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FLOW AND SOUND FIELDS OF HEATED SUBSONIC TURBULENT JETS

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ABSTRACT

Large-eddy simulations of isothermal and hot round jets have been performed to investigate the influence of temperature on the flow and acoustic fields of initially disturbed high subsonic jets. The jets have an identical velocity yielding a Mach number $\mathrm{M} = u_j/c_a = 0.9$, diameter-based Reynolds numbers around 10^5, and temperatures $T_j = T_a$, $T_j = 1.5T_a$ and $T_j = 2.25T_a$, where subscripts j and a denote nozzle-exit and ambient conditions, respectively. Very similar exit flow parameters, including 9% of peak turbulence intensity, are also imposed. With increasing temperature, the jets are found to develop more rapidly with higher turbulence levels. The variations of the mixing-layer properties with T_j/T_a are however stronger for jets at a fixed $\mathrm{Re}_D = u_jD/\nu_a$ (and a decreasing $\mathrm{Re}_j = u_jD/\nu_j$) than for jets at a constant Re_j. As for the sound field, an elevated temperature leads to noisier jets in the former case but quieter jets in the latter. An increase in low-frequency noise is however observed in all cases.

INTRODUCTION

The effects of temperature are known to be significant on the characteristics of subsonic turbulent jets, especially regarding mixing and noise generation. As observed experimentally by Lepicovsky (1999) and Kearney-Fischer et al. (2009) for jets at Mach numbers 0.8 and 0.9, respectively, an increase of flow temperature leads to a shortening of the jet potential core followed by a rapid decrease in centerline velocity. Based on the work by Amielh et al. (1996) on variable density jets for instance, this trend is largely due to the lowering of flow density in heated jets. The influence of temperature on jet noise has also been investigated by many authors over the past forty years. Measurements by Fisher et al. (1973), Hoch et al. (1973) and Tanna (1977) clearly showed that heated jets are noisier that cold jets at Mach numbers lower than 0.7, but quieter at higher Mach numbers. The variations of sound spectra with increasing jet temperature appear to be more confusing. Noise levels are however typically found to increase at low frequencies but to decrease at high frequencies, see in Tanna (1977) and Panda (2007). It is also widely accepted that heating jets creates extra acoustic sources, of the dipole type according to the theoretical developments conducted by Morfey (1973) in the seventies, but there is still no consensus on this point. Indeed, as argued by Viswanathan (2004), additional features in sound spectra of hot jets might result in some cases from spurious facility noise or from changes in the jet initial conditions and Reynolds number.

Given these issues, one isothermal and four hot round jets have been computed by large-eddy simulation (LES) in order to study the effects of temperature on the flow and acoustic fields of turbulent subsonic jets. The jets have an identical initial velocity u_j yielding an acoustic Mach number $\mathrm{M} = u_j/c_a = 0.9$, and Reynolds numbers around 10^5 (c_a is the ambient speed of sound). At the exit of a pipe nozzle of diameter D, they are characterized by very similar flow conditions, including mean velocity profiles corresponding to a Blasius laminar profile and, thanks to the use of a boundary-layer trip-like excitation, 9% of peak turbulence intensity. The isothermal jet is that at a temperature $T_j = T_a$ and a Reynolds number $\mathrm{Re}_D = u_jD/\nu_a = 10^5$ considered in Bogey et al. (2011, 2012a, 2012b) (T_a and ν_a are the ambient temperature and kinematic molecular viscosity). The four hot jets are at $T_j = 1.5T_a$ and $T_j = 2.25T_a$. The first two ones have the same Reynolds number $\mathrm{Re}_D = 10^5$ as the isothermal jet, whereas the last two ones have values of Re_D set to 2×10^5 for $T_j = 1.5T_a$ and to 4×10^5 for $T_j = 2.25T_a$, such that $\mathrm{Re}_j = u_jD/\nu_j$ remains constant to 10^5 (ν_j is the viscosity at the nozzle exit). In this way, direct and indirect temperature effects, due to density and viscosity variations, respectively, are both examined.

PARAMETERS

The main study parameters are given in this section. More details can be found in Bogey et al. (2011, 2012a, 2012b) and in Bogey and Marsden (2013a, 2013b).

Numerical methods

The LES have been carried out by solving the three-dimensional filtered compressible Navier-Stokes equations in cylindrical coordinates (r,θ,z) using low-dissipation low-dispersion explicit schemes designed in Bogey and Bailly (2004). Fourth-order eleven-point centered finite differences are used for spatial discretization, and a second-order six-stage Runge-Kutta algorithm is implemented for time integration. A sixth-order eleven-point centered filter is applied every time step to the flow variables to remove grid-to-grid oscillations. The filtering also acts as a relaxation filtering (RF) dissipating subgrid-scale energy without significantly affecting the large turbulent scales, refer to Bogey and Bailly (2006) and Fauconnier et al. (2013) for instance. This LES-RF approach was developed to avoid the effective flow Reynolds number to be artificially decreased by the subgrid-scale model.

Jet definition

One isothermal and four hot jets at a Mach number $M = u_j/c_a = 0.9$ are considered. They originate from a pipe nozzle of diameter $D = 2r_0$ and length $2r_0$, whose lip is $0.053r_0$ thick. Their main initial parameters are collected in table 1. The first jet is at a temperature $T_j = T_a$ and a Reynolds number $\mathrm{Re}_D = u_jD/\nu_a = 10^5$. The next two jets are at $T_j = 1.5T_a$ and $T_j = 2.25T_a$, and have the same diameter, hence the same Reynolds number $\mathrm{Re}_D = 10^5$, as the isothermal jet. Due to the variations of molecular viscosity ν_j with increasing T_j, their Reynolds numbers $\mathrm{Re}_j = u_jD/\nu_j$ based on the exit flow conditions however decrease, and are equal to $\mathrm{Re}_j = 5\times10^4$ and $\mathrm{Re}_j = 2.5\times10^4$. The last two jets are also at temperatures $T_j = 1.5T_a$ and $T_j = 2.25T_a$, but their Reynolds numbers Re_D are set to values of 2×10^5 and to 4×10^5 such that $\mathrm{Re}_j = 10^5$ as in the isothermal case. The objective in the latter case is to minimize the temperature effects due to the variations of viscosity with heating, or in other words Reynolds number effects.

Table 1. Jet parameters: flow temperature T_j/T_a, Reynolds numbers $\mathrm{Re}_D = u_jD/\nu_a$ and $\mathrm{Re}_j = u_jD/\nu_j$, boundary-layer momentum thickness $\delta_\theta(0)$ and peak turbulence intensity u'_e/u_j at the nozzle exit.

T_j/T_a	Re_D	Re_j	$\delta_\theta(0)/r_0$	u'_e/u_j
1	10^5	10^5	1.85%	9.18%
1.5	10^5	5×10^4	1.91%	9.14%
2.25	10^5	2.5×10^4	2%	9.17%
1.5	2×10^5	10^5	1.85%	9.15%
2.25	4×10^5	10^5	1.85%	9.15%

At the pipe inlet at $z = -2r_0$, laminar Blasius boundary-layer profiles of thickness $\delta = 0.15r_0$ or momentum thickness $\delta_\theta = 0.018r_0$ are imposed for the axial velocity. The boundary layers are tripped inside the pipe at $z = -0.95r_0$ by adding random weak vortical disturbances decorrelated in the azimuthal direction, using a procedure detailed in Bogey et al. (2011). The tripping magnitudes are empirically chosen to provide a peak turbulence intensity $u'_e/u_j = 9\%$ in all cases. The profiles of mean and rms axial velocities thus obtained at the nozzle exit for the five jets are presented in figure 1. They are comparable to those measured in a tripped jet at $\mathrm{Re}_D = 10^5$ by Zaman (1985). The mean velocity profiles do not appreciably differ from the Blasius profiles fixed at the pipe inlet, leading to shape factors H around 2.3 and exit boundary-layer momentum thicknesses $\delta_\theta(0)/r_0 = 0.018 - 0.02$ as reported in table 1. As a result, the Reynolds number $\mathrm{Re}_\theta = u_j\delta_\theta/\nu_j$ based on the initial mixing-layer thickness is about 940 for the three isothermal and hot jets at $\mathrm{Re}_j = 10^5$, but is equal to 485 and 254 for the two hot jets at $\mathrm{Re}_j = 5\times10^4$ and 2.5×10^4, respectively. Finally, the peak intensities of velocity fluctuations are close to 9% as intended, see in table 1 for the exact values.

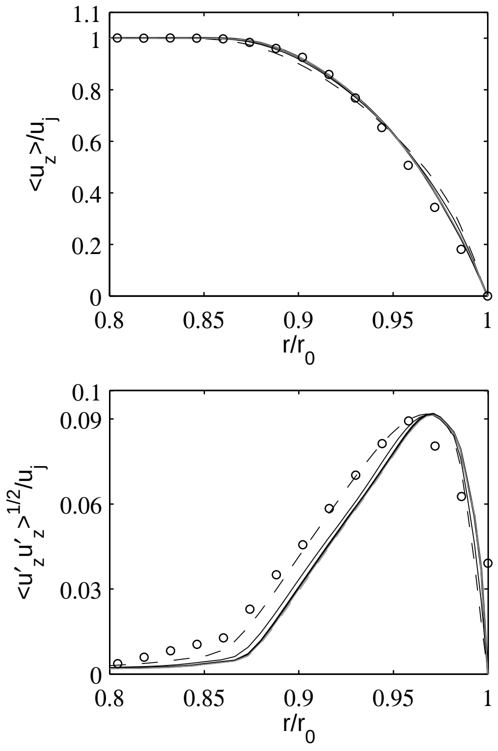

Figure 1. Nozzle-exit profiles of mean velocity $<u_z>$ and of the rms values of velocity u'_z for: ——— $T_j = T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 10^5$, – – – $T_j = 2.25T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 2\times10^5$, – – – $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$; $\circ$ measurements of Zaman (1985) for a jet at $\mathrm{Re}_D = 10^5$.

Simulation parameters

The five simulations have been carried using a grid containing $n_r\times n_\theta\times n_z = 256\times1024\times962 = 252$ million points. The minimum mesh spacings in the radial, azimuthal and axial directions are $\Delta r = 0.36$, $r_0\Delta\theta = 0.61$ and $\Delta z = 0.72$ per cent of the jet radius, corresponding to about 0.20, 0.34 and 0.40 times $\delta_\theta(0)$. The quality of discretization was explored in Bogey et al. (2011) for the isothermal jet. It was found that the flow properties at the nozzle exit and in the mixing layers are practically converged with respect to the grid. Large-scale turbulent structures were also shown to be well resolved and damped by molecular viscosity rather than by the relaxation filtering, which is important in order to reproduce Reynolds number effects as in Bogey et al. (2012b).

The simulation times are between $325r_0/u_j$ and $375r_0/u_j$, for a total number of 164,200 time steps in the latter case. The flow statistics are determined from time $t = 175r_0/u_j$, and they are averaged in the azimuthal direction. The LES near-field signals are recorded on a cylindrical surface at $r = 6.5r_0$ from the jet axis, and they have been propagated to the acoustic far field at a distance of $60r_0$ from the nozzle exit by solving the isentropic linearized Euler equations. Finally, the computations have been performed using NEC SX-8, then IBM Power 7 computers using OpenMP-based in-house solvers.

RESULTS

The main changes in the jet flow and acoustic properties when the jet exit temperature varies are now reported.

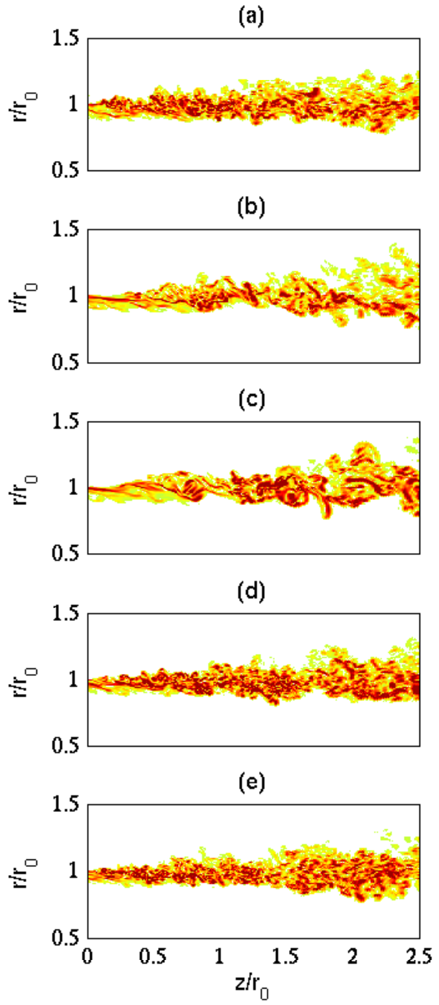

Figure 2. Snapshots of vorticity norm just downstream of the nozzle lip for: (a) $T_j = T_a$ and $\mathrm{Re}_D = 10^5$, (b) $T_j = 1.5T_a$ and $\mathrm{Re}_D = 10^5$, (c) $T_j = 2.25T_a$ and $\mathrm{Re}_D = 10^5$, (d) $T_j = 1.5T_a$ and $\mathrm{Re}_D = 2\times10^5$, (e) $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$. The color scale ranges up to the level of $27u_j/r_0$.

More results are available in Bogey and Marsden (2013b).

Vorticity and pressure snapshots

In order to illustrate the flow and sound fields from the LES, snapshots of the vorticity norm obtained up to $z = 2.5r_0$ and to $z = 20r_0$ in the jets and of the fluctuating near-field pressure are represented in figures 2 and 3. Temperature first appears to have various effects on the shear layers depending on the Reynolds number. With increasing T_j, stronger coherent structures and weaker fine-scale turbulence are indeed observed just downstream of the nozzle exit for the jets at a constant $\mathrm{Re}_D = 10^5$ (and a decreasing Re_j) in figures 2(b-c), whereas this is not the case for the jets at an increasing Re_D (and a constant $\mathrm{Re}_j = 10^5$) in figures 2(d-e). Concerning the jet development, the potential core is seen to shorten significantly with T_j whatever the Reynolds number, compare for instance figure 3(a) at $T_j = T_a$ with figures 3(c) and 3(e) at $T_j = 2.25T_a$. Finally, the pressure fields of the jets do not seem fundamentally different. A close look at the figures however suggests that, with respect to the isothermal jet in figure 3(a), the sound levels are higher for the jet at $T_j = 2.25T_a$ and

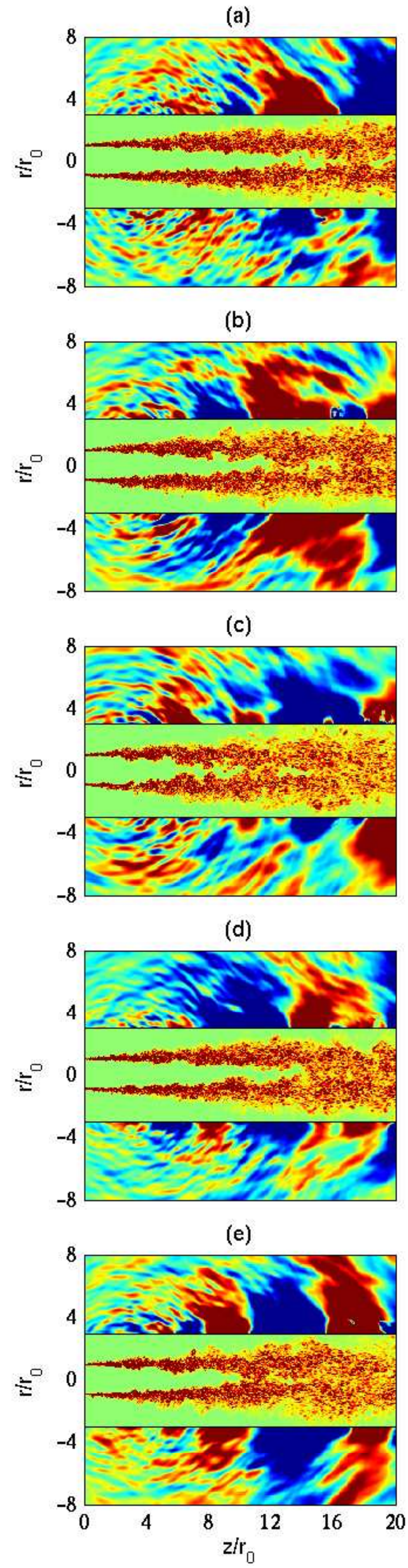

Figure 3. Snapshots of vorticity norm and fluctuating pressure for: (a) $T_j = T_a$ and $\mathrm{Re}_D = 10^5$, (b) $T_j = 1.5T_a$ and $\mathrm{Re}_D = 10^5$, (c) $T_j = 2.25T_a$ and $\mathrm{Re}_D = 10^5$, (d) $T_j = 1.5T_a$ and $\mathrm{Re}_D = 2\times10^5$, (e) $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$. The pressure color scale ranges from -62.5 to 62.5 Pa.

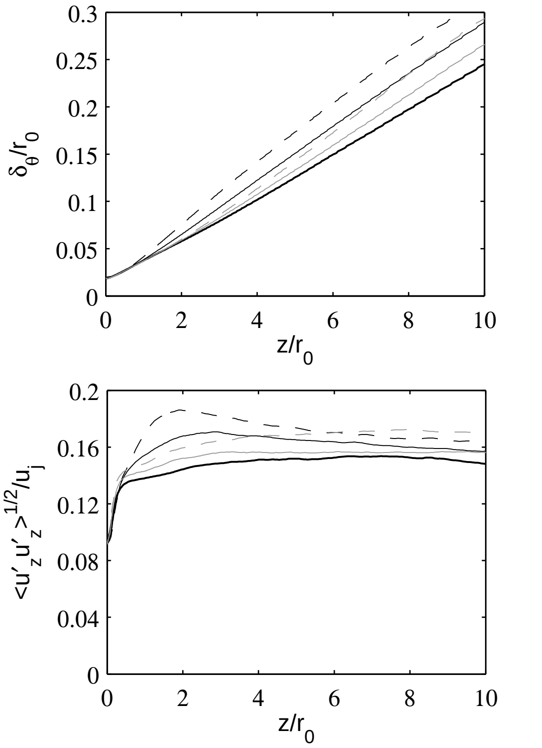

Figure 4. Variations of shear-layer momentum thickness δ_θ and of the peak rms values of velocity u'_z for: ——— $T_j = T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 10^5$, — — — $T_j = 2.25T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 2\times10^5$, — — — $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$.

$\mathrm{Re}_D = 10^5$ in figure 3(c), but lower for the jet at $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$ in figure 3(e).

Shear-layer development

To characterize the mixing-layer development, the variations between $z = 0$ and $z = 10r_0$ of the shear-layer momentum thickness δ_θ and of the maximum rms values of the axial velocity u'_z are presented in figures 4(a) and 4(b). In general, as the jet temperature increases, the mixing layers are found to develop more rapidly with higher turbulence levels. This is especially the case for the jets at $\mathrm{Re}_D = 10^5$ (cf black curves). For these jets, in figure 4(b), the rms velocity profiles reach peak values of 15.4% of u_j at $T_j = T_a$ but of 18.6% of u_j at $T_j = 2.25T_a$, see in table 2, with a nearly monotonical growth in the former case but an overshoot around $z = 2r_0$ in the latter case. These trends can be due in large part to Reynolds number effects, because Re_j and Re_θ decrease here from 10^5 and 943 at $T_j = T_a$ down to 2.5×10^4 and 254 at $T_j = 2.25T_a$. This statement is supported by the fact that similar results were obtained in Bogey et al. (2012b) in a computational study dealing with isothermal jets with Reynolds numbers Re_D between 2.5×10^4 and 2×10^5 and Re_θ between 256 and 1856. Moreover, the changes induced by increasing T_j in the mixing-layer spreading and peak rms velocity values are much less important for the jets at a constant $\mathrm{Re}_j = 10^5$ (cf grey curves) than for the others at $\mathrm{Re}_D = 10^5$ (and a decreasing Re_j).

Table 2. Axial position of the end of the potential core z_c, and peak turbulence intensities u'_{max}/u_j and u'_{axis}/u_j in the jet and on the axis.

T_j/T_a	Re_D	z_c/r_0	u'_{max}/u_j	u'_{axis}/u_j
1	10^5	15.9	15.4%	11.4%
1.5	10^5	12.5	17.1%	13.4%
2.25	10^5	10.6	18.6%	14.6%
1.5	2×10^5	13.2	16%	13.2%
2.25	4×10^5	11.4	17.2%	14.3%

Jet flow field

The centerline variations of the mean and rms axial velocities are presented in figures 5(a) and 5(b). Measurements obtained for Mach number 0.9 cold jets at high Reynolds numbers $\mathrm{Re}_D \geq 5\times10^5$ by Lau et al. (1979), Arakeri et al. (2003) and Fleury et al. (2008) are also depicted for the comparison. The effects of the Reynolds number appear relatively weak here. In all cases, increasing the jet temperature leads to a significant reduction of the potential core length in figure 5(a), yielding $z_c = 15.9r_0$ at $T_j = T_a$, $z_c \simeq 13r_0$ at $T_j = 1.5T_a$ and $z_c \simeq 11r_0$ at $T_j = 2.25T_a$ as reported in table 2. It also results in a more rapid velocity decay downstream of the jet core. These trends are in agreement with experimental data available for low-density and heated jets in Amielh et al. (1996), Lepicovsky (1999) and Kearney-Fischer et al. (2009). Regarding the centerline turbulence intensities in figure 5(b), their peak values are located farther upstream and slightly increase for higher jet flow temperature, from 11.4% at $T_j = T_a$ up to about 14.5% at $T_j = 2.25T_a$, refer to table 2. These results also correspond to measurements of Lepicovsky (1999) and Kearney-Fischer et al. (2009).

Acoustic field

In order to provide a glimpse into the acoustic field of the jets, far-field characteristics computed at 60 radii from the nozzle exit from the LES near-field data at $r = 6.5r_0$ are displayed in figures 6 and 7. The variations of the sound levels with the temperature seem to depend on the Reynolds number, the radiation angle and the frequency.

The overall sound pressure levels calculated at emission angles $30^o \leq \phi \leq 90^o$ relative to the jet direction are presented in figure 6. Roughly speaking, for the jets at an identical Reynolds number $\mathrm{Re}_D = 10^5$, increasing the jet temperature leads to higher noise levels (cf top figure). This tendency is probably due to the strengthening of the coherent structures and of the turbulence intensities observed in the mixing layers in figures 2(a-c) and 4(bottom, black curves) as the values of Re_j and Re_θ decrease with T_j. For the jets at a fixed Re_j, the effects of temperature are less pronounced (cf bottom figure). With respect to the isothermal jet, the hot jets appear to generate similar sound levels in the vicinity of $\phi = 45^o$, but lower sound levels at larger angles. These results are in line with experimental observations made by Tanna (1977) for jets at an acoustic Mach number of 0.9 and $\mathrm{Re}_D \simeq 10^6$. This agreement can be explained by the fact that at such high Reynolds numbers the effects due to the variations of viscosity with heating, (put

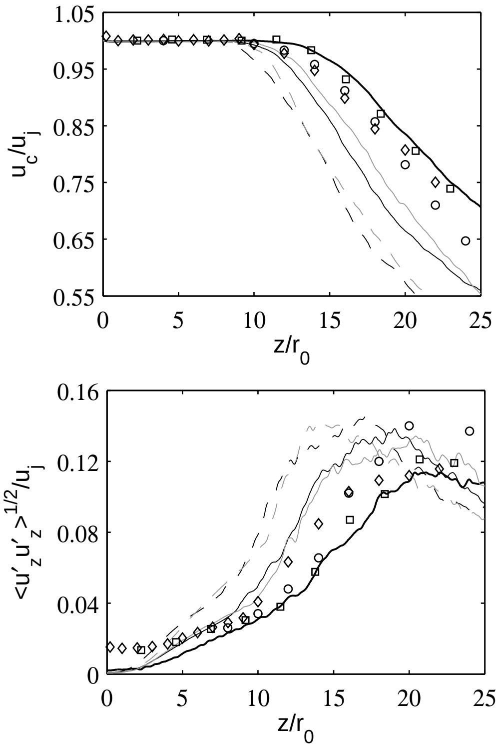

Figure 5. Variations of centerline mean axial velocity u_c and of centerline rms values of velocity u'_z for: ——— $T_j = T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 10^5$, — — — $T_j = 2.25T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 2\times10^5$, — — — $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$; measurements for cold jets at $\mathrm{M} = 0.9$ and $\mathrm{Re}_D \geq 5\times10^5$: ○ Lau et al. (1979), □ Arakeri et al. (2003), ◇ Fleury et al. (2008).

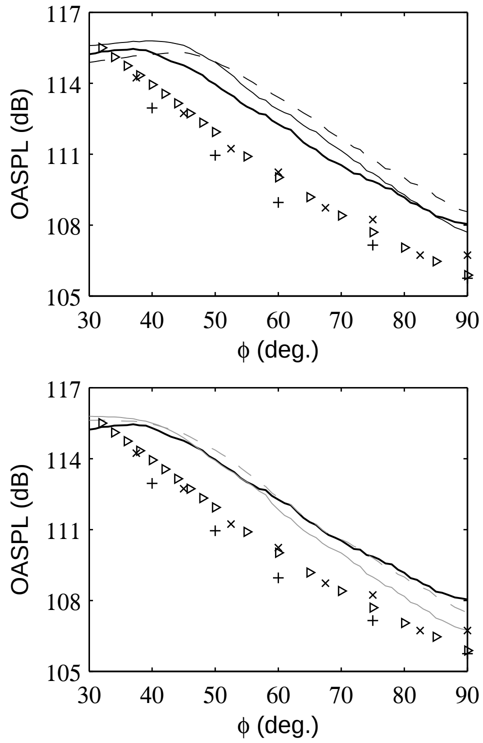

Figure 6. Overall sound pressure levels (OASPL) as a function of the emission angle ϕ at $60r_0$ from the nozzle exit for: ——— $T_j = T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 10^5$, — — — $T_j = 2.25T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 2\times10^5$, — — — $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$; measurements for cold jets at at $\mathrm{M} = 0.9$ and $\mathrm{Re}_D \geq 5\times10^5$: + Mollo-Christensen et al. (1964), × Lush (1971), ▷ Bogey et al. (2007).

more simply, Reynolds number effects) are most probably negligible, wich was the intended objective in simulating jets at a fixed Re_j.

Finally, the sound pressure spectra calculated at $60r_0$ from the nozzle exit at the angle $\phi = 60^o$ are plotted in figure 7 as a function of Strouhal number $\mathrm{St}_D = fD/u_j$. For the jets at $\mathrm{Re}_D = 10^5$, rising temperature leads to significantly higher sound levels at low frequencies for $\mathrm{St}_D \leq 0.4$, and similar or slightly higher sound levels for $\mathrm{St}_D \geq 0.4$ (top figure). For the jets at $\mathrm{Re}_j = 10^5$, a strong increase in low-frequency noise is also observed, but noise reduction is clearly obtained at all frequencies higher than $\mathrm{St}_D = 0.8$. These opposite trends with heating, namely increase and reduction of the sound levels at low and high frequencies, respectively, can be found in the 1/3 octave spectra obtained by Tanna (1977) for jets at Mach numbers of 0.5 and 0.9 and $\mathrm{Re}_D \simeq 10^6$, see also in Panda (2007).

CONCLUSION

The LES results presented in this paper show the significant influence of temperature on turbulent subsonic jets at a Mach number of 0.9. Strong effects are found on the mixing-layer development, the jet potential core length, and the generated acoustic field. At the diameter-based Reynolds numbers around 10^5 considered in this study, they appear to be of two kinds: the effects due to the changes in density, and those due to the variations of viscosity with rising temperature. Thus, heating jets at a constant $\mathrm{Re}_D = u_jD/\nu$ (and a decreasing $\mathrm{Re}_j = u_jD/\nu_j$ based on the exit flow conditions) leads to a strengthening of the mixing-layer transition and to higher sound pressure levels, two trends which are noted for cold jets with decreasing Reynolds number. The results obtained for jets at a fixed Re_j are different. In this case, in particular, increasing temperature results in noise reduction at high frequencies, which is in agreement with experimental data available for high Reynolds number jets.

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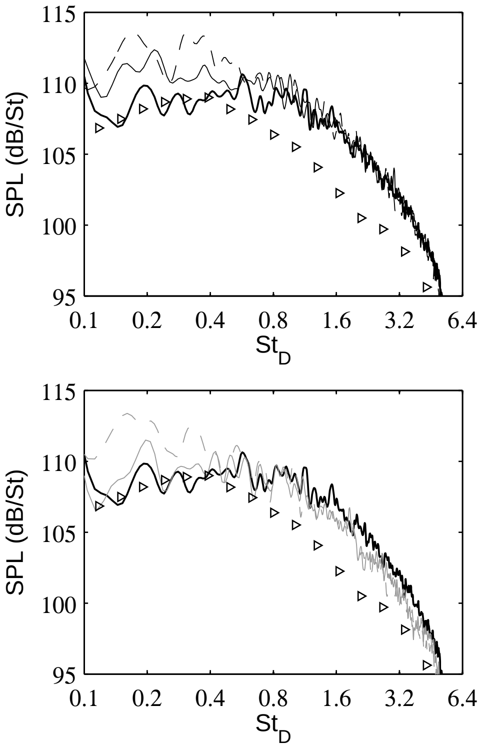

Figure 7. Sound pressure levels (SPL) at $\phi = 60^o$ as a function of $\mathrm{St}_D = fD/u_j$ at $60r_0$ from the nozzle exit for: ——— $T_j = T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 10^5$, − − − $T_j = 2.25T_a$ and $\mathrm{Re}_D = 10^5$, ——— $T_j = 1.5T_a$ and $\mathrm{Re}_D = 2\times10^5$, − − − $T_j = 2.25T_a$ and $\mathrm{Re}_D = 4\times10^5$; measurements for cold jets at at M = 0.9 and $\mathrm{Re}_D \geq 5\times10^5$: ▹ Bogey et al. (2007).

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