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Analytical and Numerical Analysis of Micro Combustor for Gas Turbine Engine

R. R. Shah[1] and D. B. Kulshreshtha[2]

[1]CHARUSAT, Anand–388421, India; 1ronak28@yahoo.com and
[1]A. D. Patel Institute of Technology, Vidhyanagar, Vitthal Udyognagar–388121, Anand, Gujarat, India
[2]Department of Mechanical Engineering, C. K. Pithawalla College of Engineering and Technology, Surat–395007, India; digvijay.kulshreshtha@ckpcet.ac.in

Abstract

Objective: For power generation through micro gas turbine, the micro combustion chamber is essential component. Due to higher flammability limits and less reaction time as compare to hydrocarbon fuel, hydrogen is selected as a fuel. For design and fabrication of micro combustion chamber analytical and numerical analysis is required to study. Analysis with variations in reactant inlet temperature from lean condition (Equivalence ratio = 0.1) to fuel rich condition (equivalence ratio = 1.2) was taken. The optimized results obtained from analytical study are used as designed parameters for design of micro combustor. Methods Statistical Analysis: O'Conaire, GRI Mech 3.0 and O'Conaire reaction mechanism with Zeldovich NO are used for hydrogen or air combustion analytical studies. O'Conaire mechanism with Zeldovich NO is used in computational fluid dynamic studies using ANSYS CFX software. For numerical study, the BVM partial premixed combustion model is used for calculation of 41 reaction and 11 reactive species with Zeldovich NO. Finding: For three different chemical reaction mechanisms, the flame temperatures at different equivalence ratio were evaluated. The increase in the equivalence ratio from 0.1 to 1.2 resulted in increase of the flame temperature up to the stoichiometric condition and thereafter decreases. Results of simulation show good agreement with analytical studies. At 0.132 equivalence ratio (), flame temperature is around 670 K, deduce from both chemical kinetics and CFD simulation. Application/Improvement: Combustion process is effectively work at lower equivalence ratio in micro scale combustor which is summarized after analytical and numerical analysis. At lower equivalence ratio, heat losses are reduced which results in higher efficiency of the micro combustor in gas turbine engine during experimental work. The main application of electricity generation via the heat released by the combustor using the Seebeck and Peltier effect.

Keywords: Equivalence Ratio, Flame Temperature, GRI Mech 3.0 Mechanism, Micro Combustion, O'Conaire Mechanism

1. Introduction:

This paper aims to make efficient micro combustion chamber for gas turbine engine before analytical and numerical analysis of micro combustion using theoretical and numerical simulation in micro combustor. The energy density of conventional hydrocarbon (40 MJ/kg) and hydrogen (120 MJ/kg) exceeds that of lithium ion batteries by factor of 35 or 100[1]. Therefore, small size of combustor having higher energy-density, higher heat and mass transfer coefficient and smaller recharge times compared to electrochemical batteries will be highly appreciated to micro power device. Thus during the last decade, many feasibility studies have focused on the development new portable power generation systems. Micro Electro-Mechanical Systems (MEMS) have led to the possibility of a new generation of micro heat engines for power generations that use a fuel such as hydrocarbon or hydrogen as an energy source.[2]

At micro scale, many difficulties occur to measure the physical quantities. Therefore combustion chamber design, numerical simulations of small-scale combustors

**Author for correspondence*

are especially important to determine the combustion features. The challenges and preliminary design of a combustor were described[3]. It is very difficult to propagate flames in a very small gap of mm size, which is known as quenching distance. This result in higher heat losses to the surrounding becomes larger as compared to a standard sized flame and stability of flame is also reduced[4]. Experimentally, the stability and feasibility of the combustion at micro scaled combustor has been proven[5]. Norton and Vlachos[6] found the premixed methane/air flames stability in a micro combustor with CFD simulation.

In Swiss role, the spiral counter-flow with heat re-circulating burner was investigated in micro scale combustion[7]. They carried out the experimental work and found stable combustion and less heat losses in double Swiss role micro combustor with using different catalyst. The Numerical analysis indicate the flame temperature is lower for the smaller combustor[8] by the fact that as the combustion chamber size decreases, the ratio of surface area to volume increases. Consequently, heat loss from the wall of chamber is increased, which effect on flame temperature. Due to wider flammability limits and an order of magnitude lower chemical reaction time than hydrocarbon fuel, hydrogen was preferred as a fuel[9]. Hydrogen combustion in the combustor given high combustion efficiency (over 99.95%), high heat release rate (up to 3.5 * 10^3MW/ (m^3.MPa)) and low NO_x emission levels (6-25 ppm) in comparison with hydrocarbon combustors[10].

Micro combustors lead to increased levels of temperature compared to conventional chambers, leading to high heat losses. This heat loss is utilized to heat the incoming air/fuel mixture[11]. This also leads to reduced fuel addition and hence lower overall equivalence ratio. The details of the combustor studies can be summarized as, "A counter flow type, with openings for reactants and products, and rectangular cross section is coiled around a central combustion zone. The reactant channels and product channels are coiled around each other to reduce heat loss and preheat the incoming reactants." The chamber is similar to the one described[12]. The present paper is an attempt to design micro combustion device for gas turbine application using the Swiss Roll Concept. The chamber is designed by first evaluating the required combustor volume using the conventional design approach[13]. It was studied numerically for CH_4-air premixed combustion in micro combustor with examine the geometry, size of chamber and inlet velocity with reference to flame temperature. Based on combustion analysis of flame, achieved maximum flame temperature with complete combustion of air-fuel.[14] It means the flame temperature is the most important parameters to characterize a combustion process [15]

High energy conversion efficiency is essential for smooth working of micro combustion chamber. It is necessary to consider the effects of heat loss, radical loss, excess enthalpy, wall-flame thermal/chemical coupling, fuel-air mixing, liquid fuel vaporization, flow field, and non-equilibrium transport on ignition, burning rate, flame temperature, and flame stabilization. All the above parameter is affected the maximum flame temperature inside the combustion zone which is analytical and numerical analysis at different equivalence ratio in paper.

2. Micro Combustor:

The present paper discusses about analytical and numerical analysis of the micro combustor chamber. A concept of the new Swiss role type micro combustion chamber which is shown in Figure 1. The combustion chamber design based on a counter flow type, with openings for reactants and products, and rectangular cross section is coiled around a central combustion zone. The reactant channel and product channels are coiled around each other to reduce heat loss and preheat the incoming reactants. Using the design data calculating the volume of combustion chamber's reactive zone volume is taken as 20 mm x 20 mm x 25 mm. The reactants enter through 1mm x 2.5mm channels and the product exit through 4mm x 2.5mm channels. The dimensional drawing of the combustion chamber is given in Figure 2. Reactant and product coils are parallel to each other. An igniter is provided in the central combustion zone. Thickness of the channel wall and combustion zone wall is about 1 mm.

3. Chemical Reaction Mechanism:

Ignition of hydrogen–oxygen mixture be studied theoretically and experimentally[16]. Developed a comprehensive H_2/O_2 chemistry mechanism consisting of 19 reactions. GRI Mech 3.0[17] based on wide spectrum of experimental data obtained in shock tubes and continuous-flow reactors of complete mixing of fuel/air. GRI Mech 3.0, O'Conaire mechanism and O'Conaire mechanism with Zeldovich NO are an optimized mechanisms designed to model natural gas combustion, including NO formation and reburn chemistry. All three mechanisms are used for the 0.1 to 1.2 equivalence ratio with 300 K inlet reactant temperature using hydrogen as fuel.

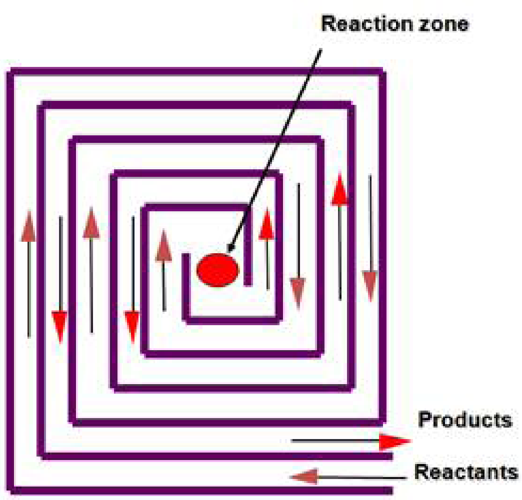

Figure 1. Combustor Concept.

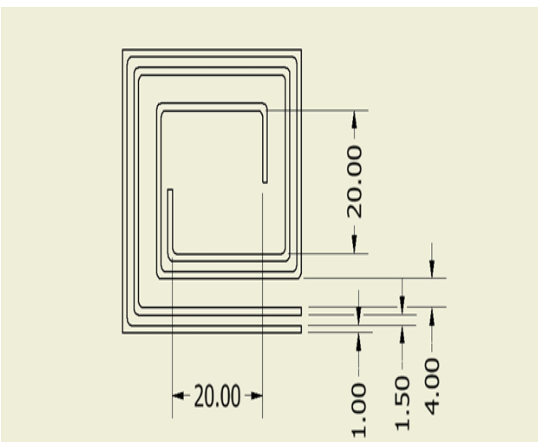

Figure 2. Dimensional Drawing (Dimensions in mm).

In the assembly of the reaction mechanism, reaction were included that involve all the important species in the hydrogen-oxygen system – H_2, O_2, H, O, OH, H_2O, HO_2, H_2O_2, N_2,NO, N and 41 reaction with O'Conaire, GRI Mech 3.0 and O'Conaire mechanism with Zeldovich NO mechanisms are used.

The flame temperature at various equivalence ratio is shown in Figure 3. The flame temperature increasing with increasing the equivalence ratio up to stoichiometric condition due to faster reaction rates with increased temperatures. Due to less availability of the O_2 in rich mixture, the flame temperature decreasing with increasing the equivalence ratio after stoichiometric conditions. The flame temperature is 730 K at ⍰= 0.132 in O'Conaire mechanism and flame temperature is 738 K at ⍰= 0.132 in GRI Mech 3.0 mechanism. At ⍰= 0.7, the flame temperature is 2018 K which is similar in both mechanism. It means the trend of temperature profile of both mechanisms is similar at various equivalence ratios which are shown in Figure 3.

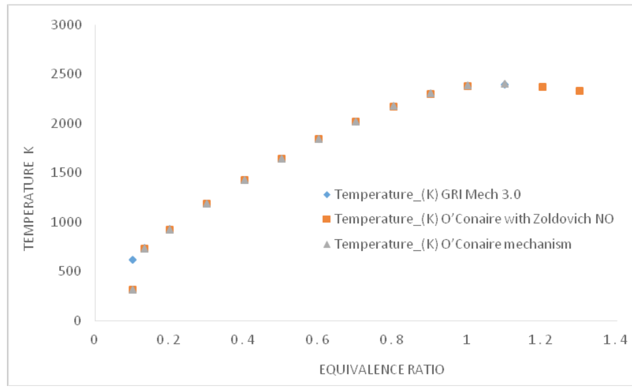

Figure 3. Flame Temperature Vs. Equivalence Ratio.

4. Numerical Analysis:

Computational Fluid Dynamics (CFD) is a tool for visualized the mixing phenomena. CFD is able to predict fluid flow, chemical reaction rate, temperature and heat transfer by solving the appropriate mathematical equations.[18] Premixed hydrogen-air mixture enter in to the combustion chamber. Mixture of reactant enters into the reactant rectangular path and product exit through reversible manor through rectangular slots, which is shown in Figure 4. The BVM Partially Premixed combustion model is used for reactive calculations for 41 reactions and 11 reactive species with Zeldovich NO. The boundary conditions are mass flow rates of reactants, outlet pressure boundary and wall boundary. Transient run is carried out for 5s at time-step of 0.0001s. Spark kernel is defined at this time-step with spark energy of 0.2J.

Initially the reactant (hydrogen and air) enters in to the combustion chamber at 300 K and 1.5 bar pressure. In combustion zone, combustion process starts to generate the high temperature. After steady state is achieved and henceforth no noticeable change is witnessed in the temperature levels in all difference equivalence ratio temperature profile.

The temperature distribution at equivalence ratio (ϕ) is 0.132 is shown in figure 5. Combustion zone temperature is maximum 670 K. Due to low velocity zone combustion is done middle of combustion zone. Low equivalence ratio, low flame temperature, low velocity region and flame stabilization achieved in the reactive zone suggest design superiority achieved. The temperature distribution at equivalence ratio (ϕ) 0.7, maximum combustion zone temperature is 2012 K achieved.

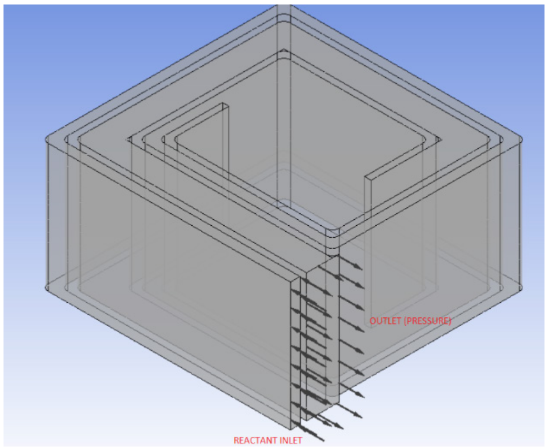

Figure 4. CFD Model with Boundary Conditions.

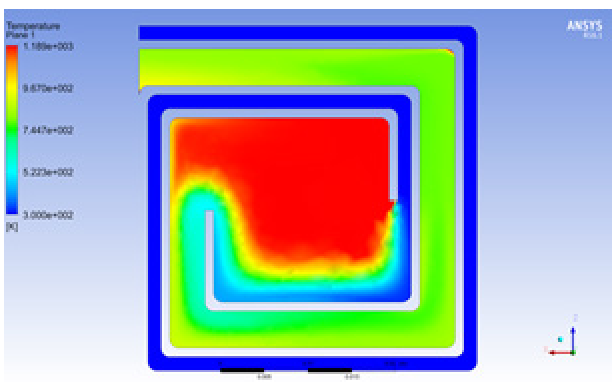

Figure 5. Temperature Profile at ⍰ = 0.132.

The stable flame is achieved at the reaction zone. But near the corners, where the chamber rectangular slots turn by 90^o, the walls show the formation of hot spots. The hot spots are formed on the walls of the chamber. Which is shown in the combustion zone temperature is 2367 at rich mixture ϕ = 1.2. After steady state condition flame is stabilized and no back pressure effect seen in .Temperature is increasing with increasing equivalence ratio with hot spot is also generated at high equivalence ratio compare with lower equivalence ratio.[19] The results are shown in Figure 6, 7 and 8 reveal that higher equivalence ratio, less residence time and generates hot spot on the product path wall which lead to reduced efficiency of micro combustor and chance for damaging the micro combustor due to poor bonding.

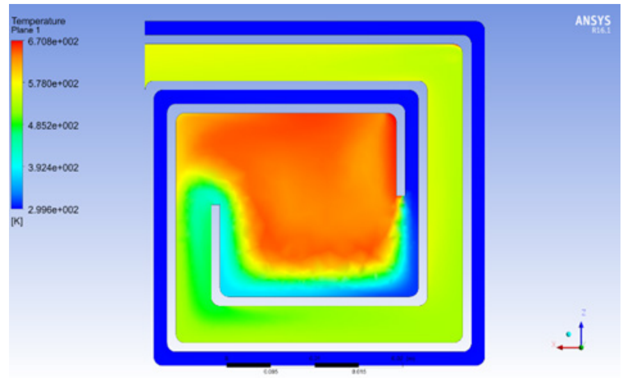

Figure 6. Temperature Profile at ⍰ = 0.3.

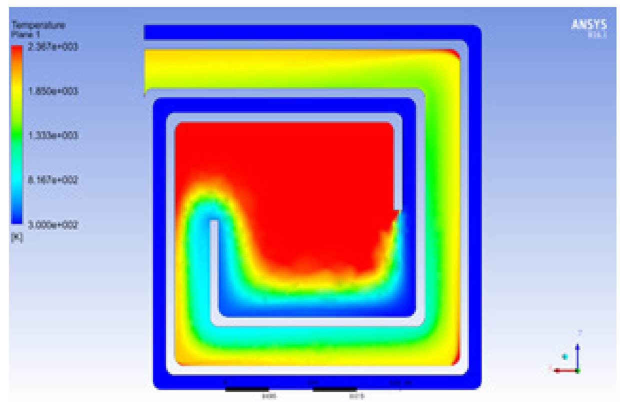

Figure 7. Temperature Profile at ⍰ = 0.7.

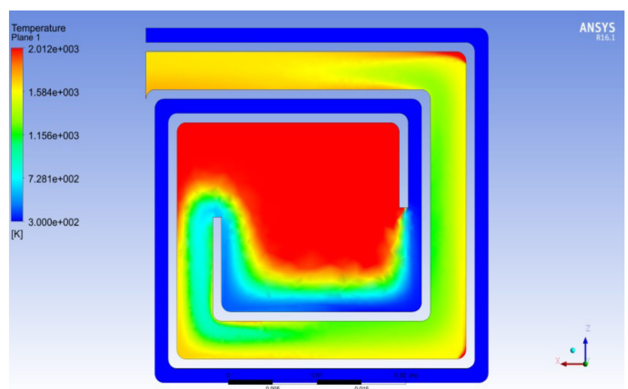

Figure 8. Temperature profile at ⍰ = 1.2.

5. Conclusion:

Chemical Reaction Mechanism and Numerical analysis of micro combustor using hydrogen fuel is carried out for micro gas turbine engine. Kinetic studied by O'Conaire mechanism with Zeldovich NO and GRI Mech 3.0 mechanism with different equivalence ratio. The temperature of burnt mixture gases is higher (2379 K) at stoichiometric mixture fraction during combustion. ANSYS CFX used BVM partially premixed model for numerical simulations. The temperature increases with increases the equivalence ratio up to stoichiometric conditions. Maximum temperature (2383 K) is achieved at stoichiometric condition. The flame temperature results at different equivalence ratio with three different reaction mechanism and CFD CFX simulation at 300 K inlet reactant temperature is shown in Figure 9. In micro combustor at lower lean equivalence ratio (0.132) combustion is completed with lower temperature (670 K) and the flame stability achieved at steady state condition. Stabilization of flame is achieved because of low velocity region in the reactive zone and reaction time is more at lower equivalence ratio. The pockets of low velocity near the wall lead to the generation of hot spots in higher equivalence ratio temperature profile. It means that micro scale combustor successfully works on lower equivalence ratio with lower temperature is studied by both kinetic mechanisms (O'Conaire mechanism with Zeldovich NO and GRI Mech 3.0 mechanism) and CFD result of temperature profile. The similar trend of flame temperature with various equivalence ratio through analytical and numerical simulation studies. Numerical analyses is useful to selecting new micro combustor chamber material, wall size and improve the efficiency of micro combustion chamber with reduction in heat losses.

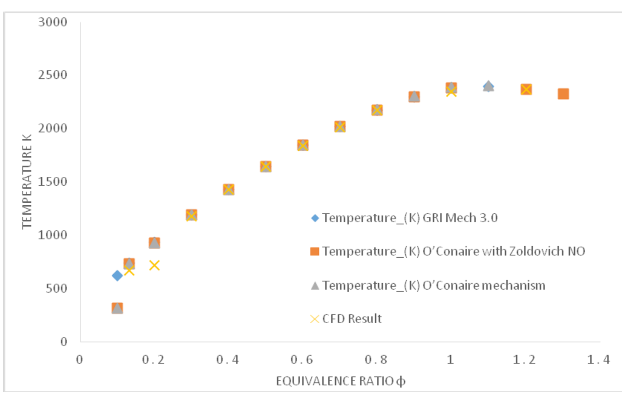

Figure 9. Flame Temperature Vs. Equivalence Ratio.

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