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Numerical investigation of combustion noise in an open turbulent spray flame

Abhishek L. Pillai*, Ryoichi Kurose

Department of Mechanical Engineering and Science, and Advanced Research Institute of Fluid Science and Engineering, Kyoto University, Kyoto daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan

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ABSTRACT

The combustion noise generated by an open turbulent spray flame with Ethanol as fuel has been investigated using Direct Numerical Simulation (DNS). The multiphase reactive flow is simulated by means of an Eulerian-Lagrangian framework with two-way coupling. The turbulent gas-phase's governing equations are solved in an Eulerian framework, while the evaporating liquid fuel droplets are tracked in a Lagrangian framework. A two-step global reaction model is used for describing Ethanol combustion chemistry. The DNS solution has been validated against experimental data, and an overall good agreement with measurements is observed for the predicted flow field statistics of droplet velocities and corresponding fluctuations, as well as gas-phase excess temperature. Analysis of the spectral content of noise generated by the spray flame reveals its broadband nature, and predominance of the monopole combustion noise sources that arise from the fluctuating heat release rate is evident from the noise directivity effects. Furthermore, reduction in sound pressure levels of the high-frequency noise emissions with increasing distance from the nozzle exit, corresponding to decreasing emission angle to the flame axis is observed. Computed noise spectra of the turbulent spray flame are comparable to the direct combustion noise similarity spectrum.

1. Introduction

Modern gas turbine engines are being extensively used for applications, such as industrial power generation and aircraft propulsion. In many commercial Aero-engines as well as ground-based gas turbine engines, the fuel is injected inside their combustors in the form of liquid sprays. Hence, turbulent spray combustion of liquid fuels results in heat addition inside the combustors of these gas turbine engines. However, such turbulent combustion of fuel is accompanied by the emission of a considerable amount of undesirable noise, which is referred to as combustion noise. For combustion occurring in confinement, as is the case for gas turbine combustors, the total noise generated consists of direct and indirect combustion noise [1]. Direct combustion noise is produced by sources originating from the interaction between turbulence and chemical reactions that create heat release rate fluctuations [1]. The heat release rate fluctuations cause unsteady volumetric expansion and contraction of the reacting gases. On the other hand, indirect combustion noise arises when the entropy inhomogeneities (hot and cold spots) and vorticity inhomogeneities get accelerated as they are transported through the nozzle at the combustor outlet [2,3].

Recently, emphasis on the development of efficient lean-burn combustors with reduced emissions of NOx and greenhouse gases has increased. However, the noise emission from lean combustion is substantially louder, because it is inherently more unsteady [4,5]. Hence, combustion noise is one of the dominant sources of engine core noise [1]. Apart from manifesting itself as noise pollution in the environment, combustion noise is also responsible for a far more serious problem in gas turbine engines, viz. thermo-acoustic instability or combustion instability [6,7]. Inside the combustor, pressure perturbations generated by unsteady combustion are reflected at the boundaries of the combustor. Feedback interaction between these reflected pressure waves and the unsteady heat release induces combustion instability inside the combustor, which is characterized by the emission of discrete tones, loud noise and enormous pressure fluctuations. The vibrations thus induced can cause fatigue cracking of combustor components [5,8]. Combustion instability also induces the phenomenon of flashback which poses a potential hazard [9–11].

Experimental studies on the direct combustion noise emitted by turbulent premixed flames [e.g., 12,13] and turbulent non-premixed flames [e.g., 14–16] have been performed previously. Numerical investigations of combustion noise generated by turbulent premixed flames using Direct Numerical Simulation (DNS) have also been

* Corresponding author.
E-mail address: pillai.abhishek.43c@st.kyoto-u.ac.jp (A.L. Pillai).

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conducted [e.g., 17,18]. Furthermore, studies on the direct combustion noise in turbulent non-premixed flames using the hybrid LES/CAA (Large Eddy Simulation/Computational Aero-Acoustics) approach are also available [e.g., 19–21]. Recently, the Random Particle Mesh for Combustion Noise (RPM-CN) method, which is a hybrid Reynolds-averaged Navier-Stokes (RANS)/CAA approach, has also been applied for simulating combustion noise of open turbulent non-premixed jet flames [22,23].

Spray combustion is an intricate multiphase phenomenon involving the turbulent dispersion of liquid fuel droplets that are convected along with the carrier gas-phase, while undergoing evaporation and subsequent combustion reaction of the evaporated fuel with the oxidizer. The above processes occur simultaneously while influencing one another, and it is this coupling of the various process between different phases that makes the analysis of spray combustion quite complicated. Experimental [e.g., 24–27] and numerical studies (using LES) [e.g., 28–33] on spray combustion which focus on spray evolution, droplet dispersion, evaporation, inter-phase exchanges of mass, momentum and energy, turbulence-chemistry interactions, assessment of the predictive capabilities of the numerical approaches and models employed, and combustion instability have been conducted. However, investigations (both experimental and numerical) regarding the combustion noise generation in open turbulent spray flames are insufficient in existing literature. Hence, a better understanding of the combustion noise characteristics in turbulent spray flames/combustion is needed to clarify the underlying mechanism, and to address the issue of noise emissions by improving combustor designs and to prevent the induction of thermo-acoustic instabilities.

In this study, DNS of an open turbulent spray flame designated EtF3 with Ethanol as the fuel is performed. This flame has been experimentally investigated by [26], at the University of Sydney. The direct combustion noise generated by the unconfined spray flame is analysed in terms of the spectral content, directivity and sound pressure levels.

2. Direct numerical simulation

The simulation is DNS in the sense that no turbulence model nor any turbulence-chemistry interaction model has been used. In this investigation, however, a two-step global reaction mechanism is used for modelling combustion chemistry. In the DNS of turbulent spray flame, the carrier gas-phase is treated as an Eulerian continuum, and the dispersed fuel droplets are tracked as Lagrangian mass points. Description of the Eulerian-Lagrangian framework employed in the simulation is now presented.

2.1. Governing equations of gas-phase

The gas-phase is solved in an Eulerian framework and its governing equations are the conservation equations for mass, momentum, energy, and species mass fraction expressed as

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \boldsymbol{u}) = S_\rho, \tag{1}$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla\cdot(\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla P + \nabla\cdot\boldsymbol{\tau} + S_{\rho u}, \tag{2}$$

$$\frac{\partial \rho h}{\partial t} + \nabla\cdot(\rho h \boldsymbol{u}) = \frac{\partial P}{\partial t} + \boldsymbol{u}\cdot\nabla P + \nabla\cdot(\rho D_h \nabla h) + \boldsymbol{\tau}:\nabla\boldsymbol{u} + S_{rad} + S_{\rho h}, \tag{3}$$

$$\frac{\partial \rho Y_k}{\partial t} + \nabla\cdot(\rho Y_k \boldsymbol{u}) = \nabla\cdot(\rho D_k \nabla Y_k) + S_{comb,k} + S_{\rho Y_k}, \tag{4}$$

along with the equation of state for ideal gas. In Eqs. (1)–(4), ρ is the density, $\boldsymbol{u}$ is the gas-phase velocity, P is the pressure, $\boldsymbol{\tau}$ is the stress tensor, h is the specific enthalpy, and Y_k is the mass fraction of k^{th} chemical species. S_{rad} is the source term for radiative heat loss and $S_{comb,k}$ is the source term due to combustion reaction. D_h and D_k are the gaseous thermal diffusivity and mass diffusion coefficient of k^{th} species, respectively and are defined as

$$D_h = \frac{\lambda}{\rho c_p},\ D_k = \frac{\lambda}{\rho c_p}. \tag{5}$$

assuming unity Lewis number ($Le = 1$). Here λ is the thermal conductivity and c_p is the specific heat.

Furthermore, phase coupling between the gas-phase and dispersed-phase (fuel droplets) is achieved through the Particle-Source-In-Cell (PSI-Cell) approach [34]. In the concept of PSI-Cell approach, each computational cell is considered as a control volume, and each droplet is regarded as a source of mass, momentum and energy to the gas-phase. As the evaporating fuel droplets pass through a cell, the change in their mass, momentum and energy is treated as a source (or sink) to the gas-phase's mass, momentum and energy, respectively. This is done via. source terms S_ρ,$S_{\rho u}$,$S_{\rho h}$, and $S_{\rho Y_k}$ appearing in Eqs. (1)–(4), which represent the interactions between gas-phase and dispersed-phase (making two-way coupling possible), and they are evaluated as follows

$$S_\rho = -\frac{1}{\Delta V}\sum_N \frac{dm_d}{dt}, \tag{6}$$

$$S_{\rho u} = -\frac{1}{\Delta V}\sum_N \frac{dm_d \boldsymbol{u}_d}{dt}, \tag{7}$$

$$S_{\rho h} = -\frac{1}{\Delta V}\sum_N \frac{dm_d h_d}{dt}, \tag{8}$$

$$S_{\rho Y_k} = -\tfrac{1}{\Delta V}\sum_N \tfrac{dm_d}{dt} \text{ for fuel } (k = F),$$
$$= 0 \text{ for other chemical species} (k \neq F). \tag{9}$$

Here ΔV is the volume of each control volume (each computational grid cell) for the gas-phase calculation, m_d the fuel droplet mass, $\boldsymbol{u}_d$ the droplet velocity, h_d the specific enthalpy of a fuel droplet, and N the number of fuel droplets within a control volume.

2.2. Governing equations of dispersed-phase

For evaporation of the fuel droplets, a non-equilibrium Langmuir-Knudsen evaporation model [35–38] is employed since, non-equilibrium effects become significant for droplet diameters $d_d < 50$ μm [37]. The spray flame in this study is dilute as the volumetric loading of droplets is small, and hence, collisions and coalescence of droplets are neglected. The evaporating fuel droplets of the dispersed-phase are tracked individually using a Lagrangian framework [36–40] by solving the equations for droplet position $x_{d,i}$, velocity $u_{d,i}$, temperature T_d, and mass m_d as follows.

$$\frac{dx_{d,i}}{dt} = u_{d,i}, \tag{10}$$

$$\frac{du_{d,i}}{dt} = \frac{f_1}{\tau_d}(u_i - u_{d,i}) + g_i, \tag{11}$$

$$\frac{dT_d}{dt} = \left(\frac{Nu}{3Pr}\right)\left(\frac{c_p}{c_{p,d}}\right)\left(\frac{f_2}{\tau_d}\right)(T - T_d) + \frac{1}{m_d}\left(\frac{dm_d}{dt}\right)\frac{L_V}{c_{p,d}}, \tag{12}$$

$$\frac{dm_d}{dt} = -\left(\frac{Sh}{3Sc}\right)\frac{m_d}{\tau_d}\ln(1 + B_M). \tag{13}$$

Here, T is the gas-phase temperature, c_p is the specific heat of gas mixture, $c_{p,d}$ is the specific heat of fuel droplet, and g_i is the gravitational acceleration. The latent heat of vaporization L_V at T_d is calculated by

$$L_V = L_{V,T_{BL,atm}}\left(\frac{T_{CL} - T_d}{T_{CL} - T_{BL,atm}}\right)^{0.38}, \tag{14}$$