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Research Paper

Comparative study of non-premixed and partially-premixed combustion simulations in a realistic Tay model combustor

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HIGHLIGHTS

- Combustion in a realistic Tay model combustor is simulated.
- Performance of three combustion models is reported.
- Predicted temperature and species concentrations are compared with experiment.
- Reasonable flame shape is simulated by RSM invoking a partially premixed model.
- ZTFSC model outperformed ECFM model by accurately estimating the progress variable.

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ABSTRACT

A comparative study of two combustion models based on non-premixed assumption and partially premixed assumptions using the overall models of Zimont Turbulent Flame Speed Closure Method (ZTFSC) and Extended Coherent Flamelet Method (ECFM) are conducted through Reynolds stress turbulence modelling of Tay model gas turbine combustor for the first time. The Tay model combustor retains all essential features of a realistic gas turbine combustor. It is seen that the non-premixed combustion model fails to predict the combustion completely due to an incorrect assumption of diffusion flame scenario invoking infinitely fast chemistry in complicated flow environments while the two partially premixed combustion models accurately predict the flame pattern in the primary region of the combustor. The ZTFSC model outperformed the ECFM model by producing a better temperature agreement with the experimental result. The latter model predicts lower temperature due to the underestimation of reaction progress. Additionally, a cross-comparison of the present RSM prediction invoking ZTFSC model with LES prediction reported in the literature is conducted. The former produces more accurate species concentration and flame pattern than the latter. This is mainly due to the incorrect assumption of non-premixed combustion used in LES prediction reported in the literature. It is interesting to find that when non-premixed combustion model is used for both RSM and LES predictions, the LES predicts higher temperature closer to the injection nozzle of combustor than the RSM model, though the flame shape in both cases is incorrect. This is mainly due to the fact that the traditional RANS model dissipates the energy of swirling flow too fast in the primary region of the combustor. The weaker centre recirculation zone (CRZ) created by vortex breakdown recirculate less air to the area near the injection nozzle resulting in fuel rich combustion. It indicates that the temperature difference between predicted results using RSM in conjunction with ZTFC model and experimental results can be improved by using less energy dissipating turbulence models such as scale resolving simulation (SRS).

1. Introduction

The advent of Gas-Turbine for military purposes tracks back to 1940s, and it is subsequently used for aviation and later for ground level power [1]. The main challenge of aviation industries nowadays is the efficiency, stability of combustion and pollutant control, such as the emission of carbon dioxide (CO_2), nitrogen oxide, and sulphur dioxide. In order to design combustors with desired features and meet with relevant criteria, improved understanding of turbulent combustion through both realistic experimental observation and numerical simulation and validation is required. The former alone is expensive for industries before a more cost-effective numerical prediction is performed. However, the accuracy

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of the numerical simulation is doubtful as it is highly dependent on the turbulence and combustion models, i.e. the mixing and chemical reactions. To improve the reliability of simulations, turbulence models which are able to resolve the majority of turbulence features together with the combustion models which can incorporate detailed chemical reactions are developed under more realistic assumptions.

Due to the complexity of a realistic gas turbine combustor, most researchers focused on performing CFD simulation in a combustor-like burner where fuel and oxidizers are injected separately and no additional oxidizers are injected from other inlets [2–6]. The non-premixed combustion models which employ the infinitely fast chemistry assumptions are commonly used to predict such diffusion flames and are presumed to be an effective model in more complicated flow configuration. While, in a realistic gas turbine combustor, two major complexities make the non-premixed combustion model incorrect: the primary jets which introduce extra oxidizer to premixed mixtures and the extended flame residence time dominated by the strong swirling flow. Hence, the non-premixed combustion models are incorrect propositions when they are used in realistic gas turbine combustors where partially premixed flame occurs due to extra reactants from other inlets.

In a realistic gas turbine combustor, when primary jets introduce extra oxidizers into the premixed mixtures, the local status of premixed mixtures is assumed to be fully burnt if infinitely fast chemistry is assumed. However, in reality, chemical reactions are never infinitely fast. The local reactions amongst mixtures/reactants are only partially progressed which is tracked through the so-called progress variable. Besides, other than the extra oxidizer introduced by primary jets, the cooling airs from porous walls of realistic combustor further reduce the confidence of using non-premixed models. Although the flow rate from the porous wall is relatively low compared to the mainstream, and is commonly assumed not to be involved in any reactions, it is argued that part of these flow is actually brought into self-ignition region by the strong centre recirculation, and they do influence the reactions due to the extended flame residence time. It might be concluded that the more complex the flow configuration is, i.e., with the strong swirling flow and multiple inlet jets, the worse the performance of non-premixed combustion models will be due to the infinitely fast chemistry assumption.

In the past, many researchers have employed non-premixed combustion models to interpret the reactions in realistic gas turbine combustors where partially premixed flame occur. Although some predictions employing non-premixed assumptions are seen in reasonable agreement with experimental results particularly those using large eddy simulation (LES), the flame pattern predicted is incorrect mainly in the primary region where two side flames near the combustor walls are predicted which is inconsistent with experimental result [7–9]. Besides, the use of LES requires huge computational power and is unaffordable for most industrial problems. On the other hand, the far less computational power required Reynolds average Navier-Stoke (RANS) method fails to predict the reacting flow in realistic gas turbine combustors accurately [10]. The principle cause is attributed to the use of the unsuitable non-premixed combustion model rather than the problem of widely used RANS models. In a simple burner, both scale resolving simulation (SRS) and RANS methods are seen to provide acceptable results with the former showing a better agreement [11,12].

Within the partially premixed combustion model, the status of local mixtures: either burnt, unburnt or partially burnt, is determined by tracking the propagation of the flame front. The burnt mixtures behind the flame front are treated similarly as in a diffusion (or non-premixed) flame, while the unburnt regions ahead of flame front are represented by cold mixtures. To track the flame front propagation, a transport equation of progress variable C is solved. The model has been applied to many simple combustor-like burners [2,13–18], but far less attention has been paid on the performance of this model in a realistic combustor. In addition, there is a lack of comparative studies on the performance of partially premixed combustion and non-premixed models in complicated flow configurations and most comparisons are only performed in a simplified burner which provides limited confidence for applying these models to realistic gas turbine combustors.

To compensate for these gaps, a realistic Tay gas turbine combustor which includes complicated features such as fuel injector, swirler, primary holes, dilution holes, discharge nozzle, and porous wall is simulated in this paper. The objectives of the current paper are first to investigate and provide remedies to the deficiencies that have been observed in past simulation [7] of realistic gas turbine combustors, and second to demonstrate an effective and efficient combustion model for predicting realistic gas turbine combustors by comparing the performance of the widely used non-premixed with partially premixed combustion models. The Reynolds stress turbulence model is chosen to solve the mixing problem, and steady laminar flamelet modelling (SLFM) is chosen to simplify chemical reactions. Pre-PDF (probability density function) method is employed for turbulent combustion interaction. To reduce the uncertainties that might be induced by chemistries, 247 chemical reactions and 50 species are employed to represent the full chemistries involved in the combustion of propane [19]. The flame front propagation in the partially premixed combustion model is tracked by solving a transport equation for the density weighted mean reaction progress variable.

2. Mathematical model

In this study, to predict the turbulent combustion in a realistic gas turbine combustor, the Reynolds Stress Model (RSM) is used to describe the mixing problem. The model is seen to provide better performance in simulating the strong swirling flow by abandoning the Boussinesq approximation for 2nd order moments and solving six Reynolds stress of τ_{ij} appearing in 3D RANS momentum equations directly. As the main objective of this study is to investigate the performance of different combustion models in gas turbine combustor where stationary flow assumption can be utilized, the RSM model is chosen for the very fast turn-around and far less computational resources requirements compared to inherently transient methodologies such as LES, and DES.

2.1. Non-premixed combustion

In the non-premixed flame, fuel and oxidizer are injected into the combustion chamber separately. The reaction rate is mainly controlled by the rate of mixing of fuel and oxidizer, and therefore, the generated flame due to this process is also called diffusion flame. The non-premixed combustion is said to be rate limiting process as the regimes of modelling this combustion requires the consideration of both reaction time and mixing time, and which is described by Damkohler number $Da = \tau_t/\tau_c$. Poinsot and Veynante [20] introduced a regime diagram for non-premixed flame according to the Damkohler number and the turbulence Reynolds number $Re_t = u'l_t/\nu$ shown in Fig. 1.

The figure divides the turbulent non-premixed combustion problem into three regimes.

(A) When the chemical reaction time is much smaller than mixing time, i.e. for fast chemistry, the reactive layer of the flame is assumed to be thinner than the diffusion layer.