# *Effect of Radiation on the Performance of a Supersonic Combustor*

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***Abstract*—Numerical investigation has been performed to study the effect of radiation on the performance of a supersonic combustor. A two dimensional, compressible, turbulent, reacting flow with multi-step chemistry has been carried out using commercial Computational Fluid Dynamics package Ansys WorkBench 14.0. The radiation modeling has been done using PI radiation model and the reaction rate for turbulent chemistry model evaluated using Finite reaction rate chemistry as available with Fluent. The influence of radiation on performance of the combustor are explored and discussed in details.**

***Keywords—Radiation, Hydrogen fuel Supersonic Combustion, Turbulent Chemistry and Reaction Mechanisms.***

## Nomenclatures

$\rho$ –Density (Kg/m$^3$)

$u_i$–Velocity component with index notation(m/s$^2$)

P – Pressure (Pa)

$\mu_{eff}$–Effective dynamic viscosity (Kg/ms)

$\mu_t$- Turbulent dynamic viscosity (Kg/ms)

$\mu$- Dynamic viscosity (Kg/ms)

h-Enthalpy (J)

$Y_k$-Mole fraction of species K

Cp-Specific heat coefficient (J/KgK)

T-*Temperature (K)*

*Pr- Prandtl Number*

*Sc- Schimdt number*

*R-Universal Gas Constant (J/Kmol.K)*

*Ar-Pre-Exponent Factor for reaction r.*

βr-Temperature Exponent.

Er-Activation Energy (J)

K-Turbulent kinetic energy (m2/s2)

e-Eddy dissipation rate(1/m)

rc-Stochimetric Ratio

$R_k$-Mixing rate of EDC

$H_v$-Heat of the reaction on (W).

$\dot{\omega}$ - Source term for the species /Radiation.

<u>*Suffix*</u>

i,j –Index

eff- Effective

v-Reaction

f-Fuel

o-Oxidiser

## I. INTRODUCTION

The major technical challenges in the development of air-breathing Scram jet engines is the need for having efficient mixing combustion in a supersonic flow field. The combustor length is of the order of a meter and the residence time for mixing and combustion is of the order of milli-seconds. This makes the combustion phenomena more complex. The key parameters in the design of supersonic combustor are the combustion efficiency and stagnation pressure recovery.

The design of supersonic combustor for air breathing propulsion system requires a tough understanding of mixing and the reaction of fuel-air at high magnitude of temperatures and velocities. There has been numerous investigation of both experimental and numerical on the supersonic combustion of hydrogen fuel. Over the years hydrogen fuel have been preferred over hydrocarbons due to its mass diffusivity, wide flammable limits, less ignition energy with distinct disadvantage of its low explosion limits and tank-age requirements.

Burrows and kurkov[1] performed analytical and experimental study of a supersonic combustion of hydrogen in a vitiated stream . The maximum temperature, concentration of hydrogen and oxygen at the center of the reaction zone obtained from the experiments found to compare well with the experimental results. However slight deviation is due to the effect of finite rate chemistry. Analytical study of $H_2$ air reaction mechanism with the application to scram jet engine was performed by Jachimowski [2]. The combustion characteristics as predicted from the developed chemical kinetic mechanism

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were compared with the observed behavior obtained from the shock-tube and the flame studies and found to agree well. The study reveals that the chemical kinetic effects are important and therefore should be taken into consideration while calculating the thrust. The capability of empirical combustion models to predict the mean reaction rate for supersonic mixing layer as evaluated by Chakraborthy et al [4] using the stored time series rate of Direct Numerical Simulation (DNS). Reaction rate profile of the various species obtained from DNS results were compared with the reaction rate profile from the combustion models. Study shows that the Eddy Dissipation Concept model based on the finite reaction rate chemistry can accurately predicted the mean reaction rate at the mixing layer and the general shape of reaction rate profile and the peak values matches well with that of the DNS date at different locations of the fluid field. The mixing and combustion of parallel hydrogen injection into a vitiated air stream in a divergent duct was numerical investigated by Chandra Murty, *et al* [5]. Different turbulence models were Investigation was carried out with infinitely fast rate kinetic and single step kinetics on an EDC-based finite chemistry model with K-ω turbulence model. Very good comparison for various fluid dynamic and chemical variables is obtained for the mixing case. Also single step reaction chemistry performances well in predicting the overall mixing and combustion process in the combustor.

Three dimensional numerical studies has been conducted by Kumaran and Babu [6] to investigate the influence of different chemistry model on the prediction of supersonic combustion in a model combustor. The analysis was carried out as turbulent reacting flow with the detailed chemistry model (37 reactions with 9 species) and the turbulence modeling was done by using Spart-Allmaras model. They used different turbulence model to model the turbulent reacting flows, namely infinitely fast reaction rate and single step reaction for modeling the $H_2$ Air reaction model with finite rate Eddy Dissipation Concept (EDC) model for combustion. The study brought that the different turbulence model K-omega turbulence model captures all essential features of flow with other models. They also reported that the single step finite rate Chemistry model can perform well in predicting the overall mixing and combustion process. Edwards et al [7] performed Large Eddy Simulation and Reynolds Averaged Navier Stocks Simulation LES/RANS of the Burrow and Kurkov reactive flow jet experiment. The simulation results showed good agreement of Mole fractions static temperature and pitot pressure with that obtained from the experimental results by Burrows and Kurkovs.

In a realistic combustion system the temperature involved are very high, therefore the radiation in gases can affect the combustion process and needs to be investigated. Inverse estimation of inlet parameters such as species mass fraction and inlet velocities of fuel oxidizers with the thermal radiation effect was done by Lee and Beak [8]. Repulsive particle swam optimization method (RSPO) was implemented as inverse solver to find the inlet mass fraction and velocities of methane and oxidant with given temperature measurements .The study reports that the Repulsive Particle Swam Optimization method can be used for the design optimization of real combustion system with unknown parameters.

The above literature review reveals that even though the gas temperatures in the combustors are very high and therefore radiation effect are significant. Only very few literatures are available in this area. The aim of the work is to numerical investigate the effect of radiation on the performance of a supersonic combustion.

## II. NUMERICAL ANALYSIS.

The numerical analysis of the problem has been performed using the commercial CFD package Ansys Workbench 14.0. The physical geometry consisting of an air inlet through which air at Mach no 3 temperature 1270 K and a pressure 17.1 bar is allowed to enter and flow through the combustor, hydrogen inlet wherein hydrogen is injected transversely at Mach no 1 temperature 500 K and pressure 1.85 bar. The top and bottom wall of the geometry are made participating in the heat exchange process by specifying the emissivity. Physical state of incoming air contains $N_2$, $O_2$ and $H_2O$ of mole fractions 0.65, 0.25 and 0.1 respectively with the fuel air equivalence ratio of 2. Figure 1 shows the schematic of present model.

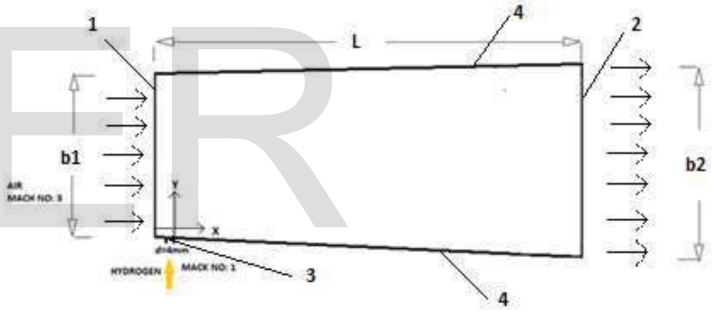

Fig.1 Schematic of present model.

**1-Air inlet (b1=140 mm) 2-Pressure outlet (b2=150 mm) 3-Hydrogen inlet (d=4 mm) 4- Combustor Wall (L=356 mm with wall emissivity 0.5)**

The flow is assumed to be steady compressible and turbulent. The K-epsilon model is used to model the turbulence flow inside the combustor. The governing equations are the following.

### A. *Continuity*

$$\frac{}{}(\rho u_i) = 0 \qquad (1)$$

### B. *Momentum*

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right. \qquad (2)$$

Where $\mu_{\text{eff}}$ contains both molecular and turbulent eddy viscosities, i.e., $\mu_{\text{eff}} = \mu + \mu_t$.

Energy

$$\frac{\partial}{\partial x_j}(\rho u_i \mathrm{h}) = \text{—}\left(\frac{\mu_{eff}}{P_{rt}}\frac{\partial h}{\partial x_j}\right) - H_v \dot{\omega}_f - \text{—} q^R \qquad (3)$$

$$h = \sum_k Y_k\, h_k = \sum_k Y_k \int_{Te}^{T} C_{pk}\,(T)dt \qquad (4)$$

$$\frac{\partial}{\partial x_j}(\rho u_i Y_i) = \text{—}\left(\frac{\mu_{eff}}{Sc_t}\frac{\partial Y_i}{\partial x_j}\right) + \dot{\omega}_i \qquad (5)$$

Where $\acute{\omega}_i$ is the source term due to mixing and reaction.

The second term $(H_v \dot{\omega}_f)$ in the equation (3) and $\dot{\omega}_i$ in equation 4 represent the source term due to combustion and reaction. The third term in equation 3 represents the radiation source term. These terms gets included in the energy equation and species transport equation by enabling the combustion (Species transport) and radiation (P1) models available in Ansys workbench 14.0. In P1 radiation model to account for the effect of wavelength dependence of gas emissivity and absorptivity for grey gas, Weighted Sum Grey Gas Method (WSGGM) Concept is employed. The scattering coefficients (0.2) and Wall emissivity (0.5) have been kept constant .The enthalpy in equation (4) enthalpy h is the sum total of energy possessed by all the species.

It is worth to mention here that $\dot{\omega}_f$ is a function of thermal diffusivity and $\dot{\omega}_i$ is a function of mass diffusivity (for details see [10]. The kinetic theory option available in Ansys workbench takes care of these coefficients. The properties effective viscosity specific heat and thermal conductivity of each species is evaluated by enabling the Sutherland law and mass weighted mixing law options available in Ansys workbench 14.0.

While employing the k-ε turbulence model and species transport model the estimation of reaction rate and mixing rate are essential. Reaction rate is found out using Arrhenius equation as shown.

$$k^{f,r} = A_r T^{\beta r} e^{-\frac{E_r}{RT}}, \qquad (6)$$

Where $k^{f,r}$ is the reaction rate for the forward reaction r. For the present model 7 step reaction mechanisms is selected based on the studies of Jachiwolski [1]. While using the reaction rate equation, the constants in equation (6) are taken from the Table given below.

Table.1 Multi-step reaction with Arrhenius constants [1]

| **Sl no** | **7 Step $H_2$-Air Reaction Mechanism [1]** | | | |
|---|---|---|---|---|
| | ***Reaction*** | ***Ar*** | **βr** | ***Er*** |
| 1 | $H_2+O_2 \rightarrow OH+OH$ | 1.70 E+13 | 0 | 48000 |
| 2 | $O_2+H \rightarrow OH+O$ | 2.20 E+14 | 0 | 16800 |
| 3 | $H_2+OH \rightarrow H_20+H$ | 2.16 E+08 | 1.51 | 3430 |
| 4 | $H_2+O \rightarrow OH+H$ | 5.06 E+04 | 2.67 | 6290 |
| 5 | $OH+OH \rightarrow H_20+O$ | 1.50 E+09 | 1.14 | 0 |
| 6 | $OH+H+N_2 \rightarrow H_2O+N_2$ | 8.62 E+21 | -2 | 0 |
| 7 | $H+H+N_2 \rightarrow H_2+N_2$ | 7.30 E+17 | -1 | 0 |

Mixing is determined using Eddy dissipation concept

## B. *Boundary Conditions*

No slip for velocity components and zero normal pressure gradients are the boundary condition used for the top and bottom walls .The wall surface is treated as radiation exchange surface and the emissivity is specified. At the inlets (Air and Hydrogen) of the computational domain the Velocities of air and hydrogen is specified where as static pressure at the exit is taken as atmospheric pressure. Mathematically the boundary condition can be described as follows

. At the inlet At the outlet

Inflow $\begin{cases} \mathrm{U} = U_i \\ \mathrm{V} = V_f \end{cases}$ Pressure outlet, P=$P_{atm}$

On the top and bottom wall,

No slip condition U=0, $\frac{\partial p}{\partial n}$ =0, ε =0.5

## C. *Computational Domain and the Grid.*

A 2D computational domain has been created for the numerical computations .The computational domain is discretilised using uniform structured Quadrilateral grids. A grid sensitivity study has been conducted to arrive at an optimum grid for the numerical simulation. A summary of the results pf the grid independence study is shown in table 2 .clearly the results shows that the peak value of hydrogen at the combustor exit is insensitive with no: of grids of 1,81,076 .

Table.2 Grid Independence study.

| **No of Grid Cells** | **Peak value of $H_2O$ Mole Fraction Without Radiation** | **Peak value of $H_2O$ Mole Fraction Without Radiation** |
|---|---|---|
| 60702 | 0.396 | 0.391 |
| 74482 | 0.385 | 0.376 |
| 83540 | 0.373 | 0.370 |
| 144605 | 0.364 | 0.363 |
| **181076** | **0.361** | **0.362** |
| 244758 | 0.359 | 0.360 |

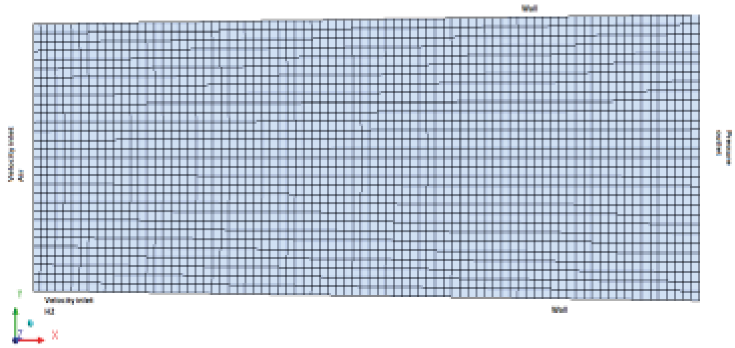

Fig.2 Computational domain and Grid.

The important parameters Considered in this study are the following:

A. *Combustion Efficiency ($\eta_c$)*

Combustion efficiency is the degree of completeness of chemical reaction. It is calculated based on the amount of fuel converted to products of combustion.

$$\eta_c = 1 - \frac{\int \rho u \, Yf \, dA}{(\rho u \, Yf \, dA)x{=}0} = 1 - \frac{(m_f)}{(m_f)_{x=0}}$$

Where $(m_f)_{x=0}$ is the mass flow rate of fuel at the injection point.

### B. *Stagnation Pressure Recovery($P_{orec}$)*

The total stagnation pressure recovery is defined as

$$P_{orec} = \frac{\int \rho \, u \, P_o \, dA}{\int \rho \, u \, (P_{o\,(x=0)})\, dA}$$

### D. *Solution Procedue .*

The fluent solver available in Ansys workbench 14.0 uses control volume approach to solve the governing equation of fluid flow, heat transfer and species transport [11,13,14 ]. The density based steady state solver has been selected for present solver. The first order upwind scheme is used to solve the continuity and momentum equation. Energy and species transport is solved by using the second order upwind scheme. The coupling between the velocity and pressure is resolved by SIMPLE .Non linearity of the equation demands the solution to be progressed in a controlled manner with the use of relaxation factors. Under relaxation factors used in the present study for pressure, momentum, energy and species are 0.1.Convergence of the solution is checked by examining the residue of mass, momentum, energy and species. Iterations terminated when maximum of all the residue reaches less than 1 x $10^{-4.}$

## III. VALIDATION

To validate the present numerical model, simulations were performed on the same geometry as that considered by Burrows and Kurkov [1] in the experimental work. In this experimental work vitiated air enters axially and hydrogen in injected parallel to the stream. All the flow and physical state of vitiated air and hydrogen is same as that employed in the experimental work of burrows and kurkov [1].

Fig. 3 shows the combustor exit $H_2O$ profile obtained from the numerical simulation without radiation and that reported in the experimental work of Burrows and kurkov [1]. The figure reveals that the nature of the $H_20$ profile in the numerical and experimental work compares well. This establishes the efficacy of the proposed methodology in solving this kind of problem. However the peak value of H2O mole fraction shows a deviation of 10.7 % for the model without considering radiation compared with the experimental work. This deviation is due to experimental uncertainties.

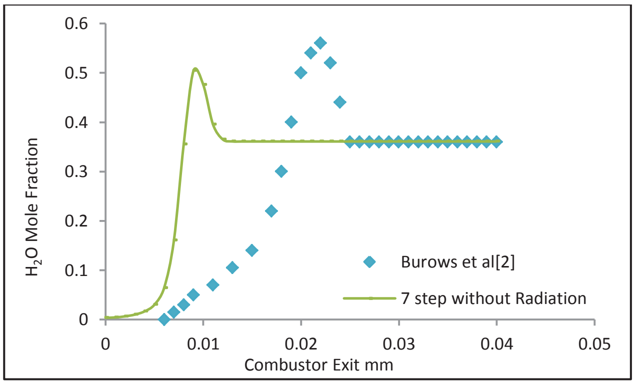

Fig.3 Combustor exit profile comparison for validation

## IV. RESULTS AND DISCUSSION

Actual reaction mechanism consists of number of reactions and to model this reaction it is difficult. According to the results of the studies conducted by Jackowlski [1] in a shock tube it was reported that a 7 step reaction mechanism could fairly accurately predict the overall performance of a supersonic combustor. With this in view we have also performed simulation by considering 7 step reactions.

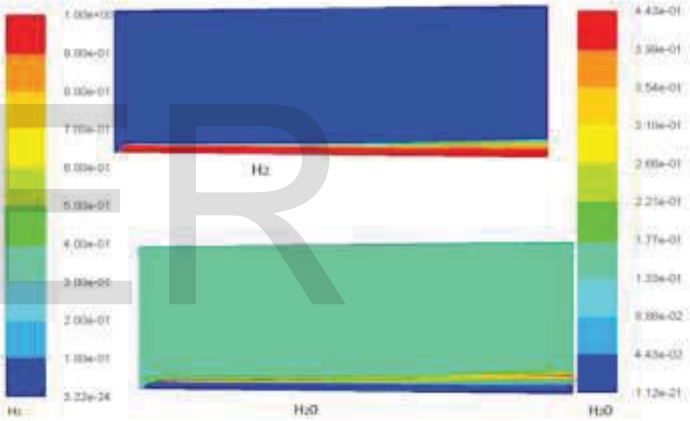

Fig.4. Contours of Mole fraction of $H_2$ and $H_2O$ for 7 Step model without Radiation.

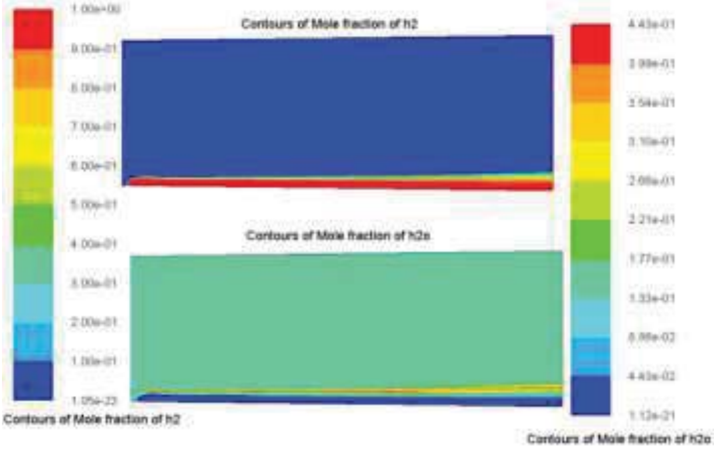

Fig.5 Contours of Mole fraction of $H_2$ and $H_2O$ for 7 Step model with Radiation.

The contours of mole fraction of $H_2$ and $H_20$ shown in Fig 4,5 depicts that the mixing and reaction of $H_2$ –Air takes place at a region near the surface of the bottom wall. When radiation is incorporated in the analysis the temperature at each section along the length of combustor increases than without considering radiation. This can be seen from the temperature profile at the exit of combustor plotted in Fig. 6. However other sections also show similar trend but not shown here for brevity. The higher temperature at the combustion exit is due to the emissivity of walls and also due to the scattering effect of the medium ($H_2$ Air mixture) .This leads to increase in the rate of reaction and an increase in the mole fraction of $H_2O$ as reported in Table 3.

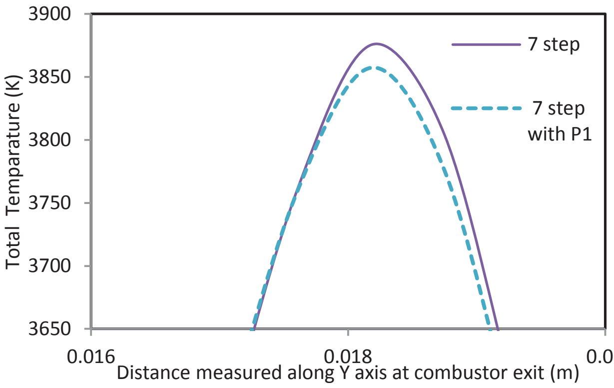

Fig 6 Total temperature (K) at combustor exit for 7 step chemistry with and without Radiation.

Table 3 Comparison of peak values of $H_2O$ at combustor exit.

| Reaction Mechanism | For Multi-step reaction with and without radiation at the axial location of y=0.01818 mm | | |
|---|---|---|---|
| | $H_2$ | $O_2$ | $H_2O$ |
| 7 Step | 0.087 | 0.013 | 0.406 |
| 7 Step with radiation. | 0.085 | 0.015 | 0.409 |

The important performance parameters of supersonic combustor are combustor efficiency and thrust. The combustion efficiency is a function of mass flow rate of fuel. For a particular section as the reaction rate increases more amount of fuel is getting converted to $H_2O$ and therefore $m_f$ decreases resulting in higher combustion efficiency. This increase in mole fraction of $H_2O$ due to the inclusion of radiation in the analysis has been explained earlier. This fact is clearer from the plot of the combustion efficiency reported in Fig. 7.

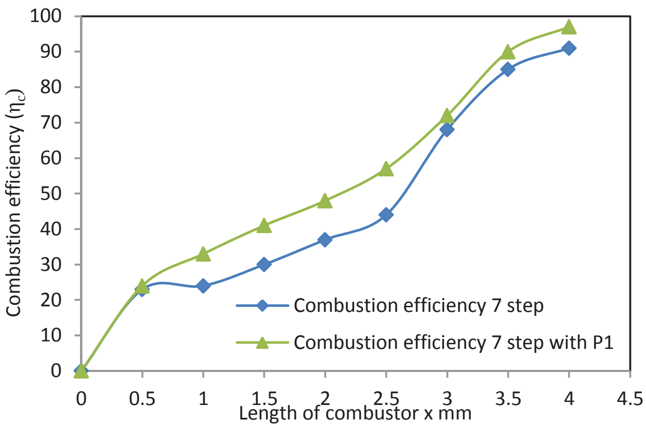

Fig 7. Combustion efficiency along the length of combustor

The thrust in a rocket chamber is a function of stagnation pressure loss [14] .The stagnation pressure loss is a function of stagnation pressure recovery. The stagnation pressure recovery depends on viscous dissipation in boundary layer, weak oblique shocks, fuel-air mixing and chemical reaction. The Mach no contour shown in Fig .8 indicates that the radiation does not affect the strength of the shock and therefore the pressure loss coefficient is not affected. Since the combustion takes place in supersonic speeds the radiation does not affect the viscous dissipation in the boundary layer. The main factor which is contributing in the pressure recovery is the mixing and reaction rate. Even though the radiation enhances both mixing and reaction rate and correspondingly there is an increase in pressure recovery as seen in Fig. 9, this pressure recovery is only marginal at the exit (Fig. 9). Therefore there is only slight variation in the thrust.

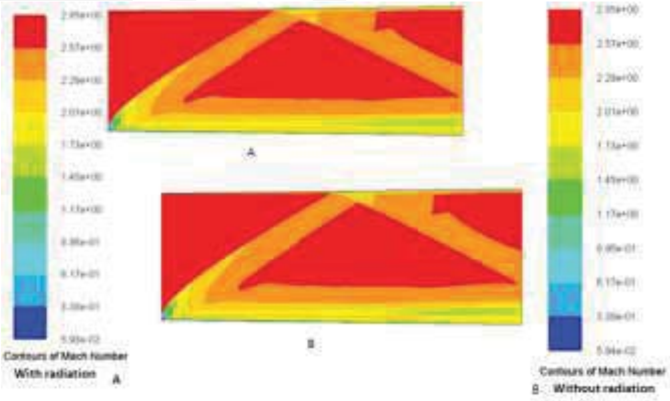

Fig .8 Mach no contours

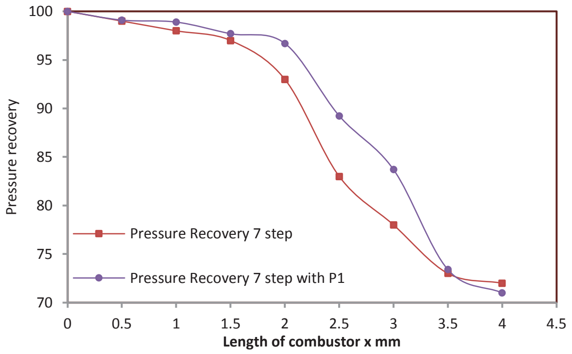

Fig 9. Pressure recovery along the length of combustor

### Effect Of Radiation On Wall Temperature Distribution

Figure 10 shows the temperature distribution on the top wall for a surface emisivity of 0.5. Since the lower wall temperature is widely affected by a layer of un-reacted hydrogen, temperature along the top wall is chosen for comparison. It can be infered from the figure the overall wall temperature is less when radiation is included. This results in reduction of cooling load in the walls of the combustion chamber. It is important to note here that at distance of approximately 17.6 cm from the inlet there is a sudden increase in temperature. This increase in temperature is almost the same for the top wall with and without emisivity. The increase in temperature is due to the reflection of the weak oblique shock as seen in Fig. 8. Since the temperature rise is the same the shock strength is affected only marginally and therefore doesnot significantly influence the pressure recovery as reported earlier. The overall surface temperature of top wall decreases by about by 10 K for the surface emisivity of 0.5.

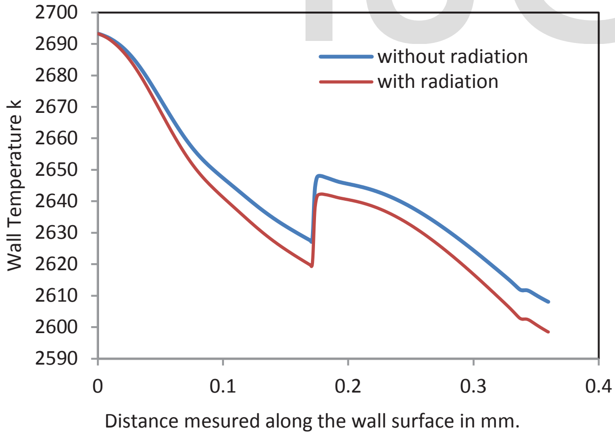

Fig 10. Top wall temperature distribution.

## V. CONCLUSION

In the study, a two dimensional finite reaction rate EDC based Turbulence chemistry model with radiation is carried out for hydrogen fuel transversely injected into a supersonic flow is simulated numerically. The presence of radiation from the wall as well as the participating medium ($H_2$ -Air mixture) to scatter can significantly affect the combustion phenomena of the supersonic combustor. The study also reveals the below facts that:

1. The $H_2O$ mole fraction profile obtained from numerical simulation compares well with the result of Borrows and Kurkov's thereby establishing the proposed methodology.
2. The combustion efficiency is found to increase when radiation model is incorporated in the analysis. This increase is attributed to the increase in the mole fraction of $H_2O$.
3. The radiation has only marginal effect on the thrust. This is because the mixing and reaction rate has only slight influence on pressure recovery.
4. The cooling load on the combustion chamber reduces because the overall wall temperature decreases due to radiation.

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