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Direct Numerical Simulation of Sound Generation by a Turbulent Premixed Flame

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Abstract

This paper presents a direct numerical simulation (DNS) study of sound generation by a conical, turbulent premixed flame. The flame is simulated in an unconfined domain using a high-order accurate solver whereby both the near and far fields are resolved. Single-step chemistry is used to reduce the computational cost. The presented results show that flame annihilation events are significant sources of noise, which is consistent with more fundamental works that have been undertaken previously by this group and others.

Introduction

Thermoaccoustic instability is a major challenge in developing low emission gas turbine combustors. This poorly understood phenomenon is commonly initiated due to the sound generated by the flame inside the combustor. The interaction of the reflected acoustic waves from the combustor's walls with the flame can introduce instability leading to failure in extreme cases. To address this problem, the mechanism of sound generation by turbulent flames need to be first understood.

It is known that fluctuations of the heat release rate play a significant role in combustion-generated sound, e.g. [4, 10, 11, 12, 14]. Furthermore, in a number of one- (1D) and two dimensional (2D) numerical studies [5, 11, 12, 13, 14], destruction of the flame surface area (known as 'flame annihilation') has been shown to have a significant contribution to the rate of change of heat release rate and therefore the generated sound. There are also several experimental studies demonstrating that destruction of the flame surface area can be viewed as a strong and important source of sound, e.g. [1, 7, 9].

Direct numerical simulation is a means to gain improved understanding of the sound generation mechanisms. However, to the best of our knowledge, DNS of noise generation by turbulent premixed flames has not been previously attempted. This may be due to the high computational cost of DNS in such cases as both near and far fields should be fully resolved. We therefore aim to address the gap in the literature by performing a DNS study of sound generation by a turbulent premixed flame. We will then investigate the role of annihilation events in the mechanism of sound generation in the simulated turbulent premixed flame.

Governing Equations

Using a single-step, irreversible chemical reaction, the governing equations for the conservation of mass, momentum, total energy, and deficient species mass fraction are respectively as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \rho u_j}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i}, \tag{2}$$

$$\frac{\partial \rho E_t}{\partial t} + \frac{\partial u_j(\rho E_t + p)}{\partial x_j} = \frac{\partial u_i \tau_{ij}}{\partial x_j} - \frac{\partial q_j}{\partial x_j}, \tag{3}$$

and

$$\frac{\partial \rho Y_F}{\partial t} + \frac{\partial \rho u_j Y_F}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D \frac{\partial Y_F}{\partial x_j}\right) - \dot{\omega}_F, \tag{4}$$

where x and t are the spatial coordinate and time respectively. In addition, ρ is the mixture density, u_j is the $j-$component of velocity, Y_F is the fuel mass fraction, p is the pressure, E_t is the total energy per unit mass (including sensible, kinetic, and chemical energy), q_j is the heat flux vector, and τ_{ij} is the $ij-$component of the viscous stress tensor. The quantities E_t, q_j (assuming constant heat capacity), τ_{ij} and p are given by,

$$E_t = \frac{p}{\rho(\gamma-1)} + \frac{1}{2} u_i u_i + Y_F Q, \tag{5}$$

$$q_j = -\lambda \frac{\partial T}{\partial x_j} - \sum_{k=1}^{N_s} \left(h_k^0 \rho D \frac{\partial Y_k}{\partial x_j} \right), \tag{6}$$

$$\tau_{ij} = \mu \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right], \tag{7}$$

and

$$p = \rho R T \sum_{k=1}^{N_s} \frac{Y_k}{M_k} = \rho \left(\frac{R}{M} \right) T, \tag{8}$$

where γ is the heat capacity ratio, Q is the heat of reaction per unit mass of reactant, h_k^0 is the chemical enthalpy of formation of species k evaluated at a reference temperature T_{ref}, μ is the dynamic viscosity, D is the binary mass diffusion coefficient, λ is the mixture thermal conductivity, R is the ideal gas constant, M_k is the species molecular weight, M is the mixture molecular weight, and δ_{ij} is the Kronecker delta. The variation of μ with temperature is modelled using a power-law,

$$\mu = \mu_{ref} \left(\frac{T}{T_{ref}} \right)^{0.76}, \tag{9}$$

where μ_{ref} is the fresh gas absolute viscosity. The fuel species reaction rate $\dot{\omega}_F$ may be obtained using the Arrhenius law,

$$\dot{\omega}_F = \Lambda \rho Y_F \ \exp\left[-\frac{\beta(1-\theta)}{1-\alpha(1-\theta)} \right], \tag{10}$$

Jet diameter	D
Domain size	15D × 16D × 16D
Grid resolution	1800 × 800 × 800
Mean inlet jet Mach number	0.4
co-flow Mach number	0.004
Non-dim. fresh mixture temperature	2.5
Heat release parameter (α)	3
Jet Reynolds number (Re)	4000
Inlet turbulence intensity ($u'/\bar{U}_j$)	0.1
δ_{th}/D	0.07
S_L/U_j	0.007
β	8.0
Da	19.44
Pr	0.75
Le	1.0

Table 1. The simulation parameters.

where

$$\Lambda = B\exp\left(-\frac{\beta}{\alpha}\right),\ \theta = \frac{T-T_u}{T_f-T_u}, \tag{11}$$

$$\alpha = \frac{T_f - T_u}{T_f}\ \text{, and } \beta = \frac{E_a(T_f - T_u)}{RT_f^2}. \tag{12}$$

Note that B is the pre-exponential factor, β is the Zel'dovich number, T_f is the adiabatic flame temperature, T_u is the fresh (unburned) mixture temperature, E_a is the activation energy and α is the heat release parameter.

Non-dimensional Variables

The following non-dimensional variables are defined:

$$Re_{ac}=\left(\frac{aL}{\nu}\right)_{ref},\ \text{Pr}=\left(\frac{\nu}{D_{th}}\right)_{ref},$$

$$\text{Le}=\left(\frac{D_{th}}{D}\right)_{ref},\ \text{and Da}=\left(\frac{\Lambda L}{a}\right)_{ref}. \tag{13}$$

Note that a is the sonic velocity, L_{ref} is the reference length which is equal to jet width D, Re_{ac} is the acoustic Reynolds number, Pr is the Prandtl number, Le is the fuel Lewis number, Da is the Damk*ö*hler number, D_{th} is the thermal diffusivity coefficient, and ν is the kinematic viscosity.

Numerical Method and Flow Configuration

The governing equations (1-4) are solved using a modified version of the numerical solver S3D [2] known as S3D-SC [6]. The solver features an 8^{th} order central differencing scheme for spatial derivatives, combined with a 6-stage, 4^{th} order explicit Runge–Kutta time integrator. It is fully parallelised using the MPI implementation. To suppress the numerical noise at high wave numbers, a 10th-order filter is applied every 10 time steps.

The computational domain is decomposed into a 3D structured Cartesian mesh. The boundary conditions are implemented based on 3D Navier-Stokes Characteristic Boundary Condition (3DNSCBC) [15]. All non-reflecting outflow boundaries are carefully treated to avoid spurious noise reflections.

A subsonic round jet of unburned premixed mixture (reactant) is injected into an open, hot environment at a temperature which is equal to the burned mixture's temperature (product). A coflow with a low velocity (1% of the jet mean velocity) surrounds the jet flame at the burned mixture's temperature to mimic natural convection around jet flames in real conditions. A velocity fluctuation, u', is imposed on the mean inlet velocity field using an auxiliary homogeneous isotropic turbulence obtained based on Passot-Pouquet energy spectrum [8]. The frozen turbulence field is added to the domain using the Taylor hypothesis. The computational, flow and flame parameters are summarised in table 1.

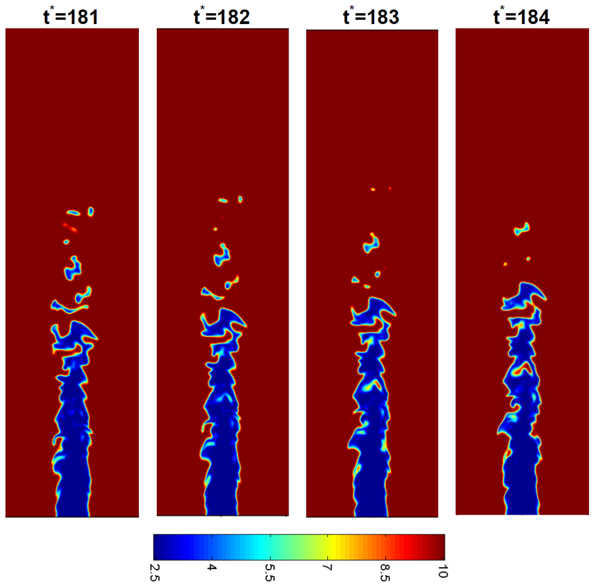

Figure 1. Several snapshots of dimensionless temperature field $T^* = T/[(\gamma-1)T_{ref}]$.

A uniform grid with a resolution of 8.250×10^{-3}D is distributed in the streamwise direction (x/D). While maintaining a uniform grid spacing of 8.250×10^{-3}D for $6 \leq |\ y/D\ | \leq 10$ and $6 \leq |\ z/D\ | \leq 10$, an algebraically stretched mesh with a stretching ratio of less than 2.5% is used in the transverse directions (y/D and z/D). Care was taken to ensure adequate resolution of the flame by having at least 8 grid points inside the flame thickness at all times. Moreover, the computational domain was long enough to properly capture the acoustic waves radiated by the flame.

Based on the prescribed inlet jet velocity and the streamwise domain length, a jet flow-through time is defined as $\tau_j = L_x/U_j$. The simulation was performed using a constant time step for $5\tau_j$ to provide a statistically stationary solution. The simulation required approximately 500,000 CPU-hours running on 7680 CPUs (Intel Xeon Sandy Bridge technology, 2.6 GHz) for 65 hours.

Results and Discussion

Flame Annihilation and Sound Production

Figure 1 shows the non-dimensional temperature field at several instants. As can be seen, the interaction of flame surfaces at downstream locations forms pockets of unburned gases. These pockets are consumed as they travel downstream. We refer to this phenomenon as 'flame island burn-out'.

To investigate the effect of the annihilation events on the produced sound, the dimensionless dilatation field $(D/a_{ref})\nabla.\vec{u}$ [3, 14] is shown in figure 2. The first striking observation is the presence of discrete monopolar sound sources. These sources clearly dominate the incoming noise at the inflow and originate some distance downstream of the nozzle.

Figure 3 shows the dilatation fields for several instants close to

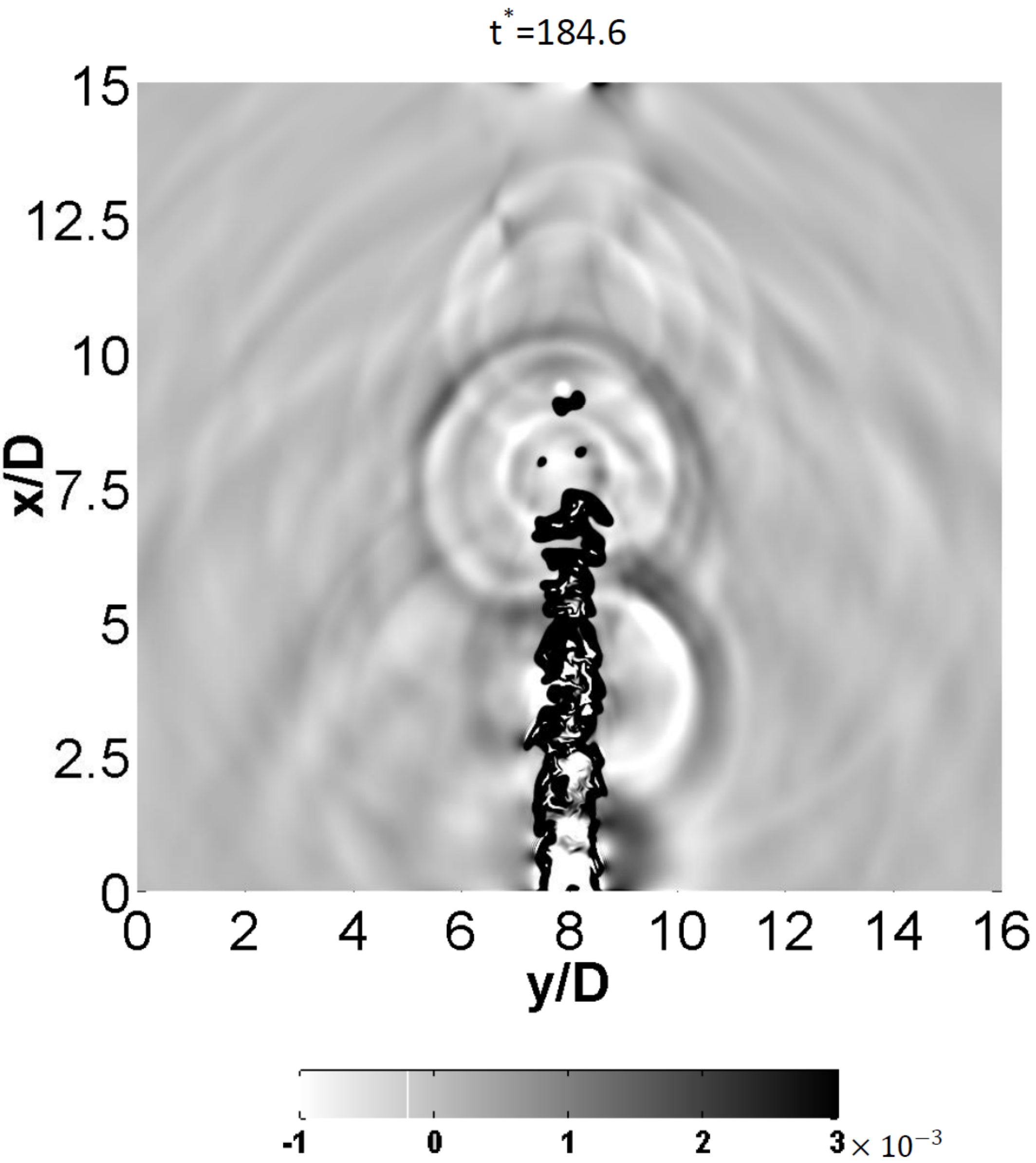

Figure 2. A slice of the dimensionless dilatation field $(L_{ref}/a_{ref})\nabla.\vec{u}$ located at the centre of the jet at dimensionless time $t^* = (t.a_{ref}/D)$=184.6.

the flame tip. As can be seen, the consumption of the pockets labelled A and B produce a monopolar acoustic wave. Our previous studies [13, 14] showed that such annihilation events are significant sound sources in acoustically excited laminar flames. This conclusion also appears to be valid for the turbulent flame presented in this paper. However, a more detailed analysis is required to determine the contribution of the flame annihilation to the overall radiated sound.

Conclusions

A direct numerical simulation (DNS) study of the sound generation by a turbulent premixed flame was presented in this paper. Single step chemistry model was used. Care was taken to fully resolve both near- and far fields. The computational domain was large enough to capture the range of the acoustic wavelengths. Three dimensional Navier-Stokes Characteristic Boundary Condition (3DNSCBC) was used at the outflow boundary to simulate non-reflecting boundary conditions. It was observed that interaction of flame surfaces creates pockets of unburned gases. These pockets were consumed as they moved further downstream and were shown to be strong monopolar sources of sound. It should be noted that a more detailed analysis is required to understand the importance of annihilation events in sound generation by the simulated turbulent flame. This is a topic of our future study.

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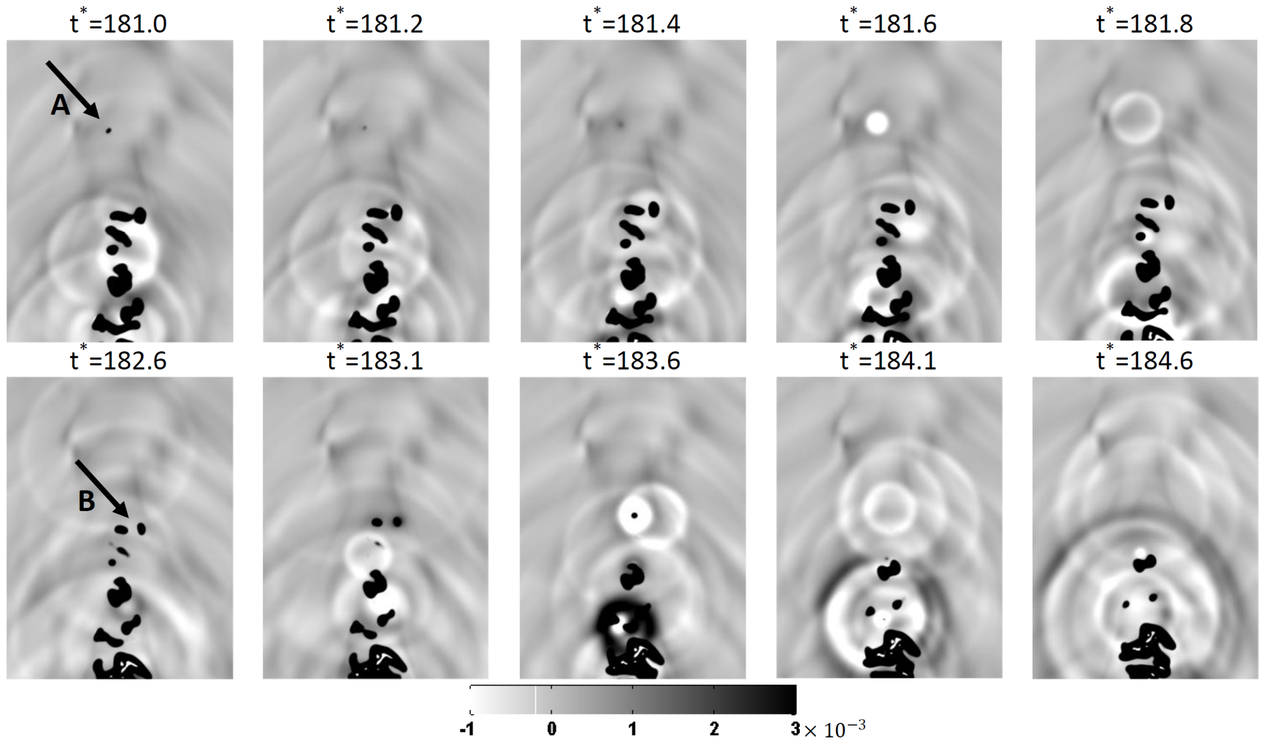

Figure 3. Several snapshots of the dimensionless dilatation field $(L_{ref}/a_{ref})\nabla.\vec{u}$.

References

[1] Candel, S., Durox, D. and Schuller, T., Flame interactions as a source of noise and combustion instabilities, in *Collection of Technical Papers-10th AIAA/CEAS Aeroacoustics Conference*, 2004, 1444–1454.

[2] Chen, J. H., Choudhary, A., De Supinski, B., DeVries, M., Hawkes, E., Klasky, S., Liao, W., Ma, K., Mellor-Crummey, J., Podhorszki, N., Sankaran, R., Shende, S. and Yoo, C., Terascale direct numerical simulations of turbulent combustion using s3d, *Comput. Sci. Discovery*, **2**, 2009, 015001.

[3] Colonius, T., Lele, S. K. and Moin, P., Sound generation in a mixing layer, *J. Fluid Mech.*, **330**, 1997, 375–409.

[4] Hurle, I., Price, R., Sugden, T. and Thomas, A., Sound emission from open turbulent premixed flames, *Proc. R. Soc. Lond. A*, **303**, 1968, 409–427.

[5] Jiménez, C., Haghiri, A., Talei, M., Brear, M. J. and Hawkes, E. R., Sound generation by premixed flame annihilation with full and simple chemistry, *Proc. Combust. Inst.*, 10.1016/j.proci.2014.05.140.

[6] Karami, S., Hawkes, E. R. and Talei, M., A direct numerical simulation study of a turbulent lifted flame in hot oxidizer, in *18th Australasian Fluid Mechanics Conference Launceston, Australia*, 2012, 8-12.

[7] Kidin, N., Librovich, V., MacQuisten, M., Roberts, J. and Vuillermoz, M., Possible acoustic source in turbulent combustion, in *Dyn. Reactive Syst. Part 1: Flames*, 1988, 336-348.

[8] Passot, T. and Pouquet, A., Numerical simulation of compressible homogeneous flows in the turbulent regime, *J. Fluid Mech.*, **181**, 1987, 441–466.

[9] Schuller, T., Durox, D. and Candel, S., Self-induced combustion oscillations of laminar premixed flames stabilized on annular burners, *Combust. Flame*, **135**, 2003, 525–537.

[10] Strahle, W. C., Combustion noise, *Prog. Energy Combust. Sci.*, **4**, 1978, 157 – 176.

[11] Talei, M., Brear, M. J. and Hawkes, E. R., Sound generation by laminar premixed flame annihilation, *J. Fluid Mech.*, **679**, 2011, 194–218.

[12] Talei, M., Brear, M. J. and Hawkes, E. R., A parametric study of sound generation by premixed laminar flame annihilation, *Combust. Flame*, **159**, 2012, 757 – 769.

[13] Talei, M., Brear, M. J. and Hawkes, E. R., A comparative study of sound generation by laminar, combusting and non-combusting jet flows, *Theor. Comp. Fluid Dyn.*, **28**, 2014, 385–408.

[14] Talei, M., Hawkes, E. R. and Brear, M. J., A direct numerical simulation study of frequency and Lewis number effects on sound generation by two-dimensional forced laminar premixed flames, *Proc. Combust. Inst.*, **34**, 2012, 1093–1100.

[15] Yoo, C. S. and Im, H. G., Characteristic boundary conditions for simulations of compressible reacting flows with multi-dimensional, viscous and reaction effects, *Combust. Theory Modelling*, **11**, 2007, 259–286.