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LARGE EDDY SIMULATIONS OF TURBULENT HEATED JETS

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ABSTRACT Large eddy simulations of turbulent heated jets have been carried out and validated against experimental data. The code employed in this work is based on the OpenFOAM platform. Heated jets with Reynolds number varying from 3800 to 8500 and with exit Froude numbers varying from 3500 to 13200 are simulated. The numerical results are validated against the experimental data provided by Anderson and Bremhorst [2002], and compared with the self-similarity laws derived by Chen and Rodi [1980] for the temperature and velocity. The validation tests are satisfactory and allow us to use the code with confidence for numerical investigations. A parametric study is presented in order to analyse the temperature influence on turbulence. It is observed that an increase of the temperature gradient decreases the turbulence intensity.

INTRODUCTION

Turbulent flows with temperature gradients are commonly found in natural or industrial processes, and display a wide range of physical phenomena. Free shear flows, such as jets, are of particular interest for a wide range of engineering applications, for instance, the ability to predict the interaction between heat transfer and turbulence in such flows constitutes a prerequisite essential for combustion or atmospheric modeling, among others.

Various experimental and numerical studies of turbulent reactive jets have been reported [Sandia TNF workshop]. Reactive flows involve a lot of physical phenomena such as turbulence, chemical reactions, radiative transfer, compressibility effects, buoyancy and so on, and it becomes difficult to isolate the effect of one physical mechanism from the others. In this study, in order to understand the interaction between heat transfer and turbulence in a free jet, we investigate non-reactive turbulent heated jets.

Incompressible turbulent jets have been extensively studied, experimentally and numerically, over the last decades [Pope 2000], while the literature about variable-density jets is less abondant. Variable density flows can be originated by the mixing of different gases, temperature gradient, or high Mach number [Chassaing *et al.* 2002]. Experimentally, variable density turbulent round jets have been generally studied by mixing air with pure helium or carbon dioxide [Panchapakesan and Lumley 1993, Amielh *et al.* 1996, Boujemaa *et al.* 2007]. However, some experimental studies of heated jets are available, such as those by Peterson and Bayazitoglu [1992], and Shabbir and George [1994]. More recently, Anderson and Bremhorst [2002] reported an experimental study of turbulent heated jets of air and presented experimental data for various turbulent physical quantities (mean values and root-mean squared velocities and temperature). Like for incompressible jets, self-similarity laws for variable-density jets have been deduced from experimental data for the mean velocity and temperature fields, and can be found in the reference survey of Chen and Rodi [1980]. In their work, decay laws for the velocity and temperature are given based on the exit Froude number defined as:

$$Fr = \frac{U_j^2 \rho_j}{gd(\rho_0 - \rho_j)} \tag{1}$$

where U_j and ρ_j are the time averaged velocity and density of the jet at the exit of the nozzle, respectively, d is the inner diameter of the nozzle, g the acceleration of gravity and ρ_0 the ambient density. Isothermal jets with variable-density and heated jets display similar behaviour in the zone where the inertial force dominates the flows, i.e., the near-field of the jet, and in the zone dominated by the buoyancy force, i.e., in the zone where the flow behaves like a thermal plume. In the intermediary or transition zone, buoyancy and inertial forces have both a significant effect.

The objective of this work is to validate a large eddy simulation (LES) code of turbulent jets of heated air from the inertial zone to the intermediary zone, and to study the influence of temperature on the flow in order to give physical insight about the influence of the heat transfer on the turbulence. LES have been carried out for isothermal variable-density jets [*e.g.* Wang *et al.* 2008, Foysi *et al.* 2010], and it has been shown the ability of the LES models to study the structure of the turbulence in a jet. LES studies of heated jets have been carried out for high Mach number in order to predict the noise [Bodony and Lele 1996]. Zhou *et al.* [2001] focused on weakly compressible turbulent jets. They simulated heated jets with a low Reynolds number (around 1000), and investigated the inertia-dominated zone using LES. To the authors knowledge, no validated experimentally LES of the interaction between heat transfer and turbulence in turbulent heated jets is available in the literature. This is the subject of the present article.

Heated jets with Reynolds number varying from 3800 to 8500 and with Froude numbers varying from 3500 to 13200 are simulated using LES. The computer code employed in this work is based on the solver buoyantPimpleFoam of the OpenFOAM platform. OpenFOAM is a set of object-oriented open source CFD toolboxes written in C++ [*e.g.* Weller *et al.* 1998]. Various mathematical and numerical tools, utilities and solvers are available in the platform, including massive parallelization. In the buoyantPimpleFoam solver, the discretized compressible Navier-Stokes equations, coupled with the enthalpy equation, are solved using the finite-volume method. In this work, the numerical simulations are validated against the experimental data reported by Anderson and Bremhorst [2002], and compared with the similarity laws given by Chen and Rodi [1980].

In the next section, the physical and numerical models are detailed. The results are presented and discussed in the following section, and the paper ends with a summary of the work carried out.

LES MODEL AND NUMERICAL DETAILS

The conservation equations for LES of compressible heated jets are the continuity, the momentum and the enthalpy equations :

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial \overline{\rho}\widetilde{u}_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\sigma}_{ij}}{\partial x_j} + \overline{\rho g_i} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

$$\frac{\partial \bar{\rho}\tilde{h}}{\partial t} + \frac{\partial}{\partial x_i}\bar{\rho}\tilde{u}_i\tilde{h} = \frac{Dp}{Dt} + \frac{\partial}{\partial x_i}[\frac{\lambda}{c_p}\frac{\partial \tilde{h}}{\partial x_i}] - \frac{\partial q_i}{\partial x_i} \tag{4}$$

where the overbar denotes a filtered quantity, and the tilde a Favre-filtered quantity. In the following, time-averaged values will be denoted by $\langle\rangle$.

The one-equation eddy viscosity model is chosen for modelling the subgrid-scale stress tensor $\tau_{ij} = \bar{\rho}(\widetilde{u_i u_j} - \tilde{u}_i\tilde{u}_j)$. This model has been proposed by Yoshizawa and Horiuti [1985], and investigated in compressible flows by Fureby [1996] who showed the good efficiency of this model. Moreover, it has been observed by Baba-Ahmadi and Tabor [2009] that this model allows the use of a coarser grid than the Smagorinsky model. The one-equation eddy viscosity model consists in solving the following transport equation for the subgrid-scale turbulent kinetic energy $k_{SGS} = \frac{1}{2}(\widetilde{u_i^2} - \tilde{u}_i^2)$:

$$\frac{\partial \bar{\rho}k_{SGS}}{\partial t} + \frac{\partial}{\partial x_i}\bar{\rho}\tilde{u}_i k_{SGS} = \frac{\partial}{\partial x_i}[(\nu + \nu_{SGS})\frac{\partial k_{SGS}}{\partial x_i}] - \tau_{ij}\frac{\partial \bar{\rho}\tilde{u}_i}{\partial x_j} - \bar{\rho}\varepsilon \tag{5}$$

In this equation, the dissipation ε is expressed by $\varepsilon = C_\varepsilon k^{\frac{3}{2}}/\Delta$ where $C_\varepsilon = 1.048$ is a model constant. The subgrid-scale (SGS) stress tensor is modelled using the eddy viscosity assumption which introduces a subgrid-scale eddy viscosity, ν_{SGS}, according to the following relationship:

$$\tau_{ij} = -2\nu_{SGS}\tilde{S}_{ij} + \frac{2}{3}k_{SGS}\delta_{ij} \tag{6}$$

where $\tilde{S}_{ij}$ is the resolved rate-of-strain tensor $\tilde{S}_{ij} = \frac{1}{2}(\frac{\partial \tilde{u}_j}{\partial x_i} + \frac{\partial \tilde{u}_i}{\partial x_j})$. The following expression for ν_{SGS} is assumed :

$$\nu_{SGS} = C_k \Delta \sqrt{k_{SGS}} \tag{7}$$

where Δ is the length scale and $C_k = 0.094$ is another model constant. The two constants C_k and C_ε are chosen according to the study of Fureby [1996]. The SGS heat flux $q_i = (\widetilde{u_i h} - \tilde{u}_i\tilde{h})$ is modeled using the gradient transport model,

$$q_i = -\frac{\bar{\rho}\nu_{SGS}}{Pr_t}\frac{\partial \tilde{h}}{\partial x_i} \tag{8}$$

assuming a constant turbulent Prandtl number of $Pr_t = 0.81$ as suggested in the experimental study of Chua and Antonia [1990] for turbulent round jets.

The code used in this study is based on the solver buoyantPimpleFoam of the OpenFOAM platform. The finite-volume method in Cartesian coordinates is used to discretize the governing equations. The second-order central differencing scheme has been used for all the spatial derivative terms, along with a second-order implicit backward time scheme. The pressure-velocity coupling is based on the PIMPLE algorithm (based on SIMPLE and PISO), which offers a better stability compared to the PISO algorithm in weakly compressible jets like those simulated in this work.

The computational domain is a conical cylinder with the jet centerline located along the x-

direction. The dimensions of the domain are in the range $5d-10d$ in the radial r-direction (this dimension increases along the axial direction), 2π in the azimuthal φ-direction and $60d$ in the axial x-direction. The grid is composed by unstructured polyhedral generated by the utility blockMesh of the OpenFOAM platform. Nonuniform grid lines are distributed along the axial and radial directions, in order to refine the mesh near the nozzle exit and in the shear layer.

Three meshes have been tested, a coarser mesh with 577920 cells ($140\times86\times48$), a second mesh with 962560 cells ($160\times94\times64$), and a finer mesh with 1331200 cells ($200\times104\times64$). Little change is observed between the results obtained with the second and the third meshes, showing the appropriateness of the grid resolution adopted in our simulation. Consequently, in the remainder of this study, only the results obtained with the second mesh will be presented.

Boundary conditions are non-reflective at the outlet and at the lateral side of the domain. At the inflow boundary, an hyperbolic-tangent velocity profile was used for the mean velocity as suggested in [Bodony and Lele 1996, Foysi *et al.* 2010] and the Crocco-Buseman relation has been used for the mean temperature [Garnier *et al.* 2009]. A background velocity disturbance randomly distributed in space at the exit of the nozzle has been imposed as suggested by Kim and Choi [2009], corresponding to a rms value of 1% (value experimentally observed by Anderson and Bremhorst [2002]).

RESULTS AND DISCUSSION

Two turbulent heated jets corresponding to the cases H_1 and H_2 of the experimental study of Anderson and Bremhorst [2002] have been simulated in order to validate the numerical code used in this work. Table 1 summarizes the parameters of the jets. In this table T_0 and T_j denote the ambient and the jet temperature at the nozzle exit, respectively. The nozzle diameter d is equal to 1 cm.

	U_j (m/s)	$\Delta T_j = T_j - T_0$ (K)	Reynolds	Froude
H_1	22.4	118	8000	13200
H_2	35.8	240	8500	16000

Table 1: Parameters of the heated jets

An example of the instantaneous temperature field of the jet H_1 is displayed in figure 1. It can be observed that the boundary conditions do not influence the spatial evolution of the jet.

The statistical quantities were obtained by averaging over a time period Δt, corresponding to a Strouhal number $\frac{d}{\Delta t\times U_j}=1.8\times10^{-3}$, after statistical stationarity is reached.

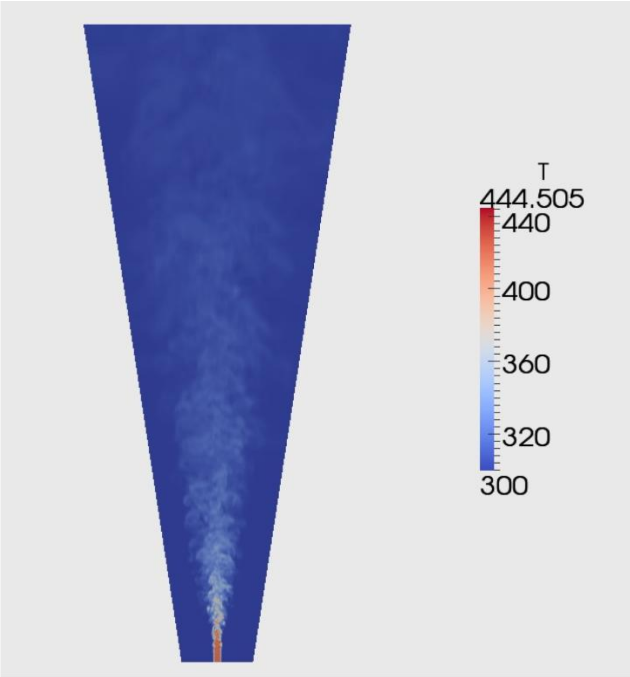

Figure 1: Example of instantaneous temperature field (in K) of the jet H_1 in a plane (x,r).

Mean velocity and temperature The decay laws derived by Chen and Rodi [1980] for the mean axial velocity and temperature along the centerline $\langle U_c \rangle$ and $\langle T_c \rangle$, are given in eqs. 9 and 10, respectively:

$$\frac{\langle U_c \rangle}{U_j} = 6.3 \times \sqrt{\frac{\rho_j}{\rho_0}} \times \frac{d}{x} \tag{9}$$

$$\frac{\langle \Delta T_c \rangle}{\Delta T_j} = \frac{\langle T_c \rangle - T_0}{T_j - T_0} 5.4 \times \sqrt{\frac{\rho_j}{\rho_0}} \frac{d}{x} \tag{10}$$

These laws are compared with the numerical results for the two jets H_1 and H_2 in figures 2 (mean centerline velocity) and 3 (mean centerline temperature).

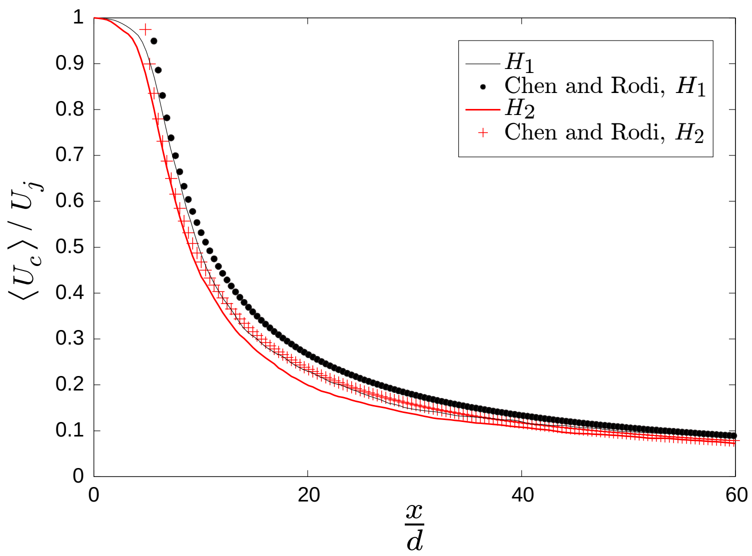

Figure 2: Mean centerline velocity $\langle U_c \rangle$ normalised by the jet velocity at the exit of the nozzle, U_j

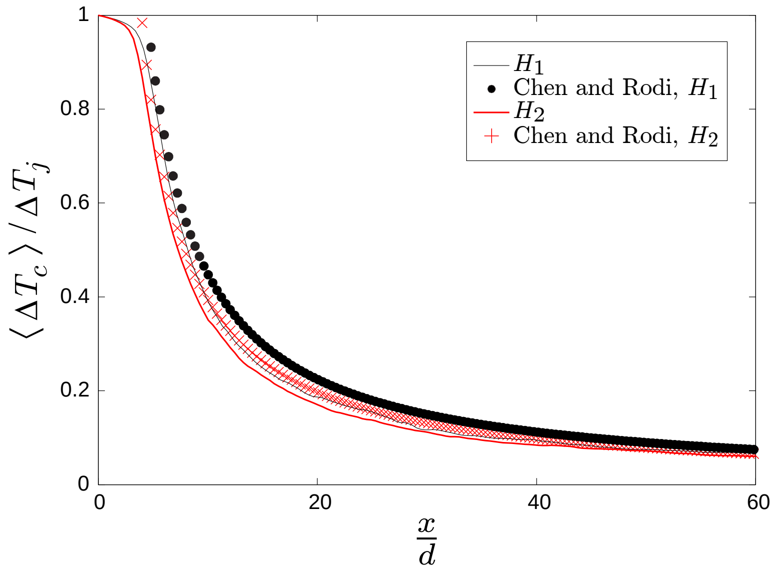

Figure 3: Mean centerline temperature variation $\langle \Delta T_c \rangle$ normalised by the difference between the jet temperature at the exit of the nozzle, T_j ,and the ambient temperature , T_0 .

In both cases, the agreement between the correlations of Chen and Rodi and the present numerical results is very good. Only a small difference can be observed, *i.e.*, the numerical results are lower than the Chen and Rodi laws for the two jets. This small difference, which has already been observed in other studies [Wang *et al.* 2008, Foysi *et al.* 2010], is due to the fact that the decay laws do not hold in the near vicinity of the nozzle. In fact, such laws yield values of $\langle U_c \rangle / U_j$ and $\langle \Delta T_c \rangle / \Delta T_j$ that tend to infinity in the limit of $x \to 0$, while the actual ratios tends to unity, as predicted by the numerical simulations. The observed discrepancies may be further due to the inflow conditions, such as the inital momentum thickness or the background disturbance, which have an influence on the size of the jet core region, as shown in [*e.g.* Kim and Choi 2009].

In the remainder, the validation tests will essentially focus on the H_2 jet, which has the highest Reynolds and Froude numbers. In figure 4, the following equation developed by Gerhke [1997] is used to fit the radial profile in [Anderson and Bremhorst 2002] :

$$\frac{\langle U \rangle}{\langle U_c \rangle} = \exp[a(r/x)^b] \qquad (11)$$

The coefficients of eq. 11 for the experimental data fit of H_2 jet are given in [Anderson and Bremhorst 2002], *i.e.*, $a = -34.478$ and $b = 1.7282$. This experimental data fit is compared with the numerical results for the jet H_2 and with a gaussian profile in figure 4. The radial profiles are displayed for various streamwise locations.

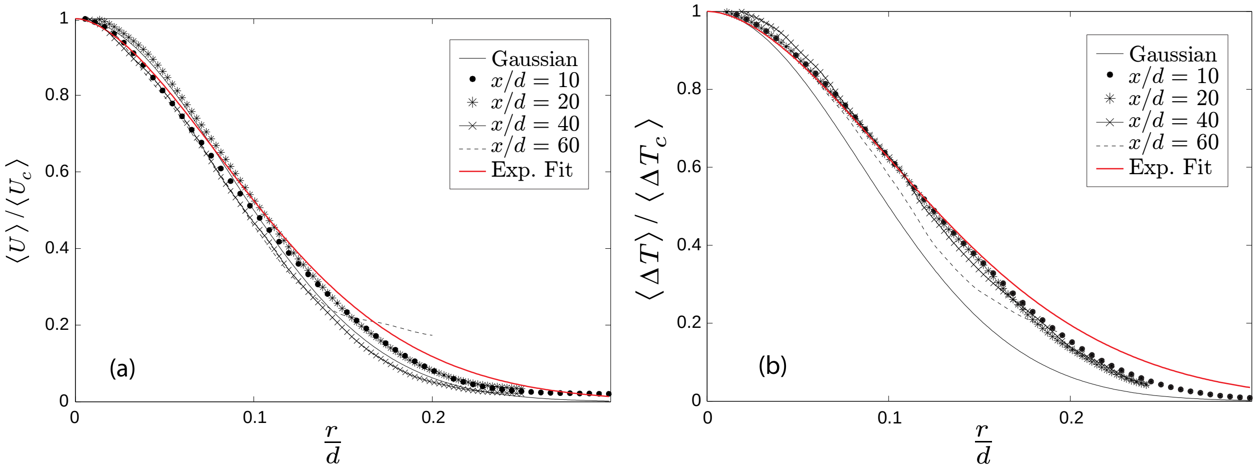

Figure 4: Radial profiles of mean axial velocity normalised by the mean centerline velocity $\langle U_c \rangle$ (a) and mean radial temperature variation $\langle \Delta T \rangle = \langle T - T_0 \rangle$ normalised by the mean centerline temperature variation $\langle \Delta T_c \rangle = \langle T_c - T_0 \rangle$ (b)

Self-similar behavior is observed between the different streamwise locations. Therefore, this confirms the statement that the pseudo-similarity is valid for variable-density jets observed in a numerical study of a helium jet [Foysi *et al*. 2010]. The spreading rate estimated for the two jets H_1 and H_2 is equal to $S \approx 0.1$. The agreement with the experimental data is also good, especially close to the jet centerline. Equation 11 was further applied to the experimental data fit of the radial profile of the mean temperature, but with different coefficients, $a = -28.9205$ and $b = 1.7871$. Once again, a good agreement is observed with the experimental data. In this case, all the radial profiles are located between the gaussian profile and the experimental data. In those figures, it is observed that the level of convergence for $x/d = 60$ is not satisfactory and must be improved.

Turbulent quantities The root-mean square (rms) of the streamwise velocity and of the temperature at the jet centerline are presented in figure 5.

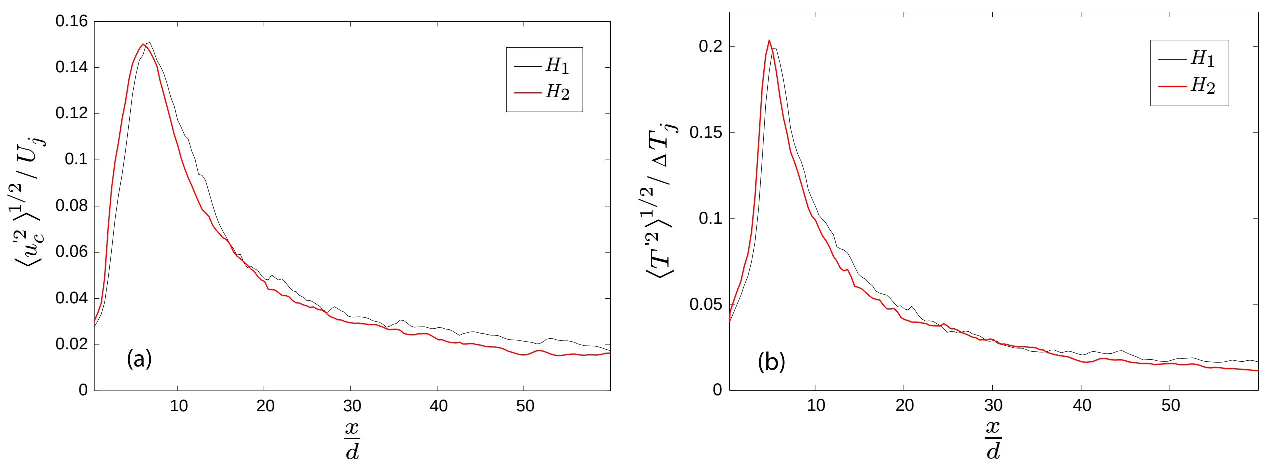

Figure 5: rms of the axial velocity component at the centerline $\sqrt{\langle u_c'^2 \rangle}$ normalised by the jet velocity, U_j (a) and rms of the temperature at the centerline $\sqrt{\langle T_c'^2 \rangle}$ normalised by the jet temperature variation ΔT_j for the two jets (b)

The evolutions of the rms of the streamwise velocity for the two jets are very close, due to the comparable Reynolds number (see table 1). A similar observation can be made for the rms temperature. The numerical values found here are consistent with the experimental data of Anderson and Bremhorst [2002]. These evolution of the rms, and the numerical values found, are also in agreement with other LES numerical studies of turbulent round jets [Wang *et al.* 2008].

The radial profiles of the rms of the streamwise and radial velocity components for the jet H_2 are compared in figure 6 with the experimental data fit obtained from equations 12 and 13:

$$\frac{\langle u'^2 \rangle}{\langle U_c \rangle^2} = a_1 (r/x)^2 \exp[b_1 (r/x)^2] + c_1 \exp[d_1 (r/x)^2] \quad (12)$$

$$\frac{\langle v'^2 \rangle}{\langle U_c \rangle^2} = a_2 \exp[b_2 (r/x)^{c_2}] \quad (13)$$

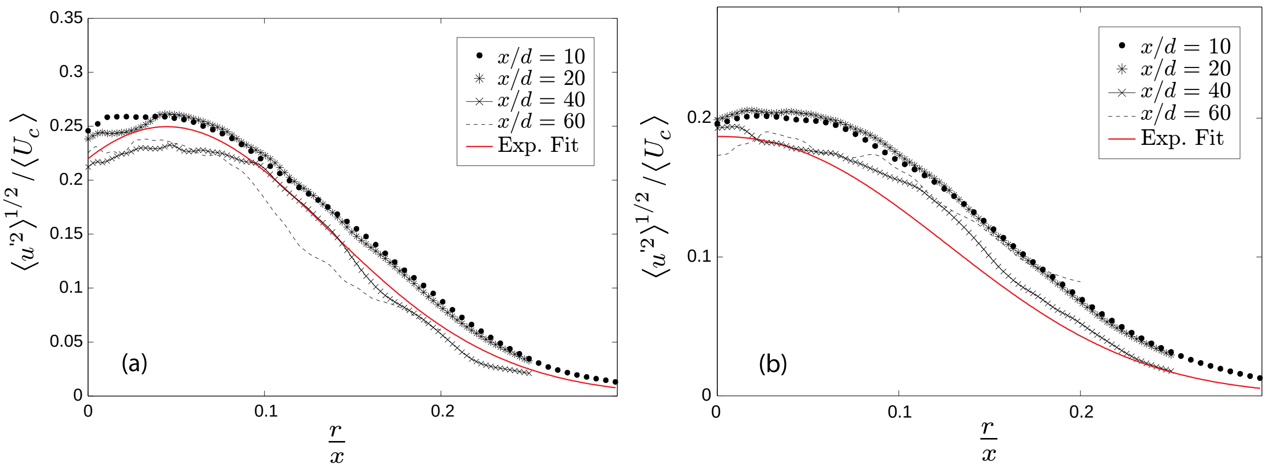

Figure 6: Radial profiles of the rms of the axial velocity, $\sqrt{\langle u'^2 \rangle}$ (a), and the radial velocity $\sqrt{\langle v'^2 \rangle}$ (b), normalised by the mean centerline velocity $\langle U_c \rangle$ for the jet H_2

The coefficients of eqs. 12 and 13 for the experimental data fit of H_2 are given in [Anderson 2002], *i.e.*, $a_1 = 1.6319$, $b_1 = -92.9937$, $c_1 = 0.22$, $d_1 = -53.975$, $a_2 = -0.0349$, $b_2 = -99.9935$ and $c_2 = 2.1931$. The agreement with the experimental data remains good for the rms of both streamwise and radial velocity components.

Overall, the validation tests for the numerical code are satisfactory. These tests have been based on the usual pseudo-similarity laws applied in the literature, on the experimental data provided by Anderson and Bremhorst [2002], and on other LES numerical studies [Wang *et al.* 2008, Foysi *et al.* 2010]. This allows us to use with confidence the code for parametric studies, such as that presented in the next paragraph.

Influence of temperature on the turbulent kinetic energy

In order to investigate the interaction between heat transfer and turbulence, jets with the same velocity as the jet H_1 but with different temperature gradients have been simulated. The selected parameters are given in table 2.

	U_j (m/s)	$\Delta T_j = T_j - T_0$ (K)	Re	Fr
Case 1: H_1	22.4	118	8000	13200
Case 2	22.4	236	5300	6500
Case 3	22.4	354	3800	4300

Table 2: Parameters of the simulated heated jets

Even though there is no clear value which delimits the transition zone from the inertia-dominated zone, the demarcation between these two regions is around $X \approx 0.5$ according to Chen and Rodi [1980] and Peterson and Bayatizoglu [1992], where X is the dimensionless streamwise distance parameter, which is defined as:

$$X = \frac{1}{\sqrt{Fr}} (\frac{\rho_j}{\rho_0})^{-1/4} \frac{x}{d} \tag{14}$$

In case 1, the H_1 jet, $X = 0.5$ corresponds to $x/d \approx 52$, while it corresponds to $x/d \approx 35$ for case 2, and $x/d \approx 27$ for case 3. These values agive an indication of the zone where buoyancy forces are influent.

The mean velocities and temperature for cases 2 and 3 display similar behaviour as the one presented in the preceeding section. Centerline mean values are in good agreement with the Chen and Rodi correlations and self-similarity is observed for the radial profiles of temperature and velocities (figures are not shown here). The spreading rates for the three cases presented in this section are equal to 0.1.

In figure 7, it is shown that the scaling law proposed by Chen and Rodi [1980] collapses the mean centerline velocity of the three jets, at least until $x^*/d = 30$. Further downstream, the buoyancy forces become influent on the flow for cases 2 and 3.

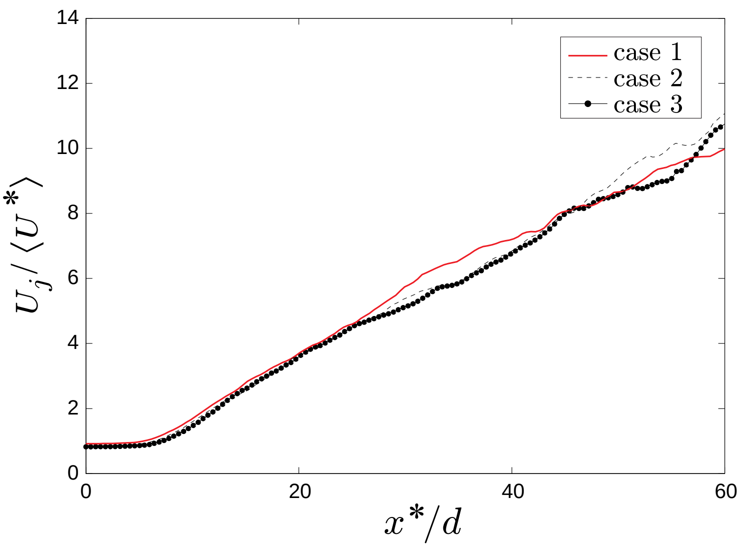

Figure 7: Centerline velocity decay using the scaling law proposed by Chen and Rodi [1980], *i.e.*, $x^* = s^{-1/4}x$ and $\langle U^* \rangle = s^{-1/4} \langle U_c \rangle$ with $s = \rho_j / \rho_0$

Hence, it can be concluded that Chen and Rodi correlations are still valid for the three heated jets.

The density variations due to temperature gradients have the same influence on the mean velocity as density variations due to mixing of gases.

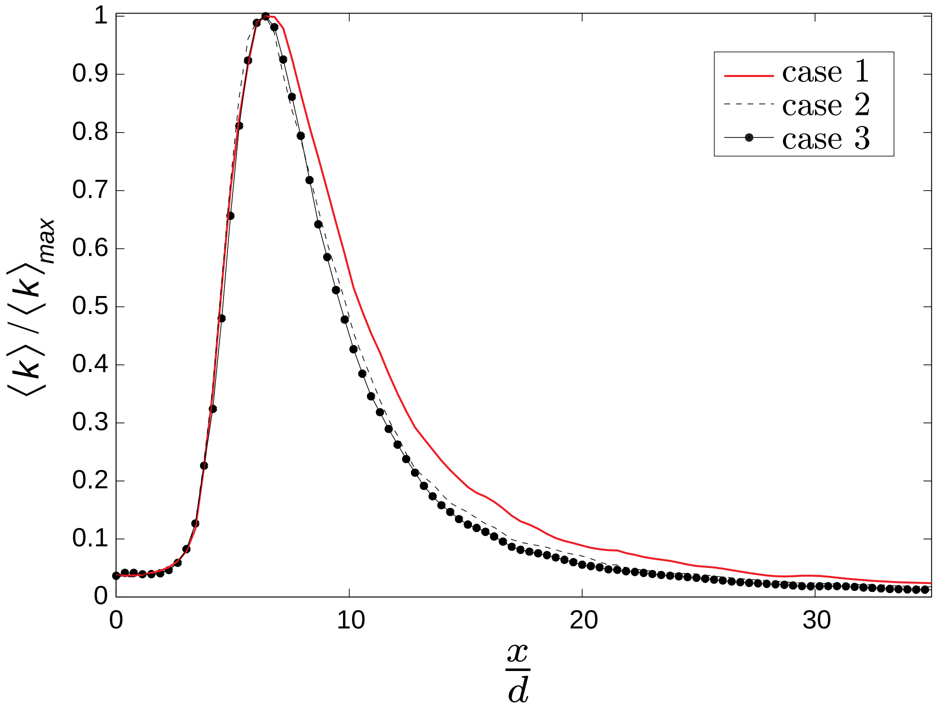

Figure 8: Mean turbulent kinetic energy $\langle k \rangle$ normalised by the maximum value k_{max} along the centerline for the three jets

In figure 8, the normalised mean turbulent kinetic velocity along the centerline is displayed for the three jets. It is observed that the normalised mean turbulent kinetic energy in case 1 remains higher than in cases 2 and 3, being higher in case 2 than in case 3, for $x/d \geq 10$. It is observed that the increase of the temperature gradient tends to decrease the turbulent kinetic energy. Unlike density variations due to mixing of gases, which increase the turbulence [Anderson and Bremhorst 2002], density variations due to temperature gradient have the opposite effect. However, the difference between the three jets is not very important, especially when comparing cases 2 and 3. Further investigations, at higher Reynolds number, and with different Froude numbers would be useful for analysis.

CONCLUSION

LES of turbulent heated jets has been carried out using a numerical code based on the solver buoyantPimpleFoam of the OpenFOAM platform. A one equation eddy-viscosity model has been applied with a finite-volume method. The numerical simulations have been validated against experimental data taken from the study of Anderson and Bremhorst [2002], and compared with the usual pseudo-similarity laws applied in the literature [Chen and Rodi 1980]. The results have also been compared with other LES numerical studies [Wang *et al*. 2008, Foysi *et al*. 2010]. The validation tests are satisfactory for the studied jets. A parametric study of the temperature influence is presented, and it is observed that an increase of the temperature tends to decrease the turbulent kinetic energy along the centerline.

However, the level of convergence must be improved in future work, and the conclusions should be confirmed by an analysis based on turbulent heated jets with higher Reynolds numbers. Moreover, in future works, simulations of turbulent reactive jets still based on the OpenFOAM platform will be carried out using LES. The influence of radiative transfer and combustion on turbulence will be investigated.

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