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# Numerical investigation of flame structure and blowout limit for lean premixed turbulent methane-air flames under high pressure conditions

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## HIGHLIGHTS

- An efficient tool to predict the behavior of lean flames near extinction is devised.
- Chemistry-turbulence interactions can be fairly captured by using simplified models.
- Baseline Reynolds Stress Model (RSM) yields good prediction of mean flow.
- Effects of operating parameters on flame structure near lean blowout are reported.

## ARTICLE INFO

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Lean blowout
Lean premixed
Methane-air
Turbulence

## ABSTRACT

With the forecast of rise in the energy usage, it is imminent that the concentration of toxic emissions such as carbon monoxide (CO) and oxides of nitrogen (NOx) in the ecosystem will increase. One of several industrial techniques to mitigate the emission levels is lean premixed combustion. However, this combustion mode often leads to the problem of Lean Blowout (LBO), which is not well understood. The present study attempts to devise an effective and computation-friendly industrial tool to predict the behavior of lean flames near extinction in a combustion chamber and estimate the lean blowout limits under high temperature and high pressure conditions. Utilizing a tabulated chemistry approach in combination with Reynolds Averaged Numerical Simulation (RANS) turbulence model, extensive validation is performed comparing plain and reacting flow simulation results with the experimental data of laboratory-scale burner at Paul Scherrer Institute (PSI). A modified Flamelet Generated Manifold (FGM) combustion model in conjunction with Reynolds Stress Model (RSM) turbulence model was found to give an accurate prediction of the flow and temperature field inside the combustor. Using this model, the study explores the impact of operational parameters, such as pressure, preheat temperature, turbulence intensity at the inlet and inlet bulk velocity on flame position, temperature, emissions and blowout limits for lean premixed methane-air flames. The combustion model was further applied to the extinguishing flames to study the flame stability limit, which is a very important criterion for an efficient combustor design. The results show that the modified FGM model can reproduce the flame stability curve within 20% of the experimental limit.

## 1. Introduction

The use of gas turbines for power generation has seen a considerable growth in the last few decades. Gas turbine technology has evolved into a highly efficient, compact and low maintenance system. Furthermore, these systems also enjoy low operation and maintenance costs, low vibration levels, low weight per net power produced ratio and increased fuel flexibility [1–3], which render them a very viable solution for power generation at different scales.

The reacting flow inside a gas turbine combustor is characterized by high turbulence levels accompanied by the intense rate of heat generation which aids in flame stabilization. Traditionally, combustion in gas turbines has been carried out in three different modes namely premixed, non-premixed and partially premixed. Prior to the introduction of strict regulatory measures with regards to NOx, diffusion flames were prevalent in the gas turbine industry since they provided a very good control on CO emissions alongside with high combustion efficiencies and low-pressure losses in combustors resulting in high

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## Nomenclature

| | |
|---|---|
| A | model constant for turbulent flame speed |
| $c_p$ | specific heat at constant pressure |
| c | reaction progress variable |
| $D_{ij}$ | mass diffusion coefficient of specie i in specie j |
| $g_{cr}$ | critical velocity gradient |
| h | enthalpy |
| k | turbulent kinetic energy |
| $l_t$ | integral length scale |
| M | molar mass |
| P | pressure in gaseous domain |
| $\dot{Q}_R$ | heat rate of reaction |
| R | gas constant |
| $Re$ | Reynolds number |
| $S_L$ | laminar flame speed |
| $T_s$ | temperature of the surroundings |
| $u_i$ | velocity in the i-direction |
| u′ | root mean square (RMS) velocity |
| $U_t$ | turbulent flame speed |
| $V_{k,i}$ | diffusion velocity |
| $x_i$ | spatial coordinate in the i-direction |
| $Y_i$ | mass fraction of specie 'i' |

*Greek variables*

| | |
|---|---|
| ε | turbulent dissipation |
| λ | thermal conductivity |
| $\rho$ | density |
| $\omega$ | rate of turbulence dissipation |
| $\dot{\omega}_k$ | net rate of specie production due to chemical reaction |
| $\dot{\omega}_T$ | rate of chemical heat release |
| $\delta_{ij}$ | Kronecker delta |
| $\mu$ | molecular viscosity |
| Π | pressure strain |
| $\xi_U$ | thermal diffusivity of unburnt mixture |
| $\chi_c$ | scalar dissipation rate |
| $\sigma_{ij}$ | Lennar-Jones parameters for individual species i and j |
| $\sigma$ | Stefan-Boltzmann constant |
| $\eta$ | Kolmogorov Length Scale |
| $\nu$ | kinematic viscosity |
| $\Omega_D$ | diffusion collision integral |

*Subscripts*

| | |
|---|---|
| f | fluid |
| cr | critical |
| s | surroundings/solid |
| i & j | species and x, y direction indices |
| k | z-direction index |
| m | mixture |
| u | unburnt mixture |
| op | operating pressure |
| abs | absolute |
| sto | stoichiometric |

energy conversion efficiencies. However, with the increasingly stringent regularization of NOx emission levels, the focus shifted on developing new combustion techniques which comply with the new environmental standards. This shift resulted in the development of lean premixed combustion technology for gas turbines.

Lean premixed (LPM) systems, however, are susceptible to some undesirable phenomena related to combustion dynamics. A critical phenomenon is the lean blowout, which has the potential to significantly harm the combustor. Lean blowout phenomenon has been explored extensively for a wide variety of combustor designs and modes of operation (premixed, non-premixed, spray flames, etc.). The determination of stable flame regime for gas turbines and other combustion systems is a difficult and expensive process. A commonly used approach to test stability for gas turbine combustors and engines is 'cut and try' testing system. Prohibitive experimental costs to test such devices has motivated combustion scientists to develop numerical tools to predict instabilities inside the combustor.

Combustion literature is rife with flame stretch and extinction studies both for premixed [4–6] and non-premixed [7–8] laminar flames. However, the flame extinction phenomenon for turbulent flames has been relatively less explored. An overview of the combustion literature on the turbulent flame extinction shows many experimental studies focused on observing the combustor dynamics and flame structure near extinction both for diffusion [9–12] and premixed flames [13–15].

There are a number of cut and try extinction studies focused on chalking out stable regimes for commercial gas turbine burners and meso scale thrust chambers for a wide variety of fuels. Sturgess et al. [10] discussed the construction of a research combustor and different design constraints which are pertinent in the context of lean blowout. In another study Sattelmayer et al. [16] presented a stable design for low emission lean premixed combustor. In another related study, Worth et al. [17] presented the experimental determination of combustor instabilities in an annular gas turbine combustor. Dawson et al. [18] presented an experimental study on extinction of lean premixed methane-air turbulent flames stabilized over a bluff body. The overall blow off transients were analyzed in his study by using OH-PLIF technique. For a meso-scale heat recirculating thrust chamber, the extinction behavior and thrust performance characteristics were studied by Shirsat et al. [19]. The afore-mentioned experimental studies provide vital physical insights into designing stable multi-scale combustion chambers for different fuel types and flow configurations. On the modeling part, however, the efforts are largely limited to validating the blowout in diffusion flames. Fundamental studies by Garmory and Mastorakos [20], Ihme and Pitsch [21] and Ayache et al. [22] amongst many others have attempted to predict extinction using large eddy simulations (LES). Besides these fundamental works, studies by Tyliszczak et al. [23], Nemitallah et al. [24] and Taamallah et al. [25], amongst others, investigated the application of numerical combustion models to predict stability and emission characteristics in gas turbines.

Despite all these useful studies on modelling combustion behavior in industrial scale gas turbines, the literature is very scarce on improving the reacting flow characteristics and combustor stability for premixed flames. Literature studies suggest that due to complex turbulence-chemistry interaction for premixed flames, there is a dearth of computational studies on the global prediction of lean blowout. Furthermore, the impact of different operating parameters on a lean premixed flame for high pressures and high Reynolds number has not been systematically studied. The present study is motivated by recognizing the afore-mentioned gaps in literature. This study presents the development and validation of a robust lean premixed combustion model under high pressure environment which can resolve the flame structure and also capture global flame extinction inside a gas turbine combustor. After validation, the model was extended to conduct parametric studies which provide useful information for optimizing the operating parameters for the combustor. The model was further used to simulate the lean combustion under high pressure environment and to produce the flame stability curve for the gas turbine combustor.