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Thermoacoustic instabilities of coaxial jet combustor; computational studies using LES

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Swirl combustion is encountered in many engineering applications since it provides efficient fuel burning. Experimental studies of turbulent swirl combustion poses challenges due to unsteady nature of the combustion phenomenon. Therefore, computational approaches are a promising alternative for the numerical studies of supersonic combustion. The present studies concerns the computational studies of swirl combustion, particularly the effect of the injection scheme on the combustion efficiency and flame stability. Therefore, the effect of the air-fuel ratio on the combustion efficiency and flame stability is subject of investigation. The combustion efficiency is assessed based on the temperature developed inside the swirl combustor. The computations are carried out using the large-eddy simulation (LES) approach along with the flamelet combustion model. The analysis reveals the unsteady nature of the flame and thus, its departure from the core of the combustor. The analysis also reveals the presence of a region of high level of temperature, NO and CO_2, inside the combustor.

I. Introduction

Swirl combustion is widely used in both mechanical and aerospace engineering applications. Generally, swirl combustion is characterized by the flow and flame unsteadiness which may affect the combustion efficiency. Moreover, the combustion instabilities are responsible for the acoustic instabilities which may damage the combustor's structure. Therefore, significant efforts have been devoted to the mitigation of the acoustic emissions associated with turbulent combustion. To be able to control and mitigate the acoustic emissions a detailed understanding and characterisation of the combustion noise source is needed. A good prediction of the spectral sound pressure distribution is also needed. The coupling between the unsteady flame and implicitly heat release and acoustic pressure oscillations lead to self-excited oscillations which further generate high-level noise and decrease of the combustion efficiency. The thermoacoustic instabilities have a direct impact on the combustor components that reduces the component lifetime and eventually results into failure of the system. According to the criterion developed by the Lord Rayleigh, the pressure wave will be amplified by and develop an instability if the heat release rate and acoustic pressure fluctuations are out of phase. Vis-a-versa, the system is stable if the heat release rate and acoustic

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pressure fluctuations are out of phase. Generally, the combustion instabilities depend on the combustor geometry, the burner, and flame types, and the injection scheme of fuel and oxidizer.

Usually, the combustion instabilities of swirl combustion are complex phenomena and depend on the interaction among flow fluctuations, acoustic pressure fluctuations and heat release. In the past the studies of swirl combustion were performed experimentally. However, creating systems that can withstand high-temperatures are costly and may not be efficient. Therefore, computational approaches are promising alternative for the study of swirl combustion. Computational approaches, for the study of supersonic combustion, must satisfy three requirements: (i) the capability to resolve and capture a wide-range of time and length-scales of turbulence, (ii) provide accurate solution of the turbulence and turbulence/combustion interaction, and (iii) resolve flow fields of complex geometries.
Computational prediction of the fuel/air mixing and combustion processes in swirl combustors pose significant challenges due to the complex interactions between the fuel and air, acoustic instabilities, etc. Therefore, the numerical prediction of these complex fluid dynamics requires advanced computational methods.
The use of unsteady-Reynolds Navier-Stokes (URANS) methods, significantly rely on turbulence models to capture all the relevant turbulence scales. RANS methods predict the noise using the mean flow properties. Due to the fact that the turbulent combustion is a multi-scale problem, involving a wide range of length and time scales, the use of RANS-based prediction methods remains limited. Although RANS methods are useful for fluid dynamics computations, holding accurately up to some extent, they are usually not suitable or reliable for an accurate prediction of turbulent combustion.

The recent improvements in the processing speed of computers make the applicability of Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) to turbulent flows more feasible. However, due to a wide range of length and time scales present in turbulent flows, the use of DNS is still limited to low-Reynolds-number flows and relatively simple geometries. It is known that the number of grid points required for DNS is proportional to $Re^{9/4}$. Direct Numerical Simulation of high-Reynolds number flows of practical interest would necessitate high resolution grid requirements that are far beyond the capability of the most powerful computers available now days. In order to overcome the grid requirements issues, turbulence has to be modelled in order to perform simulations for problems of practical interest. Large Eddy Simulation, with a lower computational cost, is a promising alternative method to DNS, for simulations of high Reynolds-number flows. LES methods are capable of simulating flows at high Reynolds number, LES method being independent of Reynolds number. In Large Eddy Simulation, the large scales are directly solved, while the small scales are modelled. Since flow transition is an unsteady process, LES is probably the most affordable computational tool to be used, since it is the only way, other than DNS, to obtain a time-accurate unsteady solution.

II. Computational method and models

In the present studies, the combustion processes and instabilities in supersonic cavity flow are investigated using LES. The 3-D simulations were performed for Mach numbers $M_\infty = 1.5$, $M_\infty = 2.0$ $M_\infty = 2.5$ and $M_\infty = 3.0$. The computational domain is presented in Figure 1.
Large-eddy simulation is a result of the space-filtering operation applied to the Navier-Stokes equations. The filtered Navier-Stokes equations are:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_j\right) = -\frac{\partial \overline{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{\mathrm{Re}}\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} \tag{2}$$

where τ_{ij} is the subgrid scale stress (SGS) given by:

$$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j \tag{3}$$

and is modeled, where $\bar{u}_i$ is the velocity component of the resolved scales, $\bar{p}$ is the corresponding pressure and Re is the Reynolds number. The filtering procedure provides the governing equations for the resolvable scales of the flow field. Although the continuity equation (1) of the resolved quantities is equal to the original unfiltered one, the filtered momentum equation (2) includes an additional term for the non-resolvable sub-grid scale stresses τ_{ij}, which results from filtering the non-linear convective fluxes. The role of τ_{ij} is to describe the influence of the small–scale structures on the larger eddies.

The Large Eddy Simulation concept leads to a closure problem similar to the one obtained by the Reynolds-averaged approach. Hence it is possible to classify the turbulence models starting with zero-equation models and ending up with Reynolds stress models. The non-resolvable small-scale turbulence in LES is much less problem-dependent than the large–scale turbulence, such that the sub-grid scale turbulence can be represented by relatively simple models such as zero-equation eddy-viscosity models. The Smagorinsky model is an eddy viscosity model based on the Boussinesq approach, assuming that in analogy to the viscous stresses in laminar flows, the turbulent stresses are proportional to the mean velocity gradients or in a general sense to the large scale strain rate tensor $\bar{S}_{ij}$:

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = 2\nu_T \bar{S}_{ij} \tag{4}$$

In the present work the SGS proposed by Smagorinsky and Lilly is used. In this analysis the value of Smagorinsky constant was set to 0.1. The SGS stresses are related to the strain rate tensor by SGS viscosity, $\nu_{T:}$

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = 2\nu_T \bar{S}_{ij} \tag{5}$$

The SGS viscosity ν_T is given by:

$$\nu_T = \rho (C_s D_{wall} \Delta)^2 \left|\bar{S}\right| \tag{6}$$

where C_s is the Smagorinsky constant, D_{wall} represents the van Driest wall damping factor, Δ is the filter width and $\left|\bar{S}\right|$ represents the magnitude of the large-scale strain-rate tensor.

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_j}\right) \tag{7}$$

$$\left(\overline{S_{ij}}\,\overline{S_{ij}}\right)^{\frac{1}{2}} = \left|\bar{S}\right| \tag{8}$$

The sub-grid length l is assumed to be proportional to the filter width $\bar{\Delta}$:

$$l = C_s \bar{\Delta} = C_s \left(\Delta_x \Delta_y \Delta_z\right)^{\frac{1}{3}} \tag{9}$$

The filter width $\bar{\Delta}$ is correlated with a typical grid spacing given by the cube root of the cell volume. Taking into account the reduction of the sub-grid length l near solid walls, the length scale is usually multiplied by a Van driest damping function, as

$$l = C_s \bar{\Delta}[1 - \exp(-y^+/25)^3]^{0.5} \tag{10}$$

Although theoretical values of $C_s \approx 0.16$ for homogenous, isotropic turbulence can be found in literature, smaller values are usually applied in LES computations of non-homogenous and non-isotropic flows. All computations in the present work were carried out with a Smagorinsky constant of $C_s = 0.1$, which is a typical value for practical applications of Smagorinsky model.

More complex SGS models have appeared in the literature (for example, the dynamic SGS eddy viscosity models), but they are beyond the scope of the present work.

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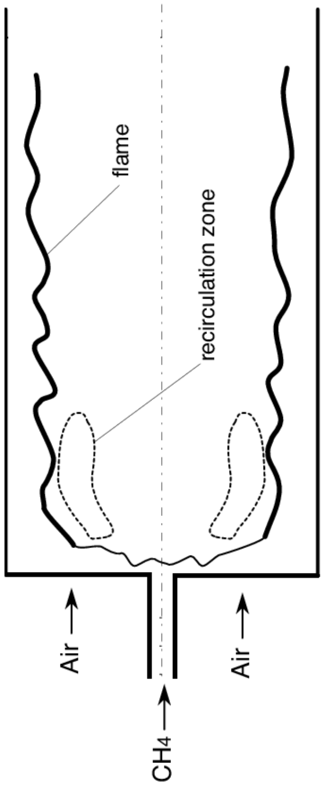


a. Schematic of the coaxial jet combustor

b. Computational domain

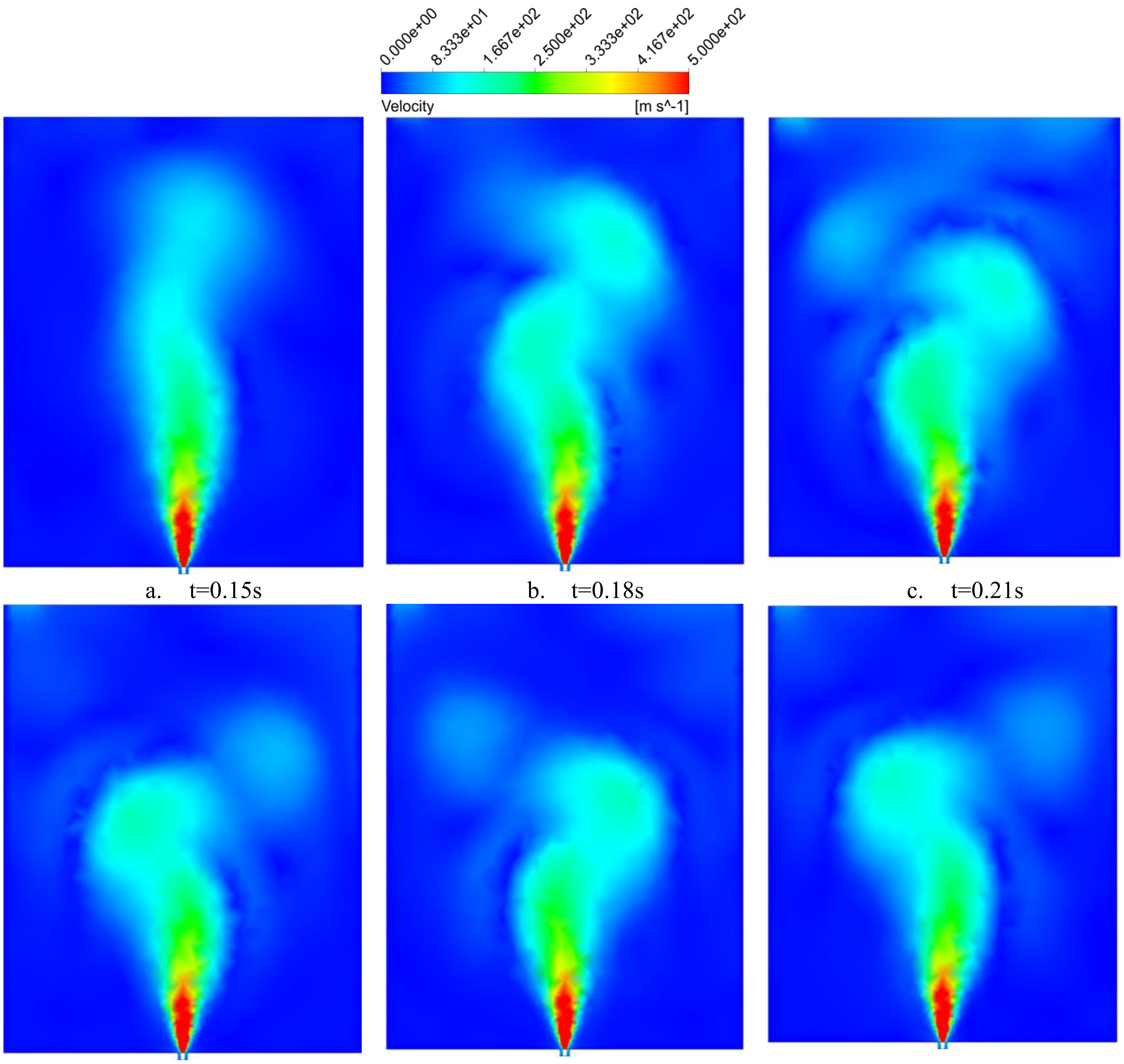
Figure 1. Coaxial jet combustor

III. Results and Discussion

Figure 2 present the time-varying velocity field at different instants in time. The analysis of the velocity field reveals the flame instability in time. Therefore, flame oscillations are seen at different instants in time. The interaction between the flame and freestream flow causes a breakup of the flame and pockets of turbulent eddies are observed at the tip of the flame. The analysis also reveals that the surrounding flow is highly turbulent and dominated by a wide-range of vortical structures. Therefore, Figure 3 reveals the presence of large vorticity levels in the region surrounding the flame. It is important noting here that the vortical structures oscillate in tandem with the flame and there is a continuous interaction between the vortical structures surrounding the flame and flame itself.

Figure 4 presents the temperature field inside the combustor. The analysis of the temperature field exhibits high values in the flame region. The flame temperature field also shows an oscillatory behavior as the velocity field. Thus, time-dependent oscillations of the temperature field are seen at different instants of time. The flame and temperature instabilities may lead to the thermosacoustic instabilities which impact the structure of the coaxial jet combustor.

Figure 5 presents the time-varying entropy inside the combustor. The analysis reveals the presence of the entropy in region of the flame. The analysis also reveals that the entropy field exhibits an oscillatory behavior similar to the temperature and velocity fields.



a. t=0.15s   b. t=0.18s   c. t=0.21s

d. t=0.33s   e. t=0.39s   f. t=0.39s

Figure 2. Velocity flow field

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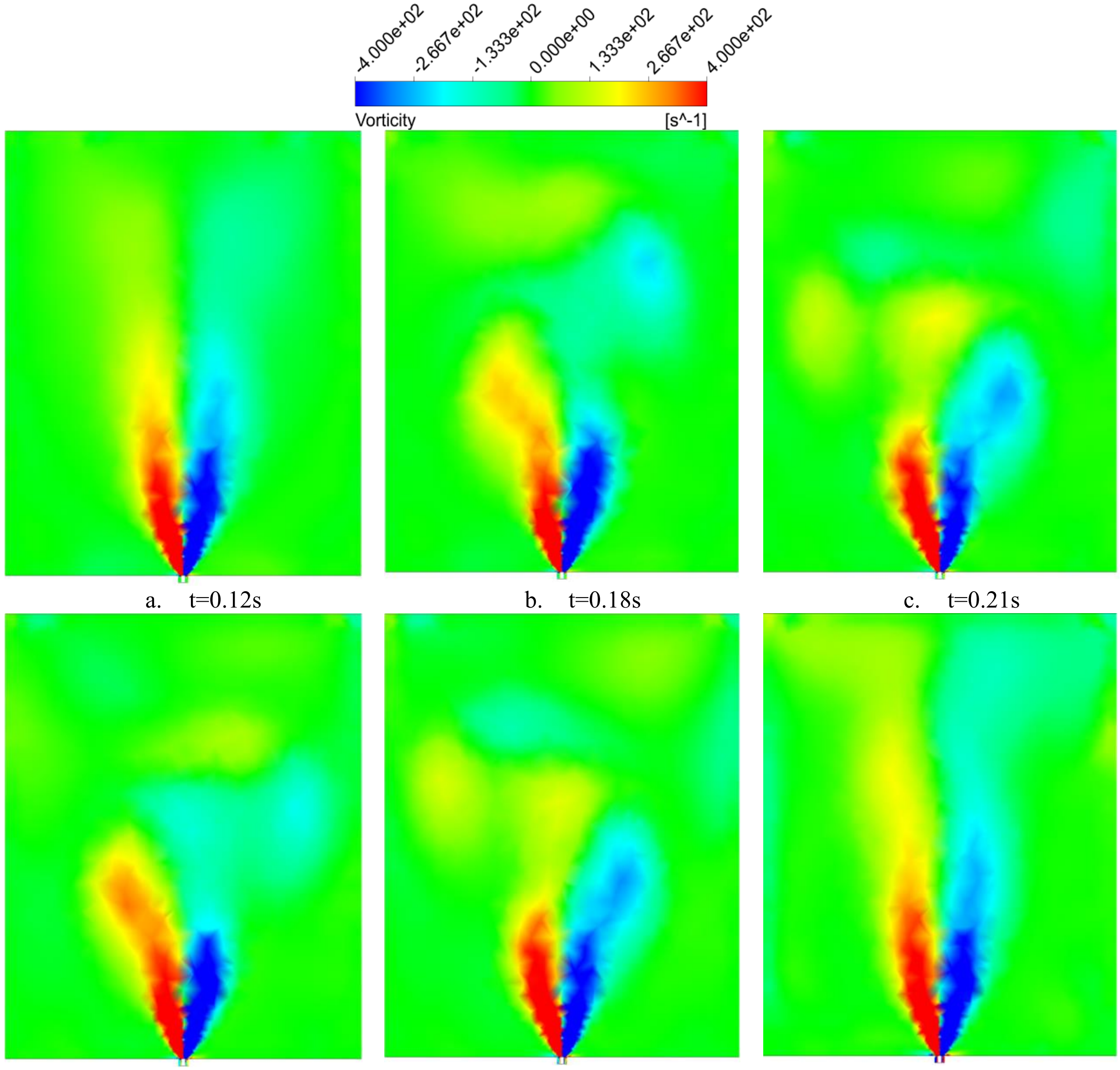

a. t=0.12s b. t=0.18s c. t=0.21s

d. t=0.36s e. t=0.42s f. t=0.39s

Figure 3. Vorticity flow field

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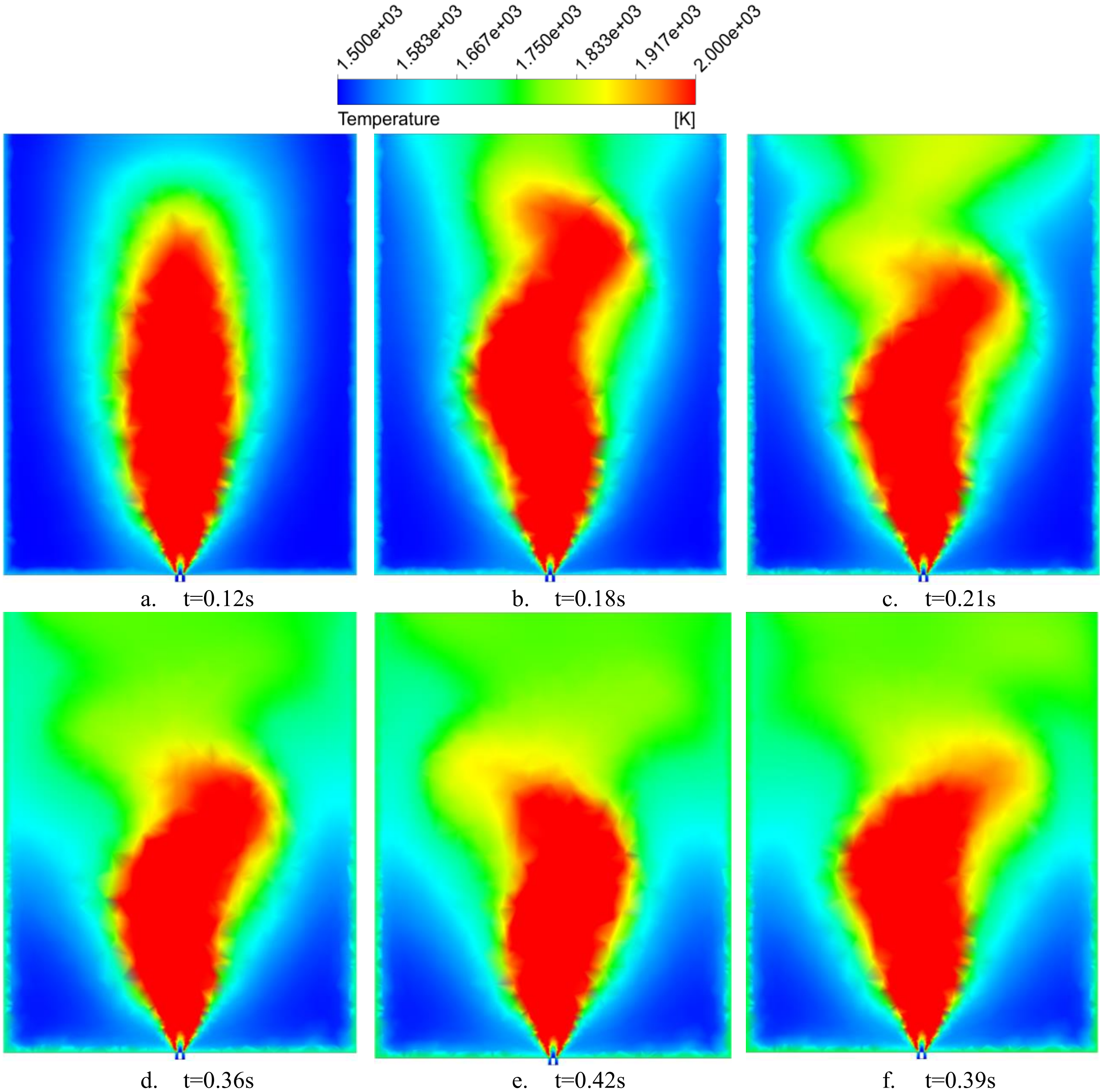

Figure 4. Temperature field

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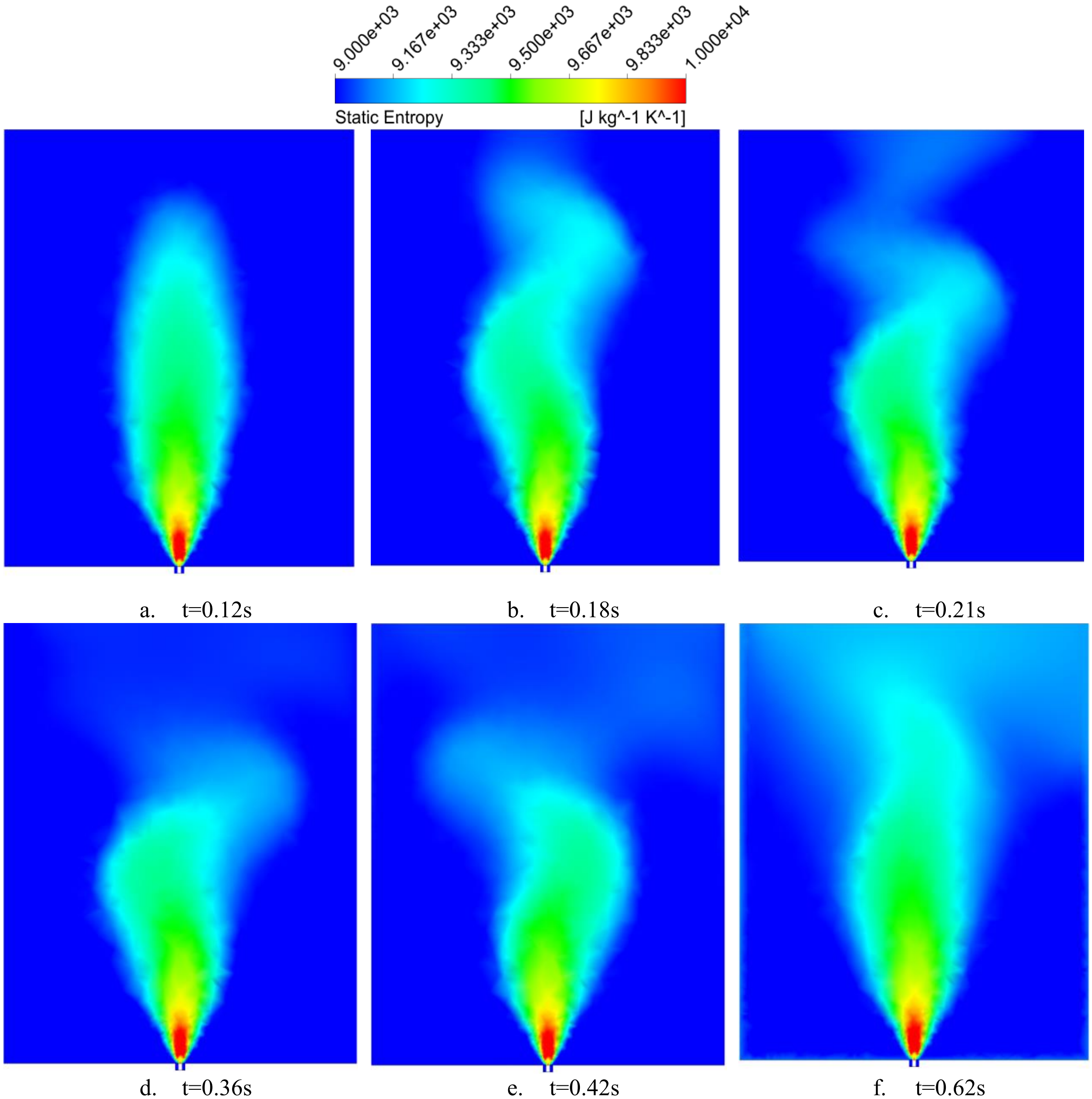
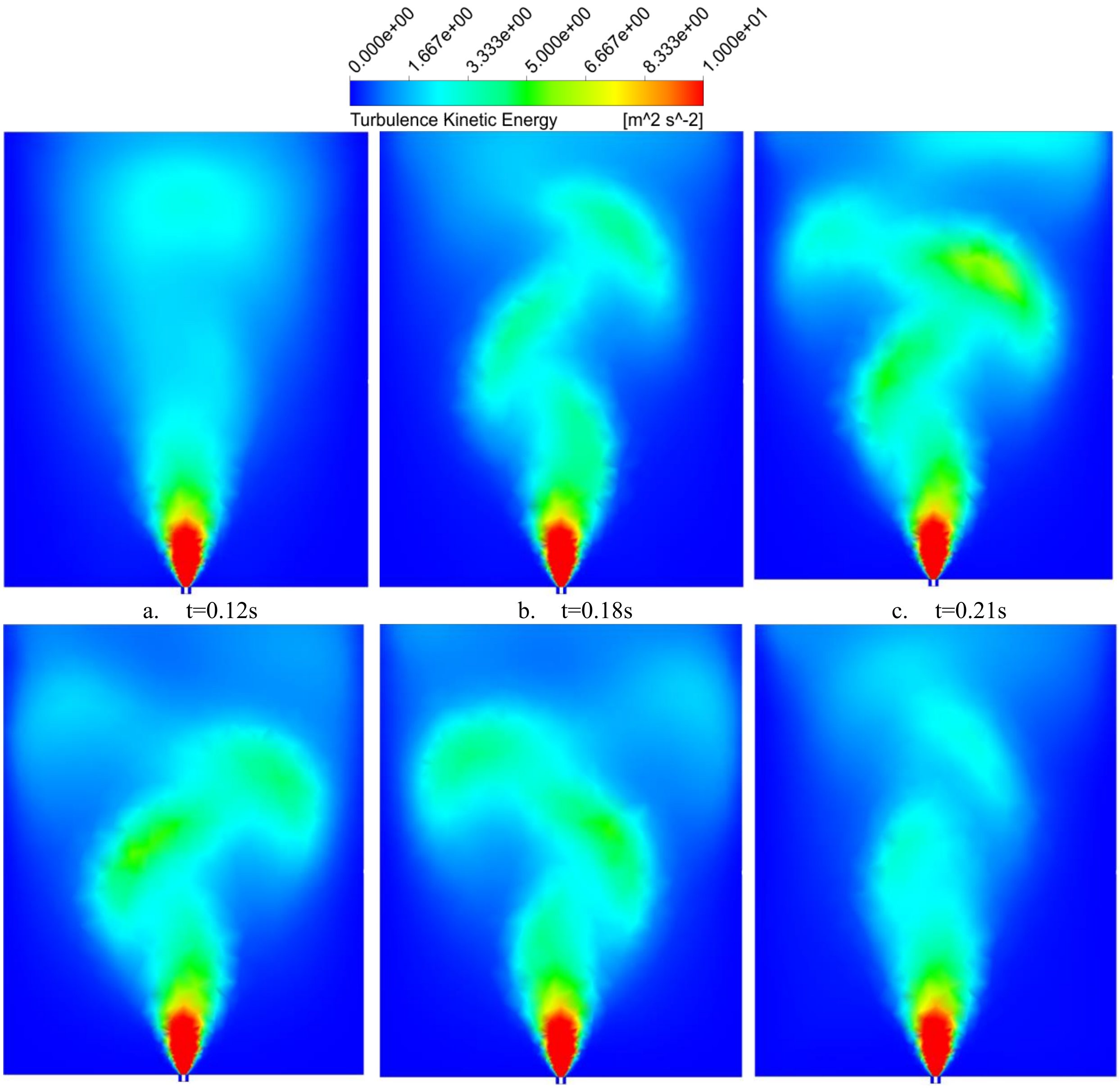


Figure 5. Entropy field



a. t=0.12s
b. t=0.18s
c. t=0.21s
d. t=0.36s
e. t=0.42s
f. t=0.62s

Figure 6. Turbulence kinetic energy

Figure 6 presents the time-varying turbulence kinetic energy inside the coaxial jet combustor. The analysis reveals the presence of highly turbulent flow inside the combustor. The turbulence kinetic energy also exhibits similar oscillations with the velocity and vorticity fields.

Figure 7 presents the time-varying of CH_4 mass fraction inside the coaxial jet combustor. Similar to the velocity and temperature fields, the CH_4 exhibits time-varying oscillations. The values of the CH_4 mass fraction decay from the inlet towards the core of the coaxial jet combustor.

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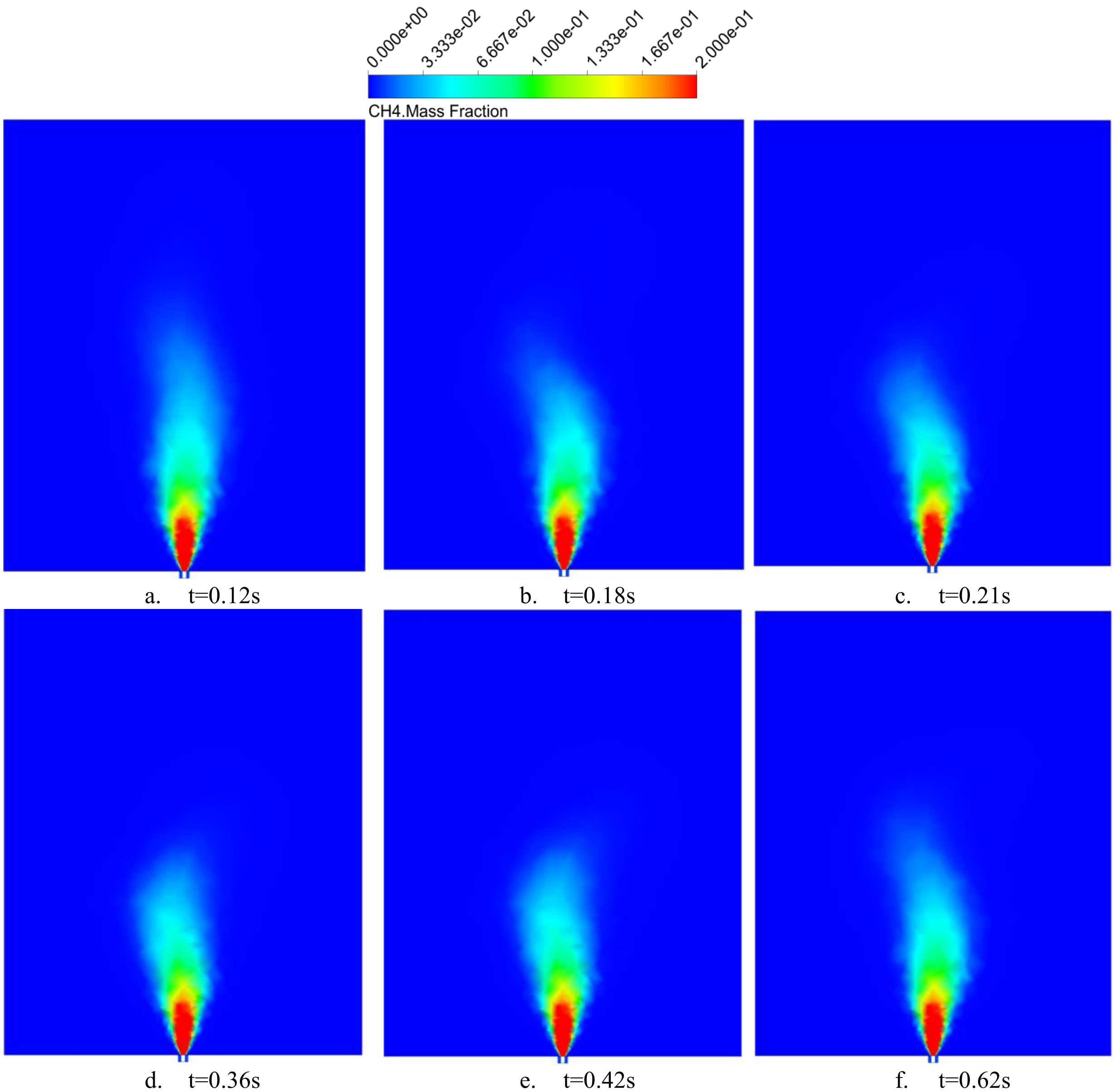

Figure 7. CH_4 mass fraction

IV. Conclusions

Combustion instabilities of coaxial jet combustor is computationally investigated using the large-eddy simulation (LES) approach. The study reveals that the LES approach captures very well the combustion phenomenon inside the coaxial jet combustor. The study also reveals that the flow variables velocity, temperature turbulence kinetic energy exhibit oscillatory motion. The analysis reveals the presence of a region of high level of temperature, NO and CO_2, inside the coaxial jet injector.

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