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Research Article

Numerical Simulation of Propagation of Unsteady Tribrachial Flames in Laminar Non-Premixed Jets

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Abstract. The characteristics of propagating Tribrachial Flames in non-premixed laminar jets have been investigated computationally, using a two dimensional model in ANSYS FLUENT 16.0. The edge of the propagating flame in a laminar jet regime has a Tribrachial flame structure: a lean premixed flame, a rich premixed flame, and a diffusion flame, all extending from a single location. This is usually observed in non-premixed combustion such occurring in burners. Such flames are important in the interaction of heat and mass transfer with chemical reactions in gas turbines and commercial burners. A computational study has been performed to assess the laminar tribrachial flame propagation in methane jets and to compare the tribrachial flame propagation for various flow rates. With an increase in the fuel jet Reynolds number, the tribrachial point is found to move closer to the nozzle. Additionally the tribrachial point is found to become larger with an increase in the Reynolds number.

Keywords. Combustion; Numerical simulation; Tribrachial flame; Laminar flame; Flame propagation

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1. Introduction

Technical flames can be classified in different ways, but probably the most common and clear is how the reactants are supplied into the reaction zone. Based on the mixing of the reactants, combustion can be classified into three categories, namely non-premixed, premixed and partially premixed combustion.

A tribrachial (or triple) flame can form in a mass diffusive mixing layer with a flammable concentration. The tribrachial flame consists of a lean premixed flame, a rich premixed flame, and a diffusion (or non-premixed) flame. Non-premixed flames in a mixing layer play interesting roles under various combustion conditions. An example is a lifted flame in a jet in which the fuel and the oxidizer are partially premixed. The flame edge typically has a tribrachial (or triple) flame structure comprising two distinct premixed flame wings, one lean and one rich, and a following diffusion flame, all stemming from a single point (tribrachial or triple point). Tribrachial flames are observed when a flame encounters concentration gradients as it propagates in a flow field with mixture stratification.

Tribrachial flame was first observed by Phillips [5] in 2-D mixing layers with stratified methane concentration. The propagation characteristics of the flame were observed to be unique and the propagation speed in the static flame rig was much larger than the stoichiometric laminar burning velocity. It was demonstrated that the propagation velocity of a tribrachial flame (PVTF), or V_f, was much larger than the laminar burning velocity of a stoichiometric mixture.

Ishikawa [2] studied similar flame structures through experiments on the transient flames. Studies were carried out on a stratified methane-air in a chamber with constant volume. The characteristics of tribrachial flames were shown in recent experimental and modelling studies on stationary lifted flames in laminar jets [4]. In an analytical study, Dold [1] described the importance of the tribrachial flame for turbulent modelling.

Ruetsch et al. [6] analytically studied the relation between the PVTF to the laminar burning velocity of a stoichiometric mixture. The results indicated that the ratio between the velocities was asymptotically converging to the square root of the density ratio of the unburned mixture to the burned mixture. Additionally, it had also been theoretically and numerically predicted that the ratio of the maximum propagation speed of a tribrachial flame to the stoichiometric laminar burning velocity in a two-dimensional uniform flow field was also following the same ratio.

However, the measured propagation speed of a stationary tribrachial flame was observed to be much lower than the predicted maximum propagation speed. Analysis of the results indicated that the propagation speed of tribrachial flames was influenced by the mixture fraction gradient [3]. In the present study, a computational study is made on laminar non-premixed jets, taking into account the chemical kinetics and multi-component diffusion phenomena. The computed results are compared with experiments of Ko and Chung [3]. Careful attention is paid to the detailed processes of the preferential diffusion of heat and species on the flame characteristics.

2. Numerical Simulation

The experimental setup used by Ko and Chung [3] consists of a fuel nozzle, flow controller, ignition system, and systems for visualization and velocity measurement. The fuel nozzle was a stainless steel tube (2.08 mm i.d. and 600 mm length) with a length to diameter ratio large enough for the fuel flow to be fully developed. The fuel was chemically pure grade methane, and the oxidizer was the ambient air. It was surrounded by a 21 cm × 21 cm × 200 cm square cylinder, which had steel meshes and optical accesses on its sides to prevent external disturbances.

The enclosure along with the edge of the nozzle has been considered for the present study. Two dimensional analysis of the experimental setup has been carried out on the mid section plane. The mesh has been generated in a systematic manner, with the smallest mesh size being 0.5 mm. This ensures there are at least four points in the nozzle region.

The fluid is considered as a mixture of methane and air. The density of the mixture is calculated through ideal gas law, while the specific heat of the mixture is determined by mixing law. For the mixture the thermal conductivity and viscosity are determined using mass-weighted mixing law. For individual species, piecewise polynomial equation is used for specific heat. Thermal conductivity and viscosity of the species are determined using kinetic theory law. Mass diffusivity of the species is determined using kinetic theory.

A single step methane combustion reaction has been used in the study. Since the flow is laminar the turbulence chemistry interaction has been determined using the laminar finite rate mechanism. The chemical reaction used in the simulation is shown in Table 1.

Table 1. Single step Methane Combustion Reaction Units are in m, s, J, kgmol and K

S. No.	Reaction	Pre-exponential factor	Activation energy J/kgmol	Temperature exponent
1	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	2.119×10^{11}	2.027×10^{8}	0

The nozzle location, where the fuel enters the computational domain is specified as a mass flow inlet. On the sides of the nozzle to mimic the experimental setup, air is allowed to flow using the pressure inlet boundary. The top edge of the computational domain is considered as outlet and is set as a pressure outlet boundary.

For transient analysis the discretization in the temporal domain has been set as 0.0001 seconds. Thus two-dimensional, incompressible, unsteady, laminar, reacting flow calculations have been carried out.

3. Results and Discussion

The simulations were performed with the help of CFD software ANSYS FLUENT 16.0 and the results are presented below.

3.1 Tribrachial Flame Formation

The contour plot for heat of reaction determined numerically is shown in Figure 1 (left side). The formation of the Tribrachial flame structure has been found to be similar to the flame structure observed in experiments [3], as shown in Figure 1 (right side). As the Tribrachial flame edge approaches the nozzle, the inner rich premixed flame cone opens its tip because insufficient air entrainment into the region near the jet axis renders the mixture non-flammable. However, the flame edge retains a Tribrachial structure.

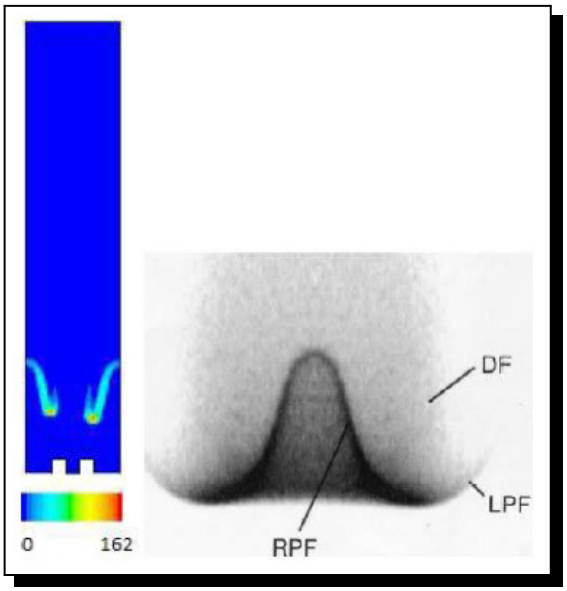

Figure 1. Contours of reaction rate obtained from simulations (left) and regions of tribrachial flame measured experimentally [3]

Further it can be visualized that the maximum reaction rate calculated in the simulations occurs at the tribrachial point. As mentioned earlier the tribrachial point is the point from which the rich premixed flame on the fuel side, the lean premixed flame on the oxidizer side and the diffusion flame starts to branch out. It is a point where the fuel and oxidiser has reached stoichiometric conditions. This feature is clearly observed in the results determined from the numerical simulation.

3.2 Temperature Plots

Apart from the contours, temperature values along different line probes located at various locations in the computational domain has been determined. The line probes are located at positions as $y/R = 0.1$, $y/R - = 0.5$, $y/R = 0.75$, $y/R = 2$, $y/R = 10$ and $y/R = 15$, where y is the vertical distance from the nozzle exit and R is the half width of the computational domain (distance from centre of nozzle to wall). The variations of temperature along these lines for different Reynolds number is shown in Figure 2. The Reynolds number is determined by the fuel jet velocity and nozzle diameter.

The maximum temperature indicates the location of the tribrachial point. The first two probes ($y/R = 0.1$; $y/R = 0.5$) for Reynolds number 160 exhibit a temperature of about 300 K, indicating the absence of flame in the location. However as the Reynolds number is increased to 214 the peak temperature occurs at probe located at $y/R = 0.5$. Thus as the Reynolds number is increased, the flame moves close to the nozzle.

It can be further visualized that as the Reynolds number is further increased to 648, the peak temperature occurs in two probes ($y/R = 0.5$; $y/R = 0.75$). It can be further observed that the maximum temperature location in the second probe ($y/R = 0.75$), is slightly offset towards the outer region. These factors suggest that the location of the tribrachial point has become larger with an increase in the x- and y-directions.

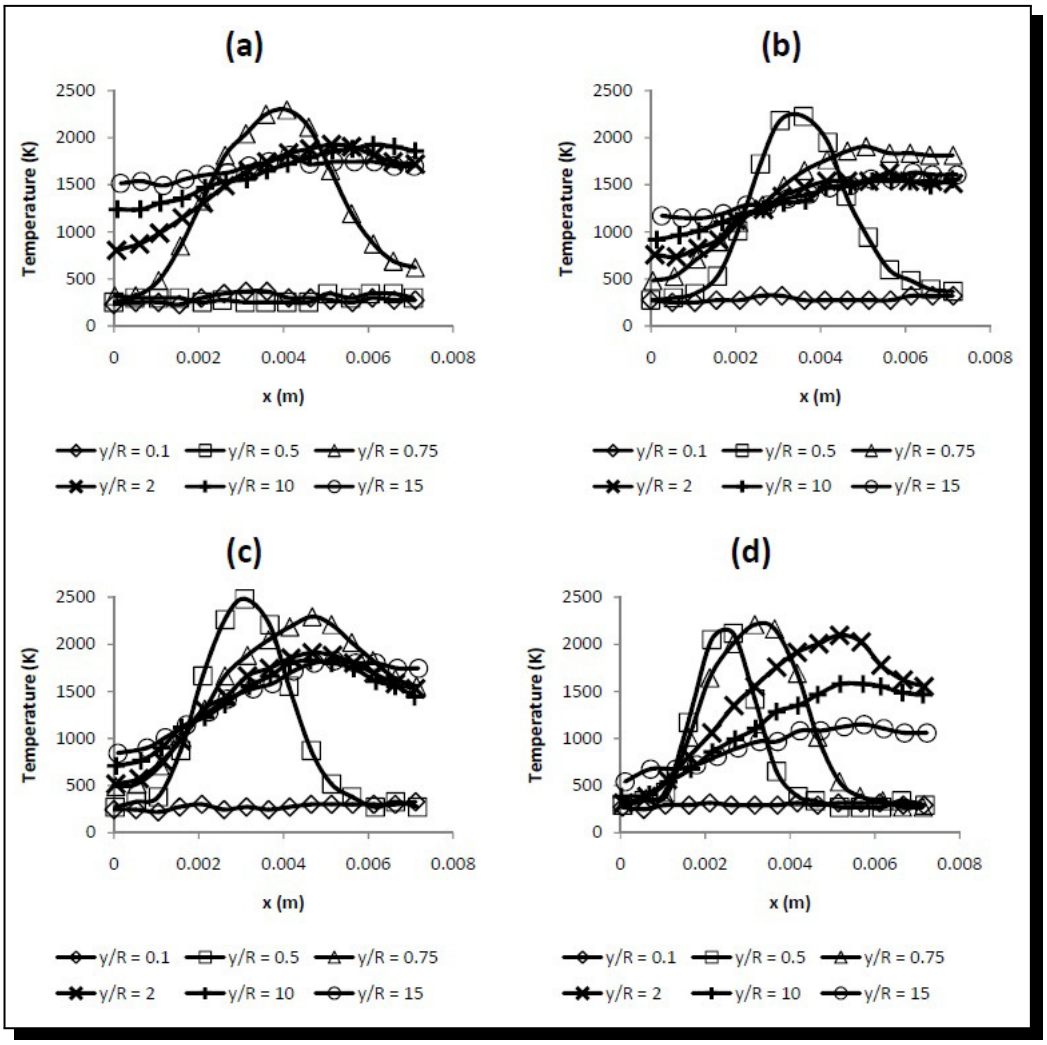

Figure 2. Temperature plots at various locations for different Reynolds number (a) 160, (b) 214, (c) 431, (d) 648

4. Conclusion

Numerical simulations of a tribrachial laminar methane flame have been carried out. The jet flames for different Reynolds number have been analysed. The simulations have been carried out using commercial software ANSYS FLUENT 16.0. In order to reduce the computational time two dimensional analysis has been carried out. Unsteady calculations are carried out with a time step size of 10^{-4} seconds. A single step methane combustion reaction has been used in the present simulation. The following are the major inferences from the simulation:

- The contours of rate of reaction are found to be reaching a value of maximum at the location of the tribrachial point, indicating high energy release at tribrachial point.
- The temperature plots along the line probes indicate that with the increase in the fuel Reynolds number, the tribrachial point is observed to move toward the nozzle.
- Additionally with increase in the jet Reynolds number, the tribrachial point has been observe to spread in both horizontal and vertical directions.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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