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Large-eddy simulation of variable-density turbulent axisymmetric jets

Ping Wang [a,*], Jochen Fröhlich [a], Vittorio Michelassi [b], Wolfgang Rodi [c]

[a] *Institute of Fluid Mechanics, Technical University of Dresden, 01062 Dresden, Germany*
[b] *Nuovo Pignone, Via Felipe Matteucci 2, 50127 Florence, Italy*
[c] *Institute of Hydromechanics, University of Karlsruhe, 76128 Karlsruhe, Germany*

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Abstract

Three cases of variable-density turbulent round jets discharging from a straight circular pipe into a weakly confined low-speed co-flowing air stream are studied with the aid of large-eddy simulation. The density ratios considered are 0.14 [Helium/air], 1.0 [air/air] and 1.52 [CO_2/air], with Reynolds numbers of 7000, 21,000 and 32,000, respectively. Detailed comparisons of the statistics show good agreement with the corresponding experiments. They confirm that a lower-density jet develops more rapidly than a denser jet with the same exit momentum flux. Pseudo-similarity behavior in the three variable-density round jets is well reproduced in the simulation. The coherent structures of the three jets are investigated by visualization of the iso-surface of pressure fluctuations and vorticity. In the developing stage of the Kelvin–Helmholtz instability, large finger-shape regions of vorticity are observed for the helium jet close to the nozzle lip. This feature, however, is not found in the air and the CO_2 jet. The occurrence of strong streamwise vorticities across the shear layer in the helium jet is demonstrated by a characteristic quantity related to the orientation of the vorticity.

Keywords: LES; Variable-density flow; Axisymmetric jet; Pseudo-similarity; Coherent structure; Streamwise vorticity

1. Introduction

Turbulent flows with variable density, which may be due to temperature variations stemming from reactions or variations in the composition by fluids of different density, exist widely in nature as well as in technical devices. The ability to predict the turbulent mixing in flows with variable density is vital for the modeling of the dynamics of such flows and a prerequisite for predicting turbulent combustion situations. Unlike the extensively studied jets with constant density, variable-density jets are less well understood. Relatively few experimental studies were reported for such cases. An experiment with helium/air mixture discharging into a confined swirling flow was carried out by Ahmed et al. (1985). Sreenivasan et al. (1989) performed an experimental study on round jets of different densities issuing into the ambient air. Their different densities were obtained by premixing helium and air in various proportions. About the same time, Monkewitz et al. (1989) and Monkewitz and Pfizenmaier (1991) carried out an experimental investigation of entrainment and mixing in transitional axisymmetric jets, where density difference were achieved by heating the air. Panchapakesan and Lumley (1993) conducted an experiment with helium injected into open quiescent air from a round nozzle. Later, Djeridane et al. (1996) and Amielh et al. (1996) performed experimental studies of variable-density turbulent jets, including helium, air and CO_2 jets exiting into a low-speed air co-flow. Numerical investigations of this type of flow are also relatively scarce. Jester-Zürker et al. (2005) performed a numerical study of turbulent non-reactive combustor flow under constant- and variable-density conditions using a Reynolds-stress turbulence model. They obtained good agreement between simulation and experiment for the constant-density flow, whereas the results for the variable-density flow were less satisfactory. Some large-eddy simulation (LES) of variable-density

* Corresponding author. Tel.: +49 351 46334910; fax: +49 351 46335246.
E-mail address: ping.wang@mailbox.tu-dresden.de (P. Wang).

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round jets were also performed recently (Zhou et al., 2001; Tyliszczak and Boguslawski, 2006). To the authors' knowledge, however, detailed comparisons of LES results and experimental data for round jets, covering density ratios both lower and larger than unity, are not available in the literature.

The aim of the present work is to perform a detailed comparison of LES results and experimental data for three round jets with density ratios 0.14, 1.0, and 1.52 respectively, to gain a deeper understanding of the effect of density differences on the jet development.

2. Numerical method

In this study, the so-called low-Mach number version of the compressible Navier–Stokes equations is employed. With this approach, the pressure P is decomposed into a spatially constant component $P^{(0)}$, interpreted as the thermodynamic pressure, and a variable component $P^{(1)}$, interpreted as the dynamic pressure. $P^{(0)}$ is connected to temperature and density, while $P^{(1)}$ is related to the velocity field only and does not influence the density. Due to this decomposition, sonic waves are eliminated from the flow, so that the time step is not restricted by the speed of sound. The dimensionless low-Mach number equations read as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = \frac{1}{Re}\frac{\partial \tau_{i,j}(\mu)}{\partial x_j} - \frac{\partial P^{(1)}}{\partial x_i} \qquad (2)$$

$$\frac{\partial \rho c}{\partial t} + \frac{\partial \rho c u_j}{\partial x_j} = \frac{1}{ReSc}\frac{\partial}{\partial x_j}(\rho\alpha\frac{\partial c}{\partial x_j}) \qquad (3)$$

$$\rho = F(P^{(0)}, T, c) \qquad (4)$$

where the symbols μ, ρ, u_i, T, c and α denote dynamic viscosity, density, velocity vector component, temperature, mass fraction of jet gas, and diffusion coefficient of jet gas into air, respectively, while $\tau_{i,j}(\mu)$ is the viscos stress. The symbol Re denotes the Reynolds number and Sc the Schmidt number. Eq. (4) represents the equation of state. For the three isothermal weakly confined jets studied in this work, $P^{(0)}$ and T are constant, so that the mixture density is determined only by the mass fraction c. Employing the ideal gas law, this reduces Eq. (4) to

$$\rho = \frac{P^{(0)}}{TR_u}\frac{M_{air}M_{gas}}{M_{gas} + c(M_{air} - M_{gas})} \qquad (5)$$

where the symbols R_u, M_{air} and M_{gas} denote the universal gas constant, molecular weight of air and molecular weight of jet gas, respectively.

Applying large-eddy filtering to the low-Mach number equations, the corresponding filtered LES equations are obtained. The unclosed terms in these equations have to be determined by subgrid scale (SGS) models. The variable-density dynamic Smagorinsky model by Moin et al. (1991) is used to determine the SGS eddy viscosity, μ_T, in the momentum equations. The SGS scalar flux is modeled by the often-used gradient diffusion model:

$$\overline{\rho c u_j} - \bar{\rho}\tilde{c}\tilde{u}_j = -\frac{\mu_T}{Sc_T}\frac{\partial \tilde{c}}{\partial x_j} \qquad (6)$$

where Sc_T is the turbulent Schmidt number. Sc_T may be determined with a dynamic procedure, as used for the SGS eddy viscosity (Moin et al., 1991). In this work it is set to $Sc_T = 0.7$.

The simulations were performed with the in-house Finite Volume code LESOCC2C, which is a compressible version of LESOCC2 (Hinterberger, 2004). LESOCC2C is highly vectorized, and parallelization is accomplished by domain decomposition and explicit message passing via MPI. It solves the low-Mach number version of the compressible Navier–Stokes equations on body-fitted curvilinear block-structured grids employing second-order central schemes for the spatial discretization and a 3-step Runge–Kutta method for the temporal discretization. The convection term of the species equation was discretized with the HLPA scheme (Zhu, 1991).

3. Computational setup

Three jets issuing into a very slow co-flow of air are studied with density ratios equal to 0.14 [Helium/air], 1.0 [air/air], and 1.52 [CO_2/air], respectively (see Fig. 1). These cases correspond to situations studied experimentally by Djeridane et al. (1996) and Amielh et al. (1996). The parameters employed are listed in Table 1, in which the Reynolds number is based on the centerline velocity at the jet exit and the jet nozzle diameter The subscripts 'j' and 'e' relate to jet flow and external co-flow, respectively. It is worth noting that the momentum flux is the same for the three cases, $M_j = 0.1N$. The reason for comparing cases with identical momentum flux is that in the flow region investigated inertial forces dominate (Djeridane et al.,

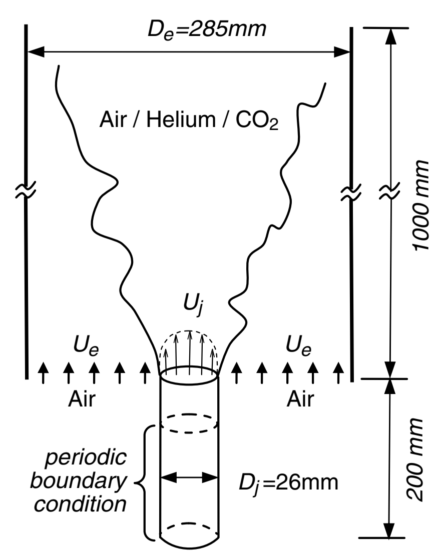

Fig. 1. Sketch of the computational domain.