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BUOYANCY-DRIVEN STRUCTURES ON JET DIFFUSION FLAMES

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ABSTRACT

DNS simulations are carried out to reveal buoyancy patterns in order to establish the relationship between oscillating low-Reynolds jet diffusion flames and buoyancy-driven vortices observed in higher Reynolds flames. DNS match experimental Strouhal numbers. In the case of small Froude number flames, no large structure can develop as it is quickly damped by the stretch of the flow along the axis. This stretch is explained by the dynamics imposed by the differential buoyant thrust within the flame. Hence, paradoxically, this is in the buoyancy-driven flame, where gravity is the main actor, that the buoyant structures reduce to oscillations.

INTRODUCTION

Flames are perturbed by the gravity field. This is due to buoyancy force which stretches the flow, because of density difference. As flames are characterized by large gradients in temperature, buoyancy instabilities play a major role. They pave the way to the development of large scale structures. This picture is subtly different for low-Reynolds / Froude number flames. Such buoyancy-driven flames exhibit only small oscillations at their tip. Depending on the Reynolds and Froude numbers, it thus seems that buoyancy affects the flame through different manners.

Buoyancy is an ingredient to be included in flame spreading behaviour and safety codes and standards. Hydrogen industries are particularly concerned [1,2]. Buoyancy force has a strong influence on the velocity patterns in plume and flame, [3-11], interacting with turbulence creation, [12,13] and mixing [14], rising challenges in its modelling [15]. Instability controls have been proposed through micro-jet injection [16]. In jet spray flames, buoyant forces induce dispersion of the droplets [17]. In [18], an experimental study conducted with the help of a centrifuge allows to investigate flame length and flickering frequency for different gravity magnitudes. Most of these efforts have been turned toward non-low Reynolds number flames, where the flow is mainly momentum-driven [19]. A comprehensive experimental description of flame instability because of buoyancy is due to Hamins *et al.* [20]: disturbances in the jet are linked to jet diameter and fuel velocity. Cetegen and Ahmed, [21], extensively investigated buoyant plumes and pool fires. Numerical simulations of the puffing phenomenon in flames have been achieved, either with LES, [22], or DNS [23-25]. DNS has been approved to be a powerful tool to address the details of the puffing phenomena.

It is the motivation of this study to elucidate oscillation phenomena at the tip of low Reynolds / Froude flames and to connect them to well-known large scale flickering in moderate Reynolds

jet flames. The next section will present the equations solved, the main features of the code and the model problem. The following section will introduce results and discussion.

CONFIGURATION AND MODEL

The compressible one-step-reactive Stokesian Navier-Stokes equations are solved by a high-order accuracy DNS code, accounting for gravity and axisymmetry. Transport coefficients follow a power law in temperature. Prandtl and Schmidt numbers are unity. To avoid any interaction with relative weight of the reactants, normalized molecular weights are used. Specific heats are constant.

The 129x257 regular rectangular mesh is bordered by an inlet at the bottom, an axisymmetric axis on one side, and two outlets on the other sides. Based on the diameter of the jet, the domain is 2x6. The numerical schemes are the 6/4/3 implicit spatial Lele's scheme, [26] and the explicit third-order low-storage Runge-Kutta time-advancement [27]. The treatment of the axisymmetric boundary is included in the spatial scheme. Other boundaries are treated through an extension of the NSCBC method ([28]), incorporating gravity. As this latter induces gradient in the pressure, velocity and density fields, it must be accounted for in the characteristic equations managing boundaries. Due to the limit in paper length, details of this development are not given here.

The prescribed inlet field for the jet is for velocity u, fuel mass fraction Y_F and oxidizer mass fraction Y_O:

$$u = U_o \tanh^2\left(\frac{r^* - .5}{.1}\right) \tag{1}$$

$$Y_F = \frac{1 + \tanh\left(\frac{r^* - .5}{.1}\right)}{2} \tag{2}$$

$$Y_O = 1 - Y_F \tag{3}$$

with r^* being the radial coordinate, non-dimensionalized by the jet diameter D serving as a reference length. Gradient of the variables have been chosen such that it fulfils the stability requirement of the high-order spatial scheme.

Two cases are compared. For the first case, the jet Reynolds number ($Re = U_o D/\nu$ – ν is the kinematic viscosity at the fuel outlet) is set to a moderately high value, 800., while the second case has a considerably lower Reynolds number close to unity (0.8). Accordingly, the Froude number ($Fr = U_o^2/g/D$ – g is the gravity acceleration) varies from 5. to 5. 10^{-6}.

RESULTS

It is interesting to begin with qualitative pictures of flames for moderate and low Reynolds numbers. The temperature field is first chosen as it may be related to real observations which mostly occur because of radiating species. Figure 1 displays buoyancy instabilities for both

flames. It is seen that the flame with a moderately high Reynolds number exhibits strong vortex shedding due to buoyancy. The low-velocity flame has only a weak perturbation on its side.

Figure 1 also provides the position of the maximum temperature along the jet axis with time. In the case of moderately high Froude / Reynolds numbers, the big buoyancy-driven structure opens the tip of the flame which is virtually pushed outside the computational domain most of the time. This explains why the corresponding curve is usually bounded by the size of the domain (dotted line). After the summit is cut by the escape of the buoyant structure downstream, the tip of the flame is abruptly recovered inside the domain: this corresponds to the sudden decrease in the graph. Capturing the whole buoyant structure during the flickering process by increasing the length of the computational domain would not have changed the description. For the flame with low Froude and Reynolds numbers, the evolution is smoother as the flame is only slightly stretched during the progression of the buoyant structure. Oscillations of the flame tip are evident. Appropriately normalized frequencies are shown almost independent of the jet velocity [20]. Oscillation magnitudes have been observed as grossly +/-25% of the mean tip height for both flames.

Pulsations for different flames (not all included here) have been compared with experimental data, Tab. 1 and very good correspondence with the scatter plot in [20] is observed.

To understand in detail the birth and nature of the growth of vortex structures, it is proposed to study the budget of the vorticity transport equation, in usual notations:

$$\frac{D\omega}{Dt} = \omega\frac{v}{r} - \omega\left[\frac{\partial u}{\partial z} + \frac{1}{r}\frac{\partial (rv)}{\partial r}\right] + \frac{1}{\rho^2}\left[\frac{\partial \rho}{\partial z}\frac{\partial p}{\partial r} - \frac{\partial \rho}{\partial r}\frac{\partial p}{\partial z}\right] - \frac{g}{\rho}\frac{\partial \rho}{\partial r} + \mu\left[\frac{\partial^2 \omega}{\partial z^2} + \frac{\partial^2 \omega}{\partial r^2} + \frac{1}{r}\frac{\partial \omega}{\partial r} - \frac{\omega}{r^2}\right] \quad (4)$$

On the RHS, first term is the stretch, second one is volumetric expansion, third one is baroclinic torque, fourth one is the gravitational term and the last one is the viscous dissipation term. This latter has been checked to be of less importance as it is a response to an established field. The first four ones are studied in details in the following sequence, Fig. 2.

Figure 2 gives a useful explanation for the damping in vortex development in low velocity flames. Gravity source term, the primary creation for vorticity, is systematically counterbalanced by strong sink terms in expansion and stretch at the same location. Given the expression for stretch and expansion (Eq. 4), and the compacity of the flame, this situation may be expected. As the flame is buoyancy-driven, a strong gradient of u along the axis exists. This gradient entrains fluid, creating both v and gradient of v towards the axis. All this ingredients, making stretch and expansion terms really disfavour structure growth, do not appear in a momentum-driven flame. In such a flame, as seen on the pictures, sink and source terms are not exactly at the same location such that a neat balance allows creating positive and negative vorticity in the jet.

CONCLUSION

High accuracy DNS of jet buoyant diffusion flames have been carried out. Flames with low and moderate Froude / Reynolds numbers were investigated. In the low velocity flame, the stretch

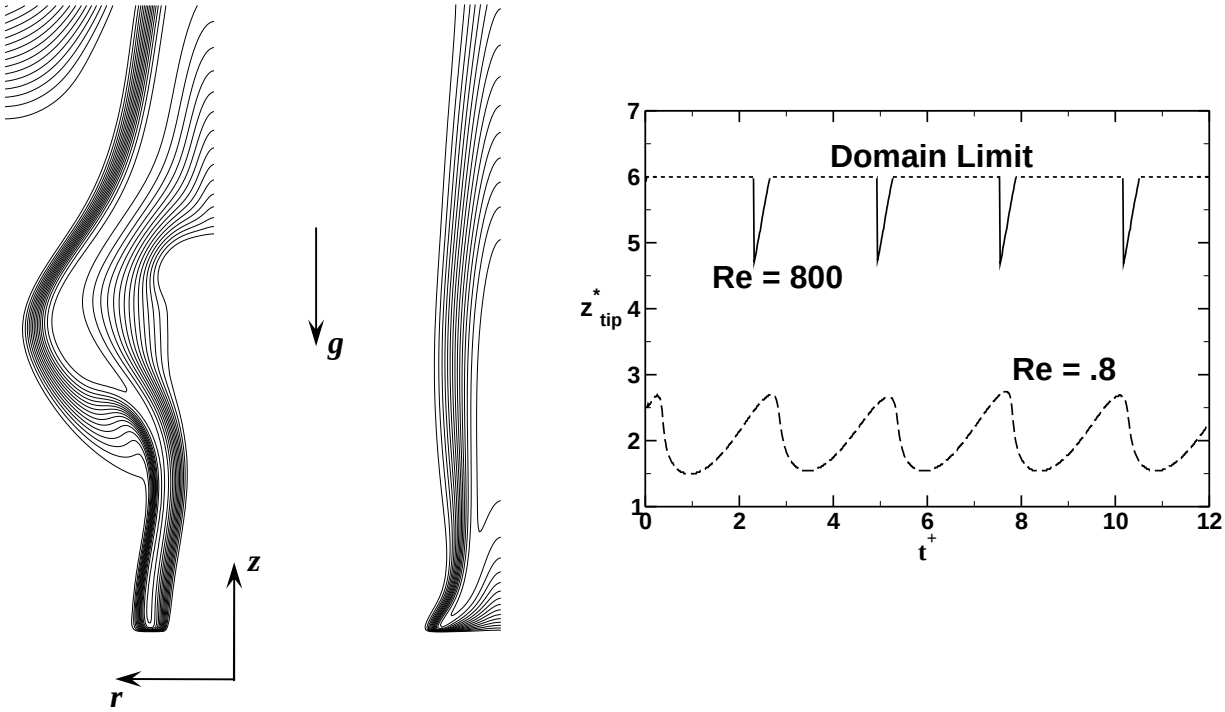

Fig. 1. Buoyancy driven vortex for moderate Reynolds / Froude numbers (800 / 5) on the left and low Reynolds / Froude numbers (.8 / 5. 10^{-6}) in the middle, temperature fields. On the right, time evolution of the maximum temperature position z_{sp} along the axis. $t^+ = t\sqrt{g/D}$.

imposed by the entrainment of the air directly perpendicular to the flame because of the strong buoyancy aspiration prevents the growing of vortical structures. Small vortices are thus transported along the flame at a specific rate, explaining the oscillation at the tip. In case of flames whose (paradoxically) dynamics is not buoyancy-driven, the vorticity creation is not damped for source and sink do not balance at the same location. Growing buoyant structures completely deform the flame, leading to flickering and edge-cutting, as observed in numerous experiments [11].

Buoyancy instability in flames being controlled by a small number of parameters easily identifiable, experimental data can be scaled to be compared to DNS computational results. It thus reveals as a good test case for DNS, which usually suffer from difficult comparisons with experiments. We are thus convinced here about the reliability of our code, especially regarding new developed boundary conditions for buoyancy. The domain has been chosen small enough to make the flame strongly interact with the frontiers. No spurious effects are visible and experimental comparison of instability is successful.

1/Fr	200000	2000	20	.2
Strouhal Exp.	180	20	1.6	.2
Strouhal DNS	181.3	18.1	1.615	.1706

Tab. 1. Strouhal number comparison between DNS and experimental data compiled in [20]. Strouhal number is defined as $St = fD/U_o$ with f the observed pulsation frequency.

To avoid complication of coflow configuration, jet flames from a burner bordered by horizontal walls have been chosen. Future work is planed to relax this and investigate effects of coflow and natural vertical entrainment on puffing phenomena.

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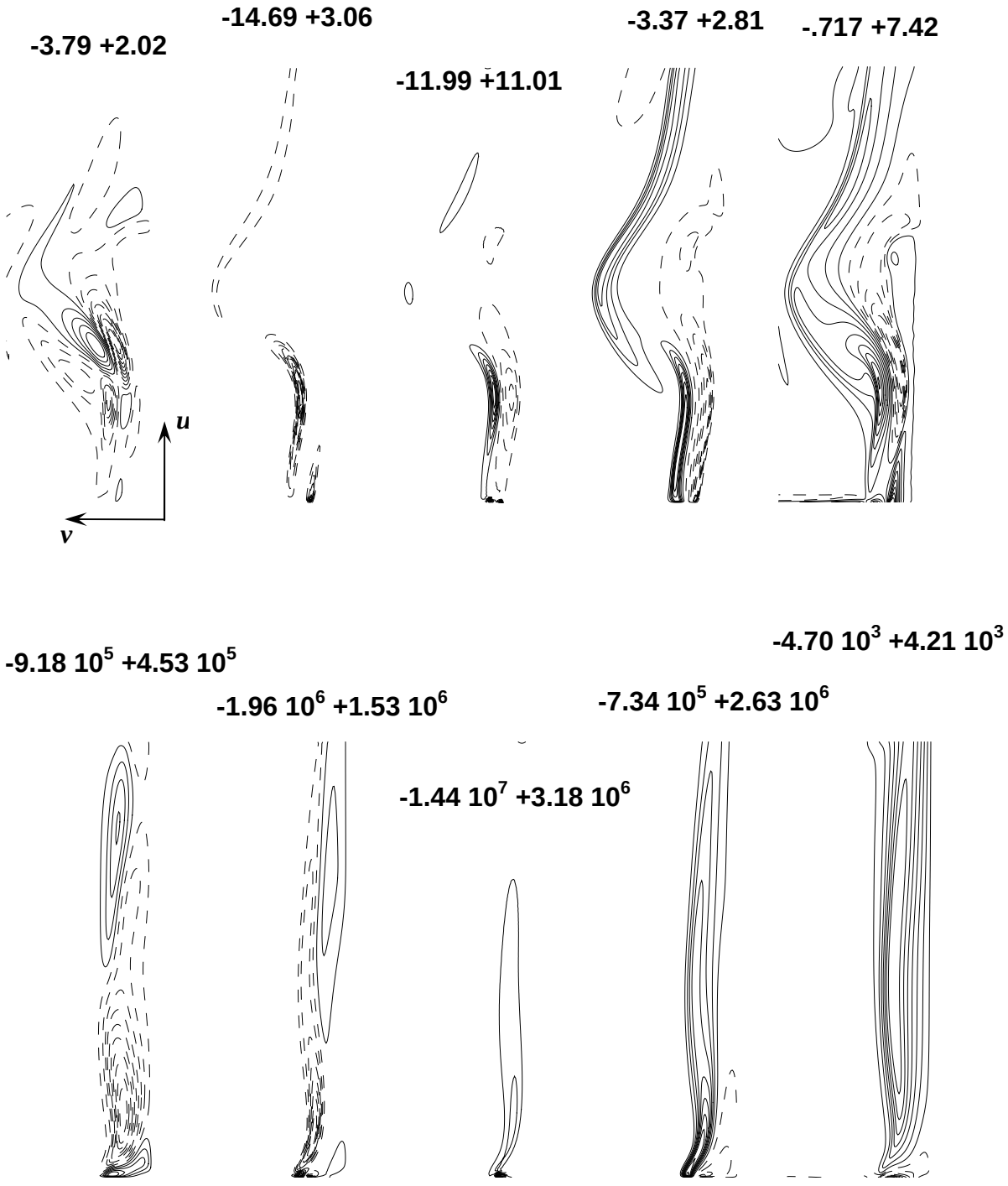

Fig. 2. Budget of the vorticity equation. From left to right: stretch, expansion, baroclinic and gravitation. Last column: vorticity. First rank: moderate Reynolds / Froude flame. Second rank: low Reynolds / Froude flame. Dimensional references are the maximum jet exit velocity U_o and the jet diameter D. Dash: negative contours.