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Numerical investigation of coaxial jets entering into a hot environment

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ABSTRACT

Coaxial jets with and without a supersonic core flow are typical for many technical applications and therefore of general interest. These jets show a lot of unsteady phenomena such as shear layer instability and transition to turbulence. Their accurate numerical simulation is still challenging despite todays available computing resources. The strategy of using high-fidelity numerical methods and a high spatial resolution helps to increase the range of resolved scales of the flow. This paper focuses on the numerical simulation of coaxial jets entering into a hot environment. Based on these results a new correlation model and optimisation criteria is proposed to predict the potential core- and supersonic length of the coaxial jet and leading to a significantly increased jet length. In particular, the enlarged supersonic jet length is of interest for special industrial applications.

1. Introduction

The instability of shear layers of compressible turbulent flows is on one hand a fundamental physical problem and on the other one present in a wide range of applications. Typical of these are free single and coaxial supersonic nozzle jets. The associated shear layers are due to an inflection point of the velocity profile at the nozzle exit. They are always convectively unstable leading to transition and finally turbulent flow. The mixing behaviour of supersonic shear layers is highly dependent on compressibility effects described by the convective Mach number, M_c (Bogdanoff [1], Papamoschou and Roshko [2]). The convective Mach number is based on the relative convection speed of large scale structures and the corresponding speed of sound. In the shear layer of a single jet the convective Mach numbers are given by Eq. (1), which holds for the same dynamic pressure of the two freestreams with respect to the large structures [1]:

$$\rho_1(u_1-u_c)^2=\rho_2(u_c-u_2)^2,\ M_{c1}=\frac{u_1-u_c}{a_1}=\frac{M_1(1-\lambda_u)}{1+\lambda_\rho^{-1/2}},$$
$$M_{c2}=\frac{u_c-u_2}{a_2}=\frac{M_1(1-\lambda_u)}{(1+\lambda_\rho^{-1/2})\lambda_\gamma^{1/2}} \quad (1)$$

with

$$\lambda_u=\frac{u_2}{u_1},\qquad \lambda_\rho=\frac{\rho_2}{\rho_1},\qquad \lambda_\gamma=\frac{\gamma_2}{\gamma_1} \quad (2)$$

Here u_c is the convective velocity of the large scale structures, u is the mean velocity of the jet, a is the speed of sound, $M = u/a$ is the Mach number, ρ is the density, γ is the specific heat ratio for the high- (1) and low-speed (2) sides of the shear layer with equal static pressures $p_1 = p_2$. The convective Mach number M_c based on the geometric average of M_{c1} and M_{c2} is [1]:

$$M_c=\frac{M_1(1-\lambda_u)}{(1+\lambda_\rho^{-1/2})\lambda_\gamma^{1/4}} \quad (3)$$

For the same specific heat ratios $\gamma_1 = \gamma_2$ the convective Mach number is often simplified by the following relation:

$$M_{c1}=M_{c2}=M_c=\frac{u_1-u_2}{a_1+a_2} \quad (4)$$

Supersonic shear flow at $M_c < 0.5$ exhibit characteristics of incompressible shear layers with two-dimensional coherent structures. The evolution of these structures in time and space are described by the Kelvin–Helmholtz instability theory. For $M_c > 0.6$ three-dimensional structures become dominant and compressible effects in the shear layer are important for stability analysis (Gutmark et al. [3]).

Even more complex physical phenomena than for a single jet are observed experimentally and numerically for compressible coaxial jets with two different shear layers. One example is a coaxial jet entering into a free space with supersonic inner-jet and subsonic outer-jet. A detailed study of coaxial jets is performed by Murakami and Papamoschou [4]. Actually experimental investigations are limited to cold ambient gas conditions. Furthermore, the receptivity of a compressible shear layer in hot environment is not well understood yet.

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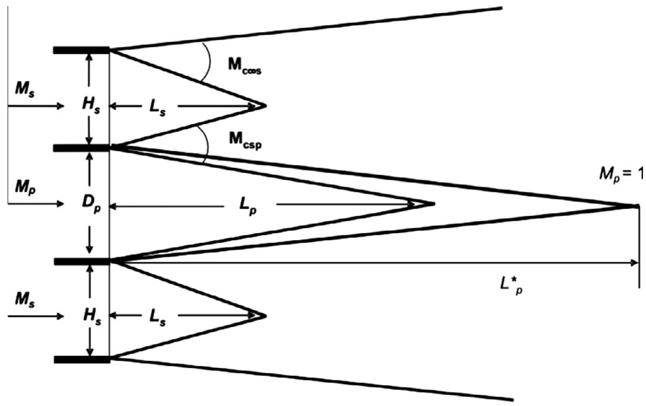

Fig. 1. Notation for coaxial jet.

Fig. 1 shows the principle structure of coaxial jets. The regions, where the flow remains homogeneous at constant properties, are the primary (L_p) and secondary (L_s) potential cores. The supersonic jet length L_p^* is defined by the location x/D_p where the local Mach number is $M_p = 1$. In comparison to a single jet, two convective Mach numbers namely between the primary and secondary jet (M_{csp}) and between the secondary jet and ambience ($M_{c\infty s}$), are of importance. A simpler form of the convective Mach numbers for $\gamma_p = \gamma_s = \gamma_\infty$ can be given by:

$$M_{csp} = \frac{u_p - u_s}{a_p + a_s}, \quad M_{c\infty s} = \frac{u_s}{a_s + a_\infty} \tag{5}$$

Subject of this paper is the numerical analysis of the mixing process and the determination of optimal flow parameters of the coaxial jet resulting in an increased stability and therewith length of the jet. The increased length of the supersonic part of the jet is of interest for several industrial applications. An typical example for this are burner and oxygen injection systems for electric arc furnaces in steel industry [8]. During the injector mode of the injection system, for a fast decarburisation an intensive transition of oxygen into the melt is necessary. This is accomplished by a supersonic jet which exits the nozzle and hits the melt with a high momentum. The integrated hot gas generator supplies a shrouded jet of hot combustion gas which covers the cold oxygen jet and thus increases the supersonic jet length.

2. Numerical method

For the numerical investigation of supersonic jet flows various computational methods have been used in the literature. Most popular are RANS (Reynolds-averaged Navier–Stokes) or unsteady RANS simulations using turbulence modeling. However, every turbulence model includes empirical constants and needs additionally modifications and validations for different jet flow conditions. The standard $k-\epsilon$ turbulence model cannot predict the potential core length of the supersonic single jet entering into a hot environment [9]. A modification of the numerical model gives better results for the velocity distribution, but underpredictes the heat transfer from the hot ambient into the turbulent shear layer of the jet. Reynolds-averaged (RANS) and hybrid Reynolds-averaged/large-eddy (RANS/LES) simulations have been performed for a supersonic coaxial jet flow for cold ambient conditions in [10]. For comparison with experiment two cases, air-helium and air-argon (primary-secondary) jets have been considered. The convective Mach numbers between primary and secondary jets were 0.7 for air-helium and 0.16 for air-argon, respectively. The air-argon jet shows a much longer potential core than the air-helium jet. However, the velocity ratios between primary and secondary jets for these cold jet and cold ambient conditions, would be the dominant parameter in the growth rate, as stated in [10]. The density ratio between the ambience and the secondary jet is equal for both cases, $\rho_\infty/\rho_s = 0.6$. But comparing the density ratios of the secondary and primary jets, $\rho_s/\rho_p = 5.8$ (air-helium) and $\rho_s/\rho_p = 0.6$ (air-argon), shows that in case of the air-argon jet the density of the primary jet is larger than for the secondary jet, which results in a higher stability of the primary jet. Direct numerical simulations (DNS) of high velocity ratio incompressible coaxial jets have been performed in [11]. For the spatial discretisation a sixth-order compact finite-difference scheme and pseudo-spectral method are used. For the time integration a third-order Runge–Kutta scheme is performed. The domain size was reduced up to 10.67–10.8 D_p and therefore a strong influence of the upstream conditions on the jet behaviour could be detected.

For the numerical simulation of an unsteady supersonic jet flow a numerical method of high spatial and temporal order and with robust shock-capturing properties is necessary. In supersonic flows large flow gradients occur e.g. due to shock waves to cause oscillations of the numerical solution. In general, these oscillations can be prevented by the introduction of explicit or implicit numerical dissipation. This is necessary but only in areas of large gradients. The numerical dissipation has not to damp small-scale structures in smooth areas. High-order methods with shock-capturing properties therefore use special algorithms to detect large gradients in the flow and there to increase the numerical dissipation. The employed WENO5 code based on fifth-order finite difference WENO (Weighted Essentially Non-Oscillatory) schemes has been developed for DNS of compressible fluid flows, which especially features these properties [5]. The fully three-dimensional, compressible, unsteady Navier–Stokes equations given by Eq. (6) for generalised coordinates $\xi = \xi(x,y,z)$, $\eta = \eta(x,y,z)$ and $\zeta = \zeta(x,y,z)$ are solved by the method described in the following:

$$\hat{\mathbf{U}}_t + \frac{1}{J}\hat{\mathbf{F}}_\xi + \frac{1}{J}\hat{\mathbf{G}}_\eta + \frac{1}{J}\hat{\mathbf{H}}_\zeta = \frac{1}{J}\hat{\mathbf{F}}^v_\xi + \frac{1}{J}\hat{\mathbf{G}}^v_\eta + \frac{1}{J}\hat{\mathbf{H}}^v_\zeta. \tag{6}$$

Here $\hat{\mathbf{U}}$ is the solution vector of the conservative variables. $\hat{\mathbf{F}}, \hat{\mathbf{G}}, \hat{\mathbf{H}}$ and $\hat{\mathbf{F}}^v, \hat{\mathbf{G}}^v, \hat{\mathbf{H}}^v$ are the inviscid and viscous fluxes respectively. The fluxes in generalised coordinates are functions of the fluxes in Cartesian coordinates (x,y,z) and the metric coefficients with the Jacobian J of the transformation. The inviscid fluxes are approximated using the WENO scheme formulation according to Jiang and Shu [6]. This scheme is of formally odd order ($N = 5$) and uses an N-point stencil for the inviscid numerical flux calculation. The actually used WENO stencil is adapted to the flow conditions. The stencil adaptivity allows high order accuracy in regions with smooth flow and simultaneously non-oscillatory behaviour near shocks and large gradients. The inviscid numerical fluxes are decomposed into a central and a WENO-upwind part. For the identification of the upwind direction a local Lax–Friedrichs flux-vector splitting technique is applied to determine the neighbour grid point fluxes $\Delta\hat{\mathbf{F}}^{m\pm}_{i+1/2}$:

$$\Delta\hat{\mathbf{F}}^{m\pm}_{i+1/2} = \hat{\mathbf{F}}^{m\pm}_{i+1} - \hat{\mathbf{F}}^{m\pm}_i, \qquad \hat{\mathbf{F}}^{m\pm}_i = 0.5(\hat{\mathbf{F}}^m_i \pm \Lambda^m_{i,max}\hat{\mathbf{U}}_i) \tag{7}$$

Here $\Lambda^m_{i,max}$ is the mth maximum eigenvalue of the flux Jacobian inside the stencil. The viscous fluxes $\hat{\mathbf{F}}^v, \hat{\mathbf{G}}^v$ and $\hat{\mathbf{H}}^v$ are calculated using central difference operators of high even order ($N + 1 = 6$). They consist of first and second derivatives of the velocity vector and temperature both using an $N + 1$ point stencil. The explicit time integration is performed with a low storage, third order Runge–Kutta TVD scheme [6].

The present work aims at to study coaxial jets for hot ambient conditions. The key interest is to determine optimum jet parameters for a maximum jet length. In the present paper the free jet is calculated as fully three dimensional in space, so that the