flow characteristics were mainly investigated. The purpose is to achieve our understanding of fundamental mechanisms dictating the flow phenomena, including jet shear layer evolution, shock system formation, shock/shear-layer interaction, turbulence behavior, and mixing property.

This paper is organized as follows. The mathematical formulation and numerical method are briefly presented in Section 2. The computational overview and validation are described in Section 3. Detailed results are then given in Section 4 and concluding remarks are addressed in Section 5.

2. Mathematical formulation and numerical methods

2.1. Governing equations and turbulence modeling

To investigate sonic coaxial jets flow characteristics, the three-dimensional Favre-filtered compressible Navier–Stokes equations and the transport equation for passive scalar in generalized coordinates are used. A complete nomenclature used in this paper is also given in appendix. Here, the uniform inflow variables including the density ρ_∞, the temperature T_∞, the speed of sound a_∞, and the inner nozzle diameter D are used as characteristic scales to nondimensionalize the equations. Then they are expressed as

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial x_i}=0, \tag{1}$$

$$\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j)}{\partial x_j}+\frac{\partial\bar{p}}{\partial x_i}-\frac{\partial(\tilde{\tau}_{ij}-\tau_{ij}^{SGS}+T_{ij}^{SGS})}{\partial x_j}=0, \tag{2}$$

$$\frac{\partial(\bar{\rho}\bar{E})}{\partial t}+\frac{\partial[(\bar{\rho}\bar{E}+\bar{p})\tilde{u}_i]}{\partial x_i}-\frac{\partial(-\tilde{q}_i+\tilde{u}_j\tilde{\tau}_{ij}-Q_i^{SGS}+\sigma_i^{SGS}-H_i^{SGS})}{\partial x_i}=0, \tag{3}$$

$$\frac{\partial(\bar{\rho}\tilde{Y}_k)}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i\tilde{Y}_k)}{\partial x_i}-\frac{\partial(\tilde{\theta}_i+W_i^{SGS})}{\partial x_i}=0, \tag{4}$$