Numerical Simulation of Pulsed Diffusion Flames

Dhanunjaini.Ch

Abstract— Combustion is a rapid oxidation process in which fuel and oxidizer take part in the reaction by liberating heat.Combustion can be classified as premixed and diffusion based on the initial mixing of fuel with oxidizer.In case of diffused combustion, oxidizer will be diffused into the flame while the combustion products are liberated out of the combustion zone.Since the oxidizer is not readily available for the fuel to combust,the extent of combustion depends on the mixing of fuel with oxidiser.It has been observed by several researchers that,by sending the fuel intermittently will improve the mixing of fuel and oxidizer and thus improves the combustion efficiency.In the present study, a numerical model for unsteady turbulent diffusion flames is developed.The flame characteristics, species concentrations and turbulent parameters are studied along the downstream of the combustion zone.The standard k-εmodel is used to solve the turbulence parameters.A single step chemistry is used to solve the reaction process.The governing equations (flow,energy,species and turbulence equations) are asolved unsteadily using FLUENT.

Key words— Diffused combustion, turbulent flames, flame characteristics, species concentrations, standard k-ε model, single step chemistry.

1 INTRODUCTION

Combustion is a chemical reaction procsess where fuel gets oxidized, thus conversion of chemical energy into thermal energy takes place by liberating heat. In premixed combustion, both the fuel and oxidiser are mixed together at molecular level before the combustion takes place. For better mixedness of the reactants, one of the reactants should be in either a gaseous state or liquid state so that its molecules can spread around easily to those of the other reactant. In diffusion combustion, both the fuel and oxidiser are not initially mixed. The reaction occurs at the interface where both the fuel and oxidiser gets mixed. An example for diffusion flames is a candle. Diffusion combustion is sometimes called as non-premixed combustion. The term diffusion means the molecular diffusion of chemical species. This means, the fuel diffuses toward oxidiser and vice versa and combustion
starts at the interface.

Pulsed diffusion flames are such type of flames where fuel is sent intermittently for the combustion to occur. By sending fuel intermittently and fully modulating (completely shutting off between pulses) better combustion can be obtained. The consumption of the fuel is an important characteristic feature. For completeness of combustion, the rate of fuel supply should be equal to the rate of combustion. Due to its simplicity the fully modulated technique can be readily combined with other combustion enhancements, such as swirl to further improve combustion performance.

Ch.Dhanunjaini, Assistant Professor, Department of Mechanical Engineering, Guntur, AP, 9490589062, dhanunjaini@gmail.com

In the current work, the effect of coflow on turbulent diffusion flames is studied numerically. For that a non-dimensional number 'P' (defined by J.C. Hermanson, R. Dugnani and H. Johari [1]) is used. Ethylene fuel is sent through a nozzle of 2mm diameter. The velocity of the jet is 22.6 m/s, which make the flow turbulent. The complete stopping and starting of fuel jet in a cyclic manner according to the given duty cycle (fuel on-time / cycle-time) is called fully modulated flow. The flow of ethylene fuel in the numerical simulation is fully modulated by controlling the fuel species coming from the axisymmetric nozzle. A single step chemical reaction is assumed in modeling the combustion.

2 LITERATURE REVIEW

Tang, Y.M.,et. al [2] studied the mechanisms which are responsible for the lean and rich limits of operation of a gas fueled, valved, Helmholtz type, pulse combustor are fundamentally different. It has been determined that this rich limit is not kinetically controlled. The driving effciency of the combustion process was quantified over a wide range of operating conditions. The results indicate that the processes which control the lean and rich limits of operation of the pulse combustor are fundamentally different. Near the lean limit of pulsations, the driving of the pulsations by the combustion process is low because of the large phase angle between the pressure and heat release oscillations. Near stoichiometric conditions, the driving process is most effcient.

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Johari.H.,et. al [3] studied experimentally about the starting vortex of an impulsively generated jet diffusion flame was studied experimentally.All flames were in the buoyancy driven regime after the starting transient.The height at which the starting vortex burned off completely was approximately the same as the mean flame length of the subsequent steady flame. The penetration of the flame tip associated with the starting vortex could be correlated by a parameter derived from the isothermal, buoyancy-driven starting plume theory of Turner. The starting vortex penetration scales with the nozzle volume

flow rate and appears unaffected by the nozzle Reynolds number in the experiments.

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The influence of buoyancy on the flame propagation is studied by Becker and Yamazaki [4]. A systematic study has been made on mass entrainment rate and momentum growth rate in vertical free turbulent diffusion flames and develops a general correlation. A parameter 'ε_L' is defined as the cube root of Richardson number. Based on this parameter, the free diffusion flame are classified as momentum driven (ε_L < 2) or buoyancy driven (ε_L >10).

In the numerical model, initially the numerical flame lengths are compared with the experimental results [1] and the numerical work is extended for different coflow strengths to study the species concentrations and turbulent parameters.

3 Physical Description of the Problem

The experimental set up for the numerical study is chosen from J.C Hermanson et al.,[1]. The schematic of the experimental set up is shown in Fig 1. It mainly consists of nozzle, coflow duct and an ignitor source. The nozzle was placed centrally inside the coflow duct. An ignitor was placed at a distance of 2mm away from the top of the nozzle.

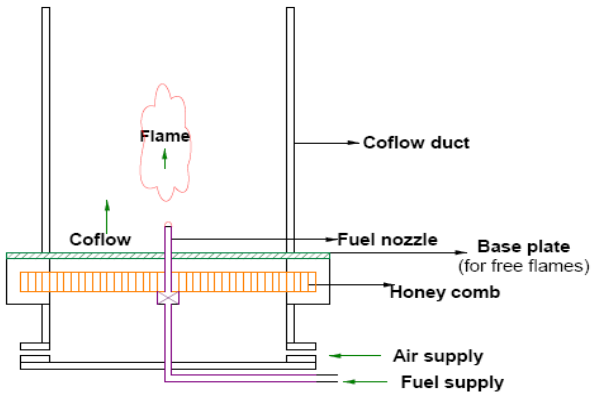


Fig. 1 Schematic of Experimental setup (J.C Hermanson et al.,[1])

The actual experiments are conducted by igniting the fuel that is coming out of the nozzle of diameter 2 mm. The coflow air enters from the bottom of the coflow duct which is 20 X 20 cm in square cross section. The coflow is aimed to improve the mixing of fuel with air, thereby better combustion takes place.

4 Geometrical Modeling

The experimental configuration that was chosen for numerical simulation was modeled as 2D axisymmetric problem. The actual experimental conditions were represented at various boundaries of the modeled geometry. A uniform flow was coming through the coflow boundary with the required coflow strength. The fuel jet was coming out from the nozzle-outlet with the given velocity. The line passing through the center of nozzle of diameter 2mm represents the axis of the nozzle in the modeled geometry.

The atmosphere above the coflow duct was represented by the ambient atmosphere boundaries. The outer surface of the coflow duct and the nozzle length were represented by the wall boundaries. A circle that represents ignitor is used to ignite the fuel coming from the nozzle. The modeled 2D axisymmetric geometry is shown in Fig 2.

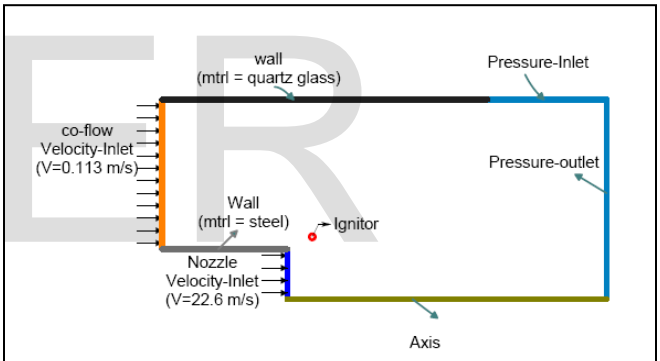


Fig. 2 2D Axisymmetric Geometric Model

4.1 Assumptions

1. The unsteady and two dimensional flow is produced by a jet of fuel coming out from a circular nozzle, which burns in a quiescent ambient atmosphere.
2. The flow is incompressible and density is assumed to follow ideal gas laws.
3. The velocity of the jet coming from the nozzle is uniform i.e., in a top-hat velocity profile.
4. Heat transfer due to thermal radiation is neglected.
5. Buoyancy effects are negligible.
6. Molecular transport of momentum, species and thermal energy is negligible compared to turbulent transport.
7. The fuel and oxidizer form products in a single step exothermic reaction. The oxidizer is present in stoichiometric or excess proportions. Thus, the fuel is completely consumed at the flame.

8. The diffusion of heat and mass are governed by Fourier's and Ficks laws respectively.
9. Sc = Pr = Le (i.e., The turbulent Schmidt, Prandtl and Lewis numbers are equal to unity).
10. Mixture properties are defined by fuel, oxidizer and product species and all are having constant molecular weight.

6 RESULTS

6.1 Validation of Numerical Model

The Numerical model is validated with the Experimental results obtained by J.C Hermanson et al.[1]. Simulation is done at coflow strength of 0.005 and at various 'P' values. Reynolds number obtained for all the cases is 5000. Validation was done to fully modulated cases. In unsteady cases the flame lengths are compared with the experimental results. The images shown in Fig 3.are taken at the end of injection period (τ = 46 ms) and at 50 ms after the injection period.

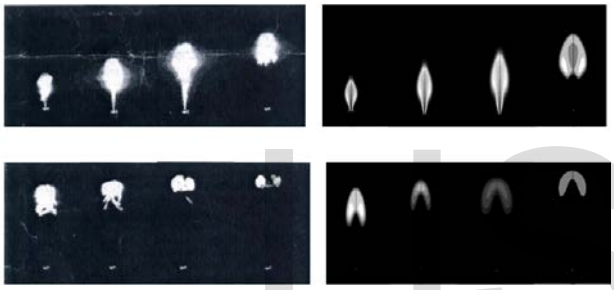


Fig. 3 Comparision of Expt. and Numerical images for a fully modulated free flames at P = 8. (Re = 5x10³ and α = 0.15)

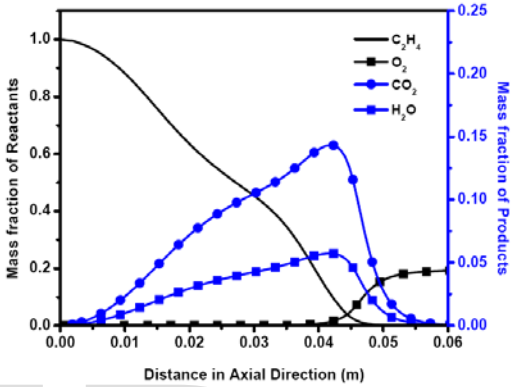
The numerical results are compared with the experimental values and it is observed that the error is within ±2%.

6.3 Study of Species Concentration with Coflow

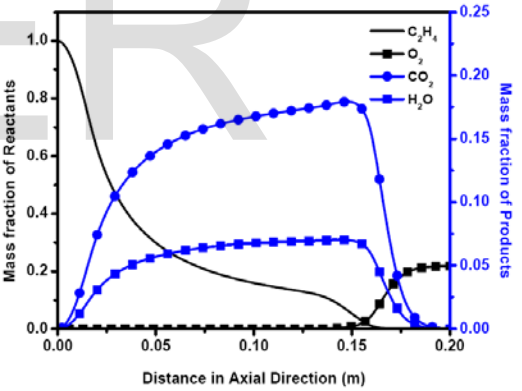
Single step chemistry is used for the reaction process. With complete combustion of hydrocarbon fuels, all hydrogen and carbon in the fuel are oxidized to H_2O and CO_2. Therefore, exhaust gas from stoichiometric combustion theoretically contains no incompletely oxidized fuel constituents and no unreacted oxygen (i.e., no carbon monoxide and no excess air or oxygen). The percentage of CO_2 contained in products of stoichiometric combustion is the maximum attainable and is referred to as the stoichiometric CO_2. The stoichiometric equation for the ethylene fuel in the combustion process is shown in equation (1)

$$C_2H_4 + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 11.28N_2 \quad (1)$$

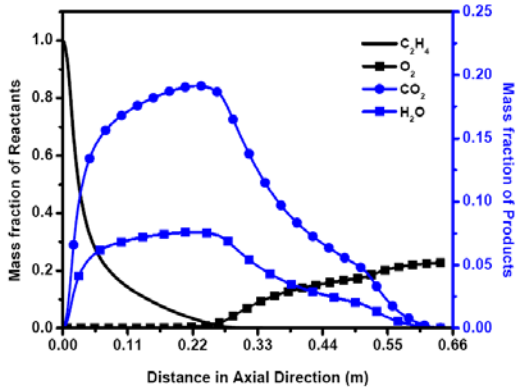
When the fuel diffuses out of the nozzle, it mixes with the surrounding atmosphere and the combustion occurs after required amount of oxygen mixes with the fuel. As the combustion starts the temperature rises and reaches to a maximum value and after the completion of combustion the temperature gradually decreases. The mixture present in the downstream side of the nozzle along the central line is lean mixture whereas the mixture present at the outlet of the nozzle is rich mixture. Stoichiometric mixture is present in between these two regions. Due to the presence of different mixture compositions the mass fraction of reactants also varies along the central line. The extent of combustion can be known depending upon the fraction of products formed or amount of fuel consumed. The variation of mass fraction of ethylene fuel (reactant) and products (CO_2 and H_2O) along the central line is studied for different 'P' (P=4, 8, 11) values.



(a) P=4



(b) P=8



(c) P= 15

Fig. 4 Variation of mass fraction of reactants and products along the central line in axial direction at end of injection period (coflow strength = 0.005).

The graphs plotted for the flames with a coflow strength of 0.005 at different 'P' values are shown in Fig. 4. From the graphs it is clear that due to the presence of coflow, it can be seen that the extent of fuel travel increases as the value of 'P' increases from P = 4 to P = 15.

The mass fraction of the fuel is maximum at the outlet of nozzle and starts' decreasing along the central line since the fuel is consumed while the combustion is taking place. At the same time, the mass fraction of CO_2 and H_2O is minimum at the nozzle outlet (due to rich mixture) and reaches maximum value at certain distance along the central line and then decreases (due to lean mixture). As the 'P' value increases from P = 4 to P = 15, the maximum amount of CO_2 formed is observed to be increased.

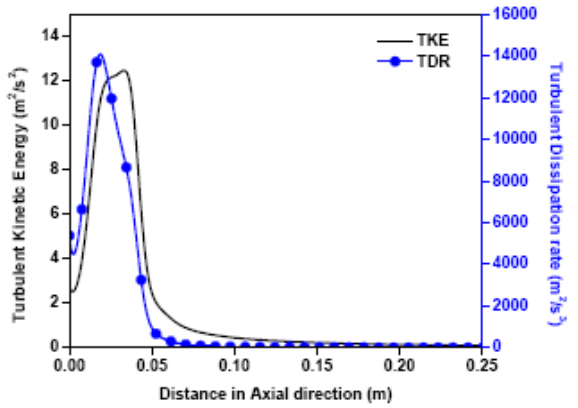
6.4 Study of Turbulence Parameters With Coflow

Turbulence or turbulent flow is a flow regime characterized by disordered property changes in fluid dynamics and this includes rapid variation of pressure and velocity in space and time. The velocity of fuel flowing through the nozzle is 22.6 m/s with Reynold's number 5000. Since the Reynold's number is greater than 2500, the flow is turbulent. Turbulent flow requires more energy for sustenance because at larger Reynolds number there is a continuous transport of energy from the free stream to larger eddies. The important parameters that describe the turbulence are turbulent kinetic energy (TKE) and turbulent dissipation rate (TDR).

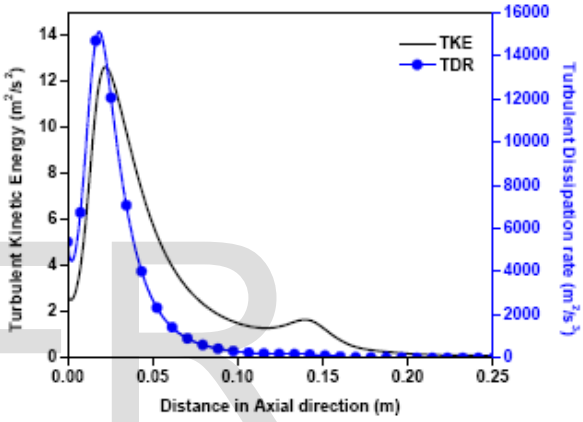
Turbulence kinetic energy (TKE) is the mean kinetic energy per unit mass associated with eddies in turbulent flow. TKE can be produced by fluid shear, friction or buoyancy. Turbulence kinetic energy is then transferred down the turbulence energy cascade, and is dissipated by viscous forces.

High Reynolds number turbulent flows have motions that range over many length scales. The largest scales correspond to the scale of the energy input mechanism. At the large scales, viscosity is unimportant. In other words, the large vortex structures exist and breakup into smaller scale vortices under the influence of pressure and inertia alone. Viscous effects are important predominantly at the smallest scales of motion. At the smallest scales the velocity gradients are smoothed out by the dissipative effect of viscosity. In a turbulent flow, the kinetic energy of the largest scale motions is transferred to successively smaller scale motions without loss. It is only at the small scales that energy dissipation occurs. Therefore the rate of dissipation of turbulent kinetic energy is turbulent dissipation rate.

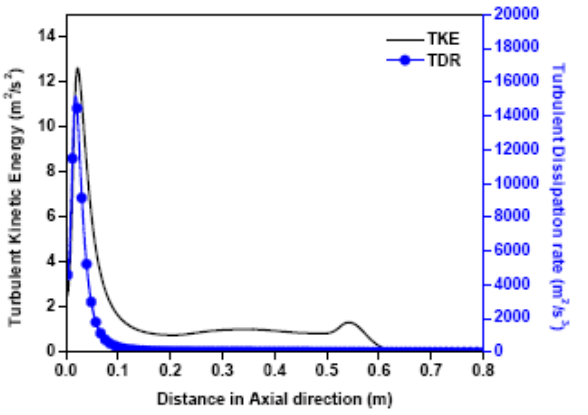
The graphs plotted for different 'P' values at a coflow strength of 0.005 are shown in Fig.5. It is observed that the fluctuations are less when a coflow duct is present. This is because; the coflow duct will direct the flow and allows the fuel to travel in the direction of the air.



(a) P=4



(b) P=8



(c) P= 15

Fig. 5 Variation of turbulence parameters along the central line at the end of injection period in axial direction (coflow strength = 0.005).

The turbulent kinetic energy is maximum at certain distance

from the nozzle and then it decreases. This is due to decrease in axial velocity which reduces mixing.

6 Conclusions

The concentration of the fuel and products is used to determine the extent of combustion. Since the reaction is stoichiometric the products formed are only CO_2 and H_2O. The mass fraction of oxygen increases at the point where the decrease in mass fraction of products (CO_2 and H_2O) is observed.

The important parameters namely turbulent kinetic energy per unit mass and its dissipation rate are studied to understand the turbulence in the flow field. For fully modulated flames, it is observed that as the injection time increases from P = 4 to P = 15 the fluctuations in velocity for both turbulent kinetic energy and turbulent dissipation rate also increases. It is also observed that fluctuations of turbulent kinetic energy are more compared to turbulent dissipation rate.

References

[1] J.C. Hermanson, R. Dugnani and H. Johari, "Structure and Flamelength of Fully Modulated Turbulent Diffusion Flames," *Combust. Sci. and Tech.*,, pp. 203-225, 2000.

[2] Tang Y.M Ku, S.H , Daniel, B.R., Jagoda, J.I., and Zinn, B.T.," Controlling the Rich Limit of Operation of Pulse Combustors," *Twenty-Third Symposium (International) on Combustion, Combustion Inst., Pittsburgh.,* pp. 1005-1010, 1995.

[3] Johari, H. Desabrais. K.J., and Hermanson J.C, "Experiments on Impulsively Started Jet Diffusion Flames," *AIAA Journal.,* pp. 1012-1017, 1997.

[4] Becker.H.A. and Yamazaki. S. "Entrainment, Momentum Flux and Temperature in Vertical Free Turbulent Diffusion Flame," *AIAA Journal.,* pp. 1012-1017, 1997.

[5] H. Johari, V. Motevalli "Flame length measurements of burning fuel puffs," ," *Combust. Sci. and Tech.*,, pp. 229-244, 1993.

[6] Kenneth K. Kuo, Principles of Combustion, 2nd edition, *John Wiley*, 2005.