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914 – 919

Title: CFD Analysis of a Swiss-Roll Combustor for Flame Stability, Temperature and Pressure Variations

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ABSTRACT

Compact energy sources are apparently the future of energy production. Evidently, Micro Electro Mechanical Systems (MEMS) are developing at a fast pace. For the production of electrical energy by thermal means, combustion is the easiest way to produce heat and it has been found that double spiral burners are very efficient in doing so. These units are a better option not only because of the space constraint present in the other sources, but also because of the kind of fuels that are being used to generate energy from these systems. Studies suggest the use of hydrocarbon fuels in micro-combustors since these fuels have been found to have high energy density as compared to the other energy sources. Efforts have been hereby made to study the effect of change of equivalence ratio on the maximum adiabatic flame temperature and pressure drop inside a Swiss-roll shaped combustion chamber, thus resulting in an approach specifically aimed at obtaining optimal conditions for the operation of the unit using computational fluid dynamics (CFD). Current work also provides an insight into the commercial aspect that is expected to go hand in hand with the technical developments of the concept.

Keywords*: Swiss-roll, MEMS, CFD, Dan-Köhler number, etc.*

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1. INTRODUCTION

Thermal energy is predominantly used in numerous operations these days. In power generation too, thermal energy plays an important role. It is a well-known fact that combustion is the easiest way of producing heat. Also, when it comes to the generation of power using heat, it all narrows down to a few factors, viz. efficiency and space requirements. To efficiently use all the space that is available at hand, efforts are being made to study micro- combustors which fit into the smallest of places and are capable of producing power. Specially designed Swiss-roll shaped combustors have been found to do the required job quite efficiently. These spiral shaped, counter-current heat-

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recirculating 'Swiss-roll' combustors have been studied for over a three-decade period of time by using simple two-dimensional CFD models for temperature dependent properties, transport, turbulent flow, one-step chemical reaction, surface-to-surface radiation, and heat losses.

The combustion chambers under the scope of study have been fed hydrocarbons as fuel, for they have high energy density as compared to even the most developed lithium-ion batteries that exist around us. Hence, the use of hydrocarbons in the combustion processes for electrical power generation provides better alternative to batteries in terms of energy storage per unit mass and in terms of power generation per unit volume. Though, there is still a need to study different aspects of combustion to reach a point where the combustors in question give us the most favourable results. Manufacturing the units pertaining to given specifications may become cumbersome and is actually quite vulnerable to failure. Hence, it is sensible to initially design a computational model which is operated upon by feeding it required constraints and then reach the optimal conditions of combustion. Computerised simulation can also be used to analyse and calculate the dimensionless parameters that affect the performance of the unit.

Following properties related to the Swiss-roll shaped combustion chamber have been studied:

- Fuel density variations
- Dan Kohler number
- Max. adiabatic temperature for different equivalence ratios
- Pressure variations in the channels
- Velocity variations in the channels

As far as the use of combustion for power generation is concerned, even today, automotive and aviation vehicles use internal combustion engines for prime moving and generation of electricity almost to the exclusion of batteries because of the advantages like space saving and efficiency. Even in vehicles whose mass is less than 1 kg, these advantages of combustion processes have not yet been exploited for the generation of electrical power viz. small scale systems like laptops, mobile phones etc. This study also tries to focus upon the commercial aspect of the subject by putting forth the future scope this concept has in store for technology.

2. OBJECTIVE

The objectives of this research are enlisted below:

- Utilising easily available fuel in the best possible manner
- Analysis fuel recirculation using CFD
- Analysis of combustion of chosen air-fuel mixture
- Obtaining stable flame and designing the inlet channel width
- Obtaining adiabatic flame temperatures and pressure drop at different equivalence ratios

The main objective of this research is providing an alternative to the conventional sources of energy generation. Using readily available fuel in the form of LPG to produce stable flame in the spiral combustor is something to be tried during the course of the research. Initial aim is to get desirable recirculation in the combustion chamber using the CFD software. Later, the combustion is to be achieved using the mixture of selected fuel and air. When combustion is achieved, a stable flame is to be obtained inside the combustion chamber. Further objectives include the study of adiabatic flame temperatures, Dan-Kohler number and pressure variations for different equivalence ratios.

3. MODELLING

A double spiral combustion chamber is designed in CREO. As can be seen from the displayed diagram, there are two channels which are used for inlet of fuel and outlet of exhaust gases respectively.

The specifications of the model are as follows:

1. Material: Stainless Steel
2. Inlet channel width: 2mm
3. Outlet channel width: 3mm
4. Spark positioning: The position of the spark is defined at the centre of the combustion chamber
5. Central chamber: The dimensions of the central chamber are 10mmX7mm

6. Wall thickness: 1.5mm
7. Mesh size: 10^{-4}mm (since 10^{-5} gets too cumbersome and anything less than 10^{-4} results in lesser accuracy) Initially the chamber size was tried as 7mmX10mm (inlet was along the 10mm side), but the results were not favourable and hence 10mmX7mm size was finalised (inlet is now along the 7mm side).

4. SIMULATION

Initial stages of the project began with trials to gain flow recirculation inside the combustion chamber. Air was used as a fluent and it was found that analysis for flow recirculation failed a few times, which is undesirable for combustion.

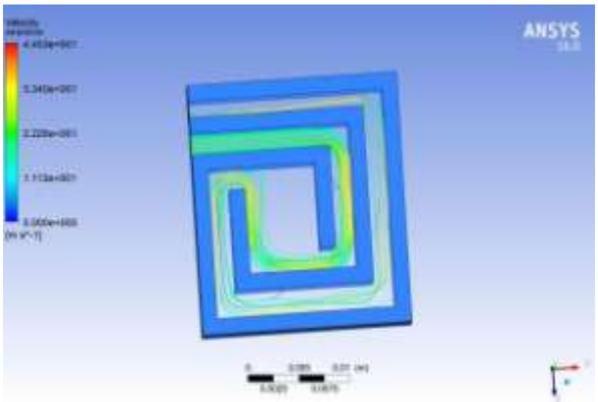

Fig.4.1.Initial recirculation
Photograph shows how recirculation obtained was ineffective

On changing the meshing size and making the mesh finer, it was seen that the results improved. Furthermore, inlet fuel velocity values were changed and on trying different values, a velocity of 4.6m/s was found to be optimal.
The exhaust wasn't favourable in the initial stages but on finer meshing, the exhaust was obtained smoothly. It meant that for the chosen fuel, the chosen air-fuel ratio and the location of the spark, the fuel recirculation and combustion obtained was optimal.

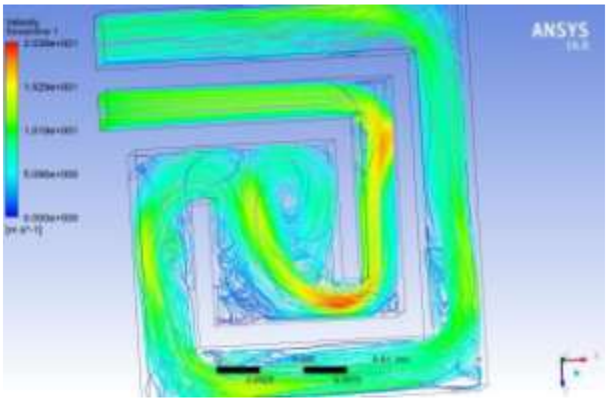

Fig.4.2 Final recirculation
Photograph shows how better recirculation of flow was obtained
Desirable exhaust was obtained

Recirculation being achieved, the next stage was combustion. On studying different papers relating to similar structures, it was decided that Reynolds' stress model be used for combustion. With the same velocity of 4.6 m/s, a mixture of LPG and air was used for combustion. The partial premix model was selected as it was found to correlate with the actual setup.

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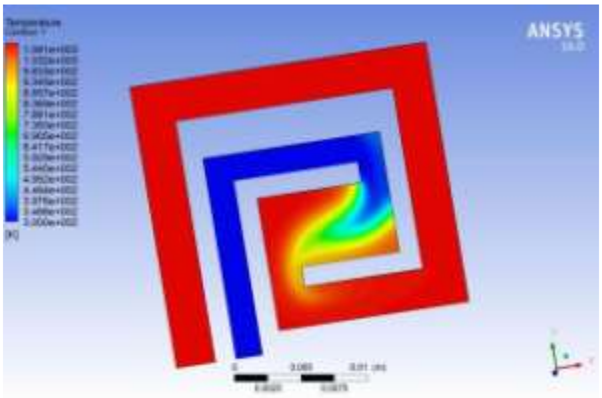

Fig.4.3. Temperature distribution

The flame was obtained in the vicinity of the centre as seen the figure and also the pressure variations can be be analysed for the simulation results.

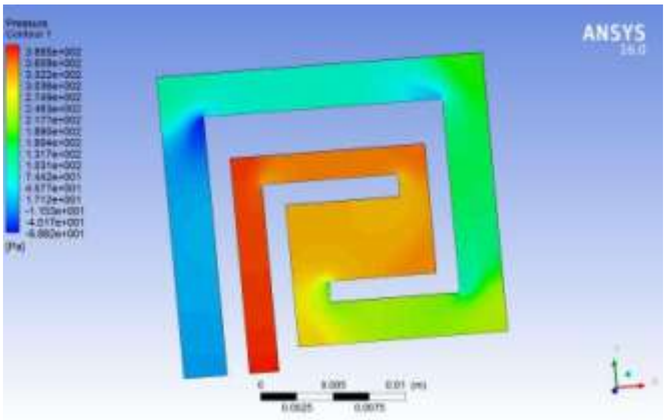

Fig.4.4. Pressure variations

5. RESULTS

The analyses for the stable flame were carried out at different equivalence ratios and the trends of the plot of equivalence ratio vs adiabatic flame temperature can be studied. The variation of Dan-Kohler number and also the pressure variations are obtained.

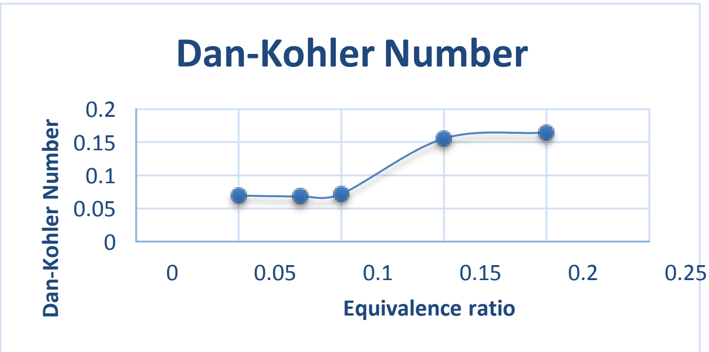

Fig.5.1. Dan-Kohler number v/s Equivalence ratio

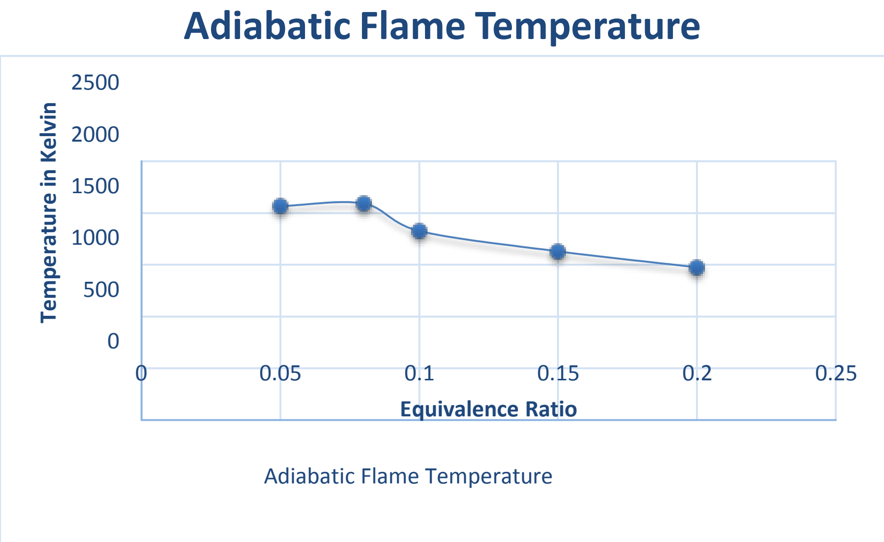

Fig.5.2. Adiabatic Flame Temperature v/s Equivalence ratio

The adiabatic flame temperature is maximum at an equivalence ratio and decreases on both the sides if we increase or decrease the equivalence ratio, so the optimum ratio is to be selected in accordance with the required Dan-Kohler number.

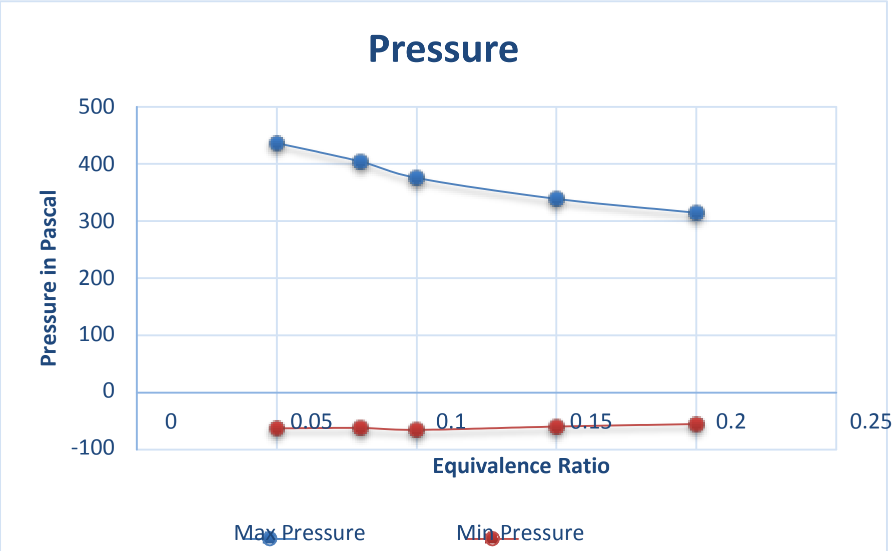

Fig.5.3. Pressure v/s Equivalence ratio

After optimizing the equivalence ratio for the required flame temperature now the pressure drop across the combustor should be taken into account. The pressure drop should be maintained in the allowable range.

6. ADVANTAGES

The advantages of the design that has been studied are:

1. By using CFD methods, many flow problems can actually be simulated in conditions closer to real-life.
2. Swiss-roll combustors accumulate lesser space.
3. Fuel used in the combustors has very high energy density as compared to lithium-ion batteries.

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CONCLUSION

A model of Swiss-roll combustor was designed in a 3D modelling software (CREO) and was operated upon in ANSYS 14.0. Analysis for flame stabilization was carried out in the micro-combustor with partially premixed LPG-air mixture. Flame stability was obtained in the vicinity of the centre of the micro-combustor. Different parameters viz. adiabatic temperatures, Dan-Köhler number, density and pressure variations inside the combustor were studied at different equivalence ratios. The power output of a thermoelectric device at the maximum obtained adiabatic flame temperature was found to be in correspondence with the power output of thermoelectric generators which are used to run low wattage devices, which is a suggestive sign that in the future high wattage devices can also be run using the same setup.

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