# Modeling of lifted jet flames using a new flame extinction model

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## Introduction

Lifted flames are observed when the velocity of a jet of fuel discharging into the surrounding air is increased beyond a certain critical value. The base of the flame has a 'tubular' appearance and the lowest point is well away from the axis of the jet [1]. The flame lift-off height increases with an increase in fuel jet velocity [2]. In turbulent lifted flames, the fuel and air achieve a degree of premixing through turbulent motion and diffusion before the flame base is reached [1]. This is a typical characteristic of many combustion systems employed for practical applications [1]. For instance, gas turbine combustors and burners in commercial boilers, where the lifted flames are utilized to reduce extensive damage to nozzle material by minimizing the contact between high temperature reaction zone and combustor walls and fuel injection systems [3]. Considering these issues, it is extremely important to accurately predict the behavior of flame under such lifted conditions.

Several models have been proposed to explain and predict the flame stabilization of lifted flames such as premixed flame propagation model [4], laminar flamelet model for non-premixed combustion [5], partially premixed flame model [6] and concept of triple flame [7,8]. However, none of these models have been completely validated for lifted flames or their implementations in computations has been quite complex [2]. Although, there is a qualitative agreement among the researchers on the dependence of flame lift-off height on jet velocity as it increases linearly with jet velocity [2]; different theories explain the flame stabilization mechanisms of lifted flames using different concepts. Multi-dimensional interaction of chemistry, temperature, turbulence and coflow play an important role of cause and effect and hence make this phenomenon even more difficult to understand [2]. A flame interacting with a turbulent flow leads to strong flow accelerations induced by heat release along with the changes in the thermodynamical properties associated with large temperature changes. This mechanism may either generate turbulence, or may lead to flow reliaminarization due to damping effect. On the other hand, turbulence can also alter the flame structure, which can further enhance the chemical reaction of completely inhibit, and lead to local or global flame quenching.

In the present work, Eddy dissipation model has been used for modeling combustion reaction and three different turbulence models are used to predict the averaged flow properties in the turbulent jet flow. For instance, modified k-ε model, standard k-ω model and modified k-ω model. The local flame extinction is assumed to occur in the computational domain where fluid time scale ($\tau_f = k/\varepsilon$) is smaller than the chemical time scale ($\tau_{ch}$). Flame is assumed to be stabilized at a point where local jet velocity equals to the flame propagation velocity. Using this model, Kumar et al. [2] have compared the predicted flame lift-off heights for various conditions and observed that the predictions are in good agreement with experimental values. Present work is a further step in validating this model by comparing the variation of various properties such as center line temperature and mass fractions of various species along the axial and radial directions using different combustion models such as EDM and flamelet models. The dependence of combustion process on the choice of domain size and on co-flow velocity has also been studied to ensure that the present studies are independent from the effects of such boundary conditions.

## Mathematical Model

The conservation equations describing a general case for three dimensional multi-component, chemically reacting flow; i.e., mass, momentum, continuity, energy, species mass fraction equations and equation of state; serve as the governing equations. Turbulence is modeled using modified $k - \varepsilon$ model, standard $k$-$\omega$ model and modified $k$-$\omega$ model to compare the predictions of various features of the jet flames with the experimentally measure values. In these models, eddy viscosity $\mu_t$ is modeled as product of turbulent velocity scale $u_t$ and

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turbulent length scale $l_t$. For modified *k*-ε model, in the ε equation, the value of molar constant ($c_{\varepsilon 1}$) is changed from 1.44 to 1.60 as it predicts the spread rate for circular jets more accurately [8]. For modified *k*-ω model, the coefficients in the ω equation are changed. $\alpha$ has been changed from 0.56 to 0.7 and $\beta$ has been changed from 0.075 to 0.06.

A combustion model based on eddy dissipation concept has been used for modeling the mean reaction rates in the concerned process. In turbulent flows, averaging of the governing equations results in mean chemical reaction source term $\overline{\dot{\omega}_i^m}$ . In the EDC based combustion model, an empirical expression for the mean reaction rate based on the assumption of mixing time scale is used (Magnussen and Hjertager [9]). It is assumed that chemical reaction occurs in the isolated regions where the dissipation of turbulent kinetic energy is significant and the reaction rates are fast enough and when they mix at the molecular level, they instantly form products. In turbulent flows, mixing time is dominated by eddy properties and hence, reaction rate is proportional to the mixing rate. The following expression gives the reaction rate using EDC concept:

$$R_k = A\frac{\varepsilon}{k}\min\left[Y_f, \frac{Y_0}{s}, B\frac{Y_p}{1+s}\right] \tag{1}$$

where, $Y_f$ = fuel mass fraction, $Y_0$ = oxidizer mass fraction, $Y_p$ = product mass fraction, $A$ = model constant used to relate mixing time scale to reaction rate, $B$ = model constant known as product limiter and $s$ is mass stoichiometry of reaction $k$.

Turbulence time scale or fluid time scale is defines as the ratio of turbulent kinetic energy to the dissipation rate of turbulent kinetic energy. Chemical time scale is derived as a function of the fuel and co-flow properties like fuel mass fraction, fuel jet velocity, co-flow temperature and oxidizer mass fraction.[3]

$$\tau_{chem} = \tau_{ref}(Y_{O_2})^{a_1}(Y_f)^{a_2}(\bar{U})^{a_3}\left[\frac{e^{(-E_a/RT_{ad})}}{e^{(-E_a/RT_{ad,new})}}\right] \tag{2}$$

where, $\tau_{ref}$ is the chemical time scale at $T$ = 300K for standard fuel-air mixture combination, $\bar{U}$ is the mean jet velocity and $a_1$, $a_2$ and $a_3$ have been found to vary as -2, -0.5 and 0.6 respectively[2]. The fluid time scale is compared with the chemical time scale at each grid point. The flame is assumed to be quenched when fluid time scale is found to be smaller than the chemical time scale or in other words if $Da < 1$ ($Da = \tau_f/\tau_{ch}$).

## Domain Description and Preliminary Results

When fuel is issued from a circular jet, the flow essentially affects the domain which is in the vicinity of the jet and constitutes of a shape of a frustum of a cone. Using the axi-symmetric property of the flow domain, the domain is reduced to an angular sector of 15°. This does not affect the final results; however, it significantly reduces the overall computational time. Computations were carried out for 3-different sizes of domain to ensure the independence of the final results from domain size. For instance, an outer radius $R$ = 0.5m, 1m and 2m was chosen to establish independence of results from domain size. It was observed that domain size had no effect on the computational results and thus an outer domain of any size varying between 0.5 to 2.0 m can be chosen. Figure 1 shows the selected domain (radius 1.0 m) along with the specific boundary locations such as inlet, wall and symmetry conditions. The experiments are generally conducted in the ambient conditions where natural coflow gets generated due to high momentum of the fuel jet. In the present wok to simulate this effect, preliminary studies were carried out to examine the effect of coflow velocity on the predicted flame lift-off height. Computational results for a jet velocity of 60 m/s and co-flow velocities ranging from 0.001 m/s to 5 m/s have been compared as shown in Fig. 2. It has been observed that the effect of co-flow velocity is minimal in the range of 0.1 to 0.5 m/s and the predicted flame lift off height is very close to the experimentally measured value. Beyond 0.5 m/s coflow velocity, flame lift-off height increases linearly with the co-flow velocity. For coflow velocities smaller than 0.1 m/s, the mixing of fuel and oxidizer is not properly predicted and leads to the prediction of very small flame lift off height as compared to the experimental observed values. Therefore, in the present work, a value equal to 0.25 m/s as coflow velocity has been thought to be appropriate and applied as a coflow boundary condition for air. A detailed comparison of the predictions with the experimental results is expected to be carried in the near future.

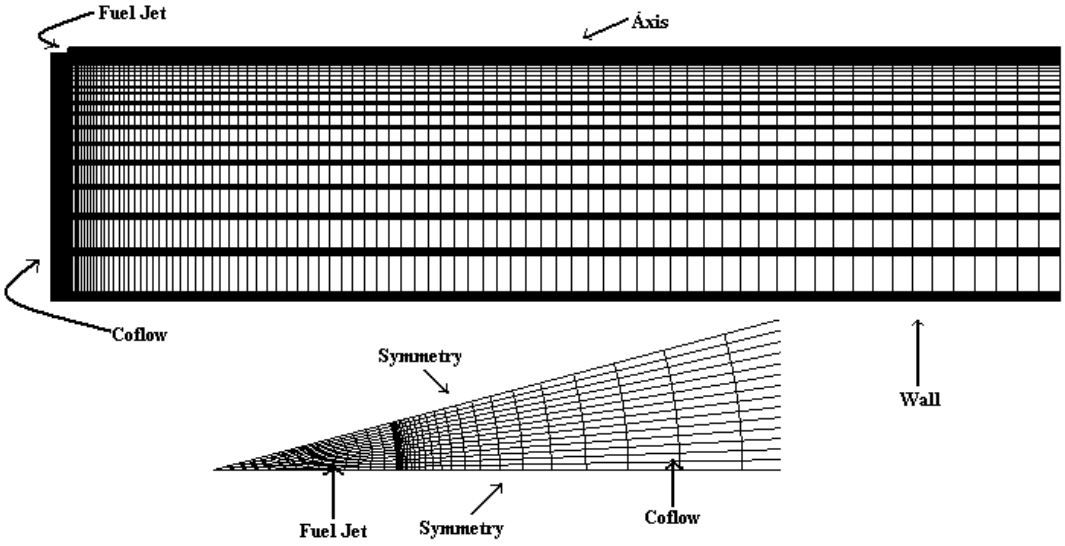


**Fig.1:** Side view of the 3-dimensional mesh with specified boundary locations (above); Enlarged view of mesh around fuel jet inlet (below).

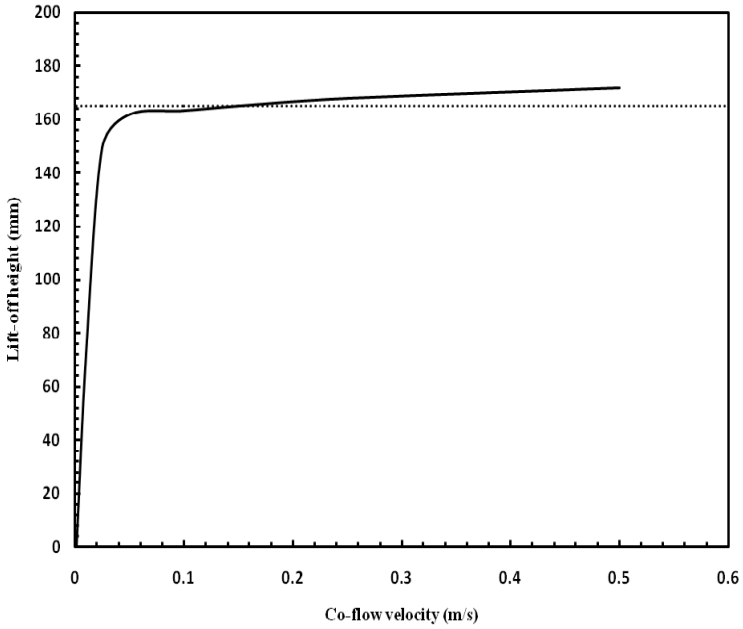


**Figure2:** Effect of Co-flow velocity on lift-off height. The dotted line shows the experimental value of lift-off height for fuel jet velocity of 60 m/s.

## Comparison Results

In the present work, the experimental conditions as described by Cabra et al. [10] have been numerically simulated. Methane fuel is issued from the fuel jet with a velocity of 100 m/s with surrounding co-flow being issued at 5.4 m/s. The results have been compared for two different grids, coarse grid (3,000 grid points) and a fine grid (having 70,000 grid points). As shown in Fig. 3, at z = d, the radial temperature profile for coarse grid using modified $k - \varepsilon$ model matches closely with the experimental results. However it is interesting to see that the difference between experimentally measured temperature and predicted temperature increases with an increase in the number of grid points. This is clear from the curves marked 'MKE fine' and .MKE coarse'. The present results with a fine grid and modified $k$-$\varepsilon$ model are not comparing well with the experimental measurements. Many researchers in the past have shown good comparisons for such lifted flames which could be

a coarse grid employed in the computations [11, 12]. The present model underpredicts the jet spread rate at these conditions. In a similar fashion, standard k-ω model was used and the comparison shows that *k-ω* model predictions match well even when a coarse grid is employed for the computations. Fig.3 shows that the results obtained using modified *k-ω* model are in good agreement with the experimental values for axial location z = d. Further predictions using modified *k-ε*, standard *k-ω* and modified *k-ω* model at a downstream position (z = 15d) are shown in Fig.4. It can be observed that out of these three models, results obtained using modified *k-ε* model are in the best agreement with experimental values. Figure 5 shows the axial temperature profiles of the flames using different models. From these comparisons, it is clear that *k-ω* model completely fails to predict the temperature profiles.

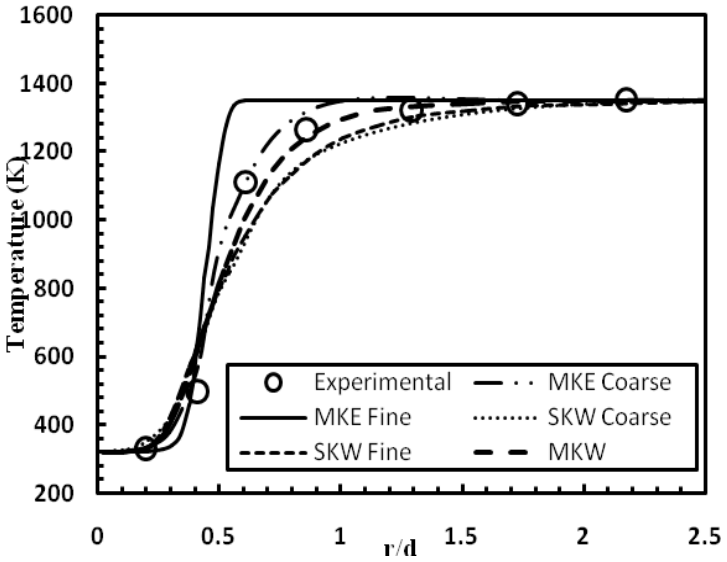


**Figure 3:** Radial profiles of Favre-averaged temperature at axial location of z = d (0.00457m). MKE = modified *k-ε* model; SKW = standard *k-ω* model and MKW = modified *k-ω* model.

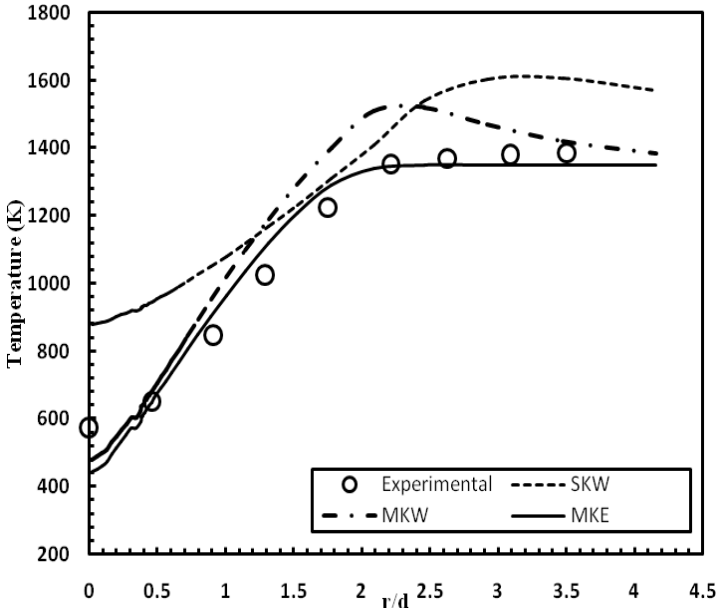


**Figure 4:** Radial profiles of Favre-averaged temperature at axial location of z = 15d (=0.06855m). MKE = modified *k-ε* model; SKW = standard k-ω model and MKW = modified *k-ω* model.

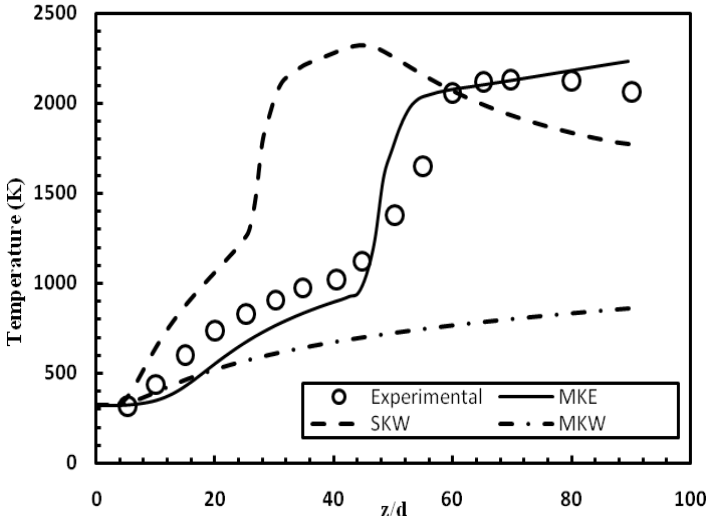


**Figure 5:** Centerline temperature profiles with increasing axial distance. MKE = modified *k-ε* model; SKW = standard *k-ω* model and MKW = modified *k-ω* model.

## Conclusion

In the present work, the lifted flames have been modeled using a new flame extinction model and a detailed comparison has been carried out with the experimental measurements. The predictions using k-ε model appear to compare well with the experimental measurements. Although *k-ω* appears to predict the initial jet spread rates quite well, the predictions at other locations in the free shear flows such as a far downstream of a jet flame are very poor. Overall, the predictions of the model are reasonably good when compared with the experimental measurements. Presently the work is under progress and the detailed comparisons will be presented in the conference.

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