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Filtered density function simulation of a realistic swirled combustor

N. Ansari [a,c,*], P.A. Strakey [b], G.M. Goldin [c], P. Givi [a]

[a] Department of Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, PA 15261, USA
[b] National Energy Technology Laboratory, Morgantown, WV 26507, USA
[c] ANSYS Inc., Canonsburg, PA 15317, USA

Abstract

The scalar filtered mass density function (SFMDF) methodology is employed for large eddy simulation (LES) of the PRECCINSTA burner from DLR. This burner involves a swirling flow configuration and provides a good model of the combustor in gas turbines. In SFMDF, the effects of unresolved scalar fluctuations are taken into account by considering the probability density function of subgrid scale scalar quantities. The modeled SFMDF transport equation is solved numerically via a Lagrangian Monte Carlo scheme coupled with a finite volume flow solver on unstructured grids. The simulated results are assessed via comparison with experimental data and show reasonable agreements. This demonstrates the capability of SFMDF for LES of complex flows, and warrants future applications of the methodology for LES of practical combustor configurations. This work represents one of the first attempts in implementing FDF for LES of a practical gas turbine combustor.

Keywords: Large eddy simulation; Filter density function; Turbulent combustion; Monte Carlo methods

1. Introduction

There is a continuing need to extend the capabilities of large eddy simulation (LES) for prediction of flames in gas turbine combustion chambers [1,2]. The filtered density function (FDF) methodology has shown good potential for LES of turbulent reacting flows [3–6]. The fundamental property of FDF is that it accounts for the effects of the subgrid scale (SGS) chemical reactions in a closed form. Because of this property, the methodology has been used by several investigators; see Refs. [7–11] for reviews of recent contributions.

Most previous applications of the FDF have been limited to LES of "simple" flows, with the primary objective of demonstrating its functionality. With the recent development of a FDF simulator on unstructured grids [12,13], and with progress in highly scalable simulation of FDF [14,15], it is now possible to utilize the methodology for prediction of more "complex" flows [11,16,17]. The complexity refers primarily to the geometrical flow configuration which has been

* Corresponding author at: University of Pittsburgh, 636 Benedum Hall, Pittsburgh, PA 15261, USA. Fax: +1 (724) 514 5096.
E-mail address: naa56@pitt.edu (N. Ansari).

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the stumbling block in conducting FDF of practical combustors [1,11].

The objective of this work is to demonstrate and assess the applicability of scalar FDF for LES of a realistic gas turbine combustor. For that, the PRECCINSTA experimental burner from the German Aerospace Center (DLR) [18] is considered. The behavior of the burner is representative of an industrial gas turbine burner [1,2,11,19]. This lean flame has been the subject of broad investigations by several other computational methodologies [20–26] and it provides a convenient setting for model validations. In addition to examination of the simulated flow structure, the capability of FDF is assessed via comparison of the predicted Reynolds-averaged statistics of various flow quantities with experimental data.

2. Formulation

2.1. Flame configuration

The schematic diagram of the PRECCINSTA burner [18] is shown in Figure 1. It features a plenum, a swirler, a square combustion chamber and a cylindrical exhaust pipe. Dry air at ambient temperature is fed via the plenum with a diameter of 78 mm through radial swirler vanes to the burner nozzle. The fuel gas (CH_4) is injected into the air flow through 12 small holes within the radial swirler with high momentum to ensure good mixing before entering the combustion chamber. The combustion chamber consists of large quartz windows of 1.5 mm thickness held by steel posts in the corners thus creating a confinement with a square cross section of 85 mm $\times$ 85 mm and a height of 114 mm. The exit of the upright combustion chamber is conically shaped leading to a short central exhaust pipe with a contraction ratio of approximately 0.2. A central conical hub upstream of the combustion chamber stabilizes and controls the position of the flame. The total mass flow rate in the burner is 12.9 g/s.

The DLR experiments [18] are evolving with consideration of more cases and continuous extraction of more data. Two flame conditions (cases) are considered. The first is a “quiet flame” with the global equivalence ratio of 0.83. The second is an unsteady “pulsating flame” with the equivalence ratio of 0.7. Laser Raman scattering measurements of major species and temperature are available in vertical planes at eight different cross-sections downstream of the injector. The statistical uncertainties in the experimental measurements are less than 2.5% and 7%, respectively, for the temperature and most of the species, except for CO and H_2 where they are in the range 20–50%. Additionally, another “quiet flame” (case 3) is also considered in which the equivalence ratio is 0.75. Only velocity measurements are available for this case and there are no thermo-chemistry experimental data available. In the simulations, we have considered cases 1 and 3. Simulation of the “pulsating flame” via FDF is postponed for future work. The thermo-chemistry results below, therefore, correspond to the first case.

2.2. SFMDF formulation

The FDF formulation is based on the compressible form of the continuity, momentum, energy (enthalpy) and species conservation equations in a low Mach number flow [2,27]. These equations govern the space ($\mathbf{x} \equiv x_i$, $i = 1,2,3$) and time (t) variations of the fluid density $\rho(\mathbf{x},t)$, the velocity vector $u_i(\mathbf{x},t)$, the pressure $p(\mathbf{x},t)$, the species mass fractions $Y_\alpha(\mathbf{x},t)$ ($\alpha = 1,2,\ldots,N_s$) and the specific enthalpy $h(\mathbf{x},t)$. Fourier's law of heat conduction and Fick's law of diffusion are employed with the assumption of unity Lewis number. The molecular viscosity μ increases with temperature (T) to the power of 0.7. The magnitude of the molecular Schmidt (and Prandtl) number is $Sc = 0.75$. Implementation of LES involves the use of the spatial filtering operation [3]: $\langle Q(\mathbf{x},t)\rangle_\ell = \int_{-\infty}^{+\infty} Q(\mathbf{x}',t)G(\mathbf{x}',\mathbf{x})d\mathbf{x}'$, where $G(\mathbf{x}',\mathbf{x})$ denotes a filter function, and $\langle Q(\mathbf{x},t)\rangle_\ell$ is the filtered value of the transport variable $Q(\mathbf{x},t)$. In variable-density flows it is convenient to use the Favré-filtered quantity $\langle Q(\mathbf{x},t)\rangle_L = \langle \rho Q\rangle_\ell / \langle \rho\rangle_\ell$. We consider a filter function that is spatially varying with the properties $G(\mathbf{x}) \geqslant 0$ and $\int_{-\infty}^{+\infty} G(\mathbf{x})d\mathbf{x} = 1$. The transport variables satisfy the conservation equations of mass, momentum, energy and species mass fractions [27]. The filtered form of these equations are:

$$\frac{\partial\langle\rho\rangle_l}{\partial t} + \frac{\partial\langle\rho\rangle_l\langle u_j\rangle_L}{\partial x_j} = 0 \tag{1}$$

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

$$\frac{\partial\langle\rho\rangle_l\langle\phi_\alpha\rangle_L}{\partial t} + \frac{\partial\langle\rho\rangle_l\langle u_j\rangle_L\langle\phi_\alpha\rangle_L}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left\langle\gamma\frac{\partial\phi_\alpha}{\partial x_j}\right\rangle_l\right) - \frac{\partial M_j^\alpha}{\partial x_j} + \langle\rho S_\alpha\rangle_l \tag{3}$$

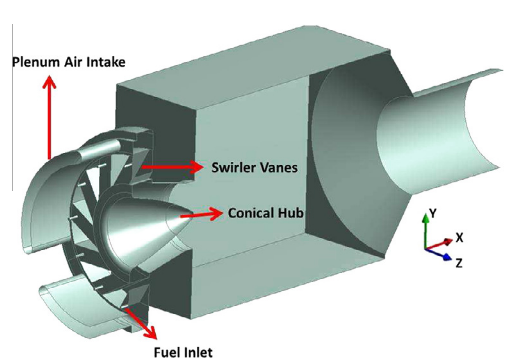

Fig. 1. Schematic of the PRECCINSTA burner [18].

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