Applied Thermal Engineering 110 (2017) 202–212

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Numerical investigation of turbulent swirling flames with validation in a gas turbine model combustor

Ali Cemal Benim [a,*], Sohail Iqbal [a], Wolfgang Meier [b], Franz Joos [c], Alexander Wiedermann [d]

[a] Center of Flow Simulation (CFS), Department of Mechanical and Process Engineering, Duesseldorf University of Applied Sciences, Josef-Gockeln-Str. 9, D-40474 Duesseldorf, Germany
[b] Institute of Combustion Technology, German Aerospace Centre (DLR), Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany
[c] Laboratory of Turbomachinery, Helmut Schmidt University, Holstenhofweg 85, D-2208 Hamburg, Germany
[d] Engineering Gas Turbines, MAN Diesel and Turbo SE, Steinbrinkstr. 1, D-46145 Oberhausen, Germany

HIGHLIGHTS

- LFM and EDC combustion models are applied to gas turbine combustor swirl flame.
- LES and URANS turbulence models are applied to gas turbine swirl flame.
- Predictions are validated by comparisons with experiments.

ARTICLE INFO

Article history:
Received 19 May 2016
Revised 29 July 2016
Accepted 22 August 2016
Available online 23 August 2016

Keywords:
Turbulent swirling flames
URANS
LES
EDC
LFM

ABSTRACT

Numerical investigation of turbulent swirling flames is performed in a model gas turbine combustor. The calculations are performed using the CFD code OpenFOAM. Large Eddy Simulation (LES) approach based on the Smagorinsky model is used as the main turbulence modelling strategy, whereas Unsteady Reynolds Averaged Numerical Simulations (URANS) are also applied, employing the Shear Stress Transport model as the turbulence model. Turbulence-chemistry interactions are modelled by the Eddy Dissipation Concept (EDC) and the Laminar Flamelet Model (LFM). In EDC, a three-step global reaction mechanism is used. In LFM, limitations of the standard non-premixed approach, based on the mixture fraction and the scalar dissipation rate, for lifted flames like the present one, is overcome by adding the progress variable as an additional dimension to the flamelet libraries. URANS is applied only with combination with LFM. LES is applied in combination with EDC and LFM. Special attention is paid to obtaining an adequate grid resolution. Predictions are compared with measurements. It is observed that LES provides a better accuracy compared to URANS, whereas the latter may still be seen useful, since its computational time is shorter. For LES, it is observed that EDC provides a similar, or even slightly better overall-accuracy compared to LFM. On the other hand, it is observed that LFM requires substantially shorter computational times compared to EDC. This makes LFM attractive especially for LES of real combustors requiring much larger grids and/or for cases where a detailed reaction mechanism is of interest.

1. Introduction

Modern gas turbines are to provide high efficiency, reliability and stability, while meeting strict low emission requirements, with emerging additional requirements such as fuel flexibility. In that respect, the combustor is obviously a core component, and a detailed understanding of the complex flow, heat and mass transfer processes in the flame is of great importance. Experimental investigation of gas turbine combustion is difficult and can provide only limited information due to practical limitations. Numerical simulations can provide detailed insight and reduce the number of costly experiments. Nevertheless, the highly complex processes in the combustor are difficult to model and the simulations are afflicted with inaccuracies. Thus, development of mathematical and numerical models for gas turbine combustion and their experimental validation has been a continuous endeavor, to which the present work is aimed to provide a contribution.

In the simulation of gas turbine combustion, one of the main challenges is turbulence modelling, which is also one of the main focuses of the present study. In gas turbine combustors, a high degree of swirl is imparted to the main combustion air for inducing

* Corresponding author.
E-mail addresses: alicemal.benim@hs-duesseldorf.de (A.C. Benim), sohail.iqbal@hs-duesseldorf.de (S. Iqbal), wolfgang.meier@dlr.de (W. Meier), joos@hsu-hh.de (F. Joos), alexander.wiedermann@man.eu (A. Wiedermann).

http://dx.doi.org/10.1016/j.applthermaleng.2016.08.143
1359-4311/

Nomenclature

C	reaction progress variable [–]
l_K	Kolmogorov length scale [m]
p	static pressure [Pa]
R_j	reaction rate for species j after chemical kinetics [s^{-1}]
S_j	source/sink term of transport equation for species j [$kg\ m^{-3}\ s^{-1}$]
T	static temperature [K]
t	time [t]
Y_i	mass fraction of species j [–]
y^+	wall distance non-dimensionalized by wall shear stress, density and viscosity [–]
Z	mixture fraction [–]

Greek symbols

β	beta PDF [–]
Δ	local finite volume cell size [m]
ε	dissipation rate of turbulence kinetic energy [$m^2\ s^{-3}$]
Υ^*	mass fraction occupied by fine structures [–]
ν	kinematic viscosity [$m^2\ s^{-1}$]
ρ	density [$kg\ m^{-3}$]
τ^*	time scale corresponding to fine structures [s]
ϕ	thermo-chemical variable to be extracted from flamelet libraries [–]
χ	scalar dissipation rate [s^{-1}]
ψ	reacting fraction of fine structures [–]

Superscripts

~	Favre averaged/filtered value
–	Reynolds averaged/filtered value
"	Favre fluctuational value
*	belonging to fine structures
0	belonging to surroundings

Subscripts

b	burnt
st	stoichiometric
u	unburnt

Abbreviations

EDC	Eddy Dissipation Concept
GI	Grid Index
IRZ	Inner Recirculation Zone
LFM	Laminar Flamelet Method
LES	Large Eddy Simulations
PDF	Probability Density Function
RANS	Reynolds-Averaged Numerical Simulations
RMS	Root Mean Square
SST	Shear Stress Transport model
URANS	Unsteady RANS

a vortex breakdown recirculation zone along the combustor axis that ensures high combustion efficiency and flame stability. In highly swirling flows, however, due to the effects of flow curvature and pressure gradient onto the Reynolds stresses, which lead to an increased anisotropy, turbulence modelling becomes especially challenging [1]. For investigating turbulence modelling in an isolated manner (without the interactions with the combustion modelling), isothermal turbulent swirling flow in a model combustor (the same model combustor used in the present study) was analyzed in the initial phase of the investigation, as a continuation of a series of validation studies of the present authors [2–5], where Reynolds Averaged Numerical Simulations (RANS), Unsteady RANS (URANS) and Large Eddy Simulation (LES) turbulence modelling approaches were applied. In the great majority of LES formulations found in the literature, the filter size is chosen to be proportional to the grid size. Thus, for an LES study to be meaningful, a sufficiently large portion of the turbulent scales needs to be resolved by the computational grid. Pope [6] suggests, e.g. that 80% of the turbulent kinetic energy should be resolved by the grid remote from the wall. In the previous applications of LES to gas turbine combustors, the adequacy of the applied grid resolution was addressed very seldom. In their LES investigation of a model combustor, Jiang and Campbell [7] showed that their grid was sufficiently fine, without, however, investigating the effect of grid resolution on the accuracy. This issue, i.e. the effect of grid resolution on the accuracy of LES predictions was analyzed in detail in the above-mentioned preliminary investigation [5], guiding the grid generation for the present analysis.

Modelling of the turbulence-chemistry interaction is the further main challenge, of course. Lörstad et al. [8] analyzed the reacting flow in the Siemens SGT-800 burner experimentally and numerically applying RANS and LES approaches, along with an Eddy Dissipation Concept (EDC) type combustion model, a focus of the work being on the effect of burner fuel distribution on flame dynamics. A recent study on URANS and LES modelling of gas turbine combustion for a Siemens scaled combustor was presented by Goldin et al. [9] using the flamelet generated manifold model as combustion model with LES and turbulent flame speed models with URANS. They found that LES predictions of mean and rms axial velocity, mixture fraction and temperature did not show much improvement over the RANS. Again recently, ALSTOM's reheat combustor was successfully analyzed by Kulkarni et al. [10] applying a novel combustion model based on a composite reaction progress variable, along with a tabulated chemistry approach and the stochastic-fields turbulence-chemistry interaction model.

A method, which is found to be adequate in modelling turbulence-chemistry interaction is the Eddy Dissipation Concept (EDC) [11]. A drawback of EDC is, however, that an individual transport equation needs to be solved for each species, leading to an increase in computational demand in proportion with the considered number of species. Integration of the reactor equations for each cell is a further cause that increases computational times. For meeting the current demands of combustion technology, reaction mechanisms with always increasing level of sophistication are required that incorporate a rather large number of species. In combination with computationally demanding turbulence modelling approaches such as URANS and LES, which are necessary for sufficient accuracy as discussed above, the computational costs become extremely high, especially for real applications in industrial development environment. On the other hand, the Laminar Flamelet Method (LFM) [12], provides a very efficient way of considering detailed reaction kinetics in turbulent combustion, where a complete detailed reaction mechanism can be incorporated via a few variables that describe flamelet characteristics. Although the validity of the LFM for gas turbine combustion was questioned in the past, based on Damköhler number arguments, it was shown, later [13,14], that purely dimensional arguments neglecting the