A Review on the Effect of Geometries of the Small Scale Combustor on its Performance

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ABSTRACT

With the advent of the new micro scale technologies fabrication of the small scale power generator has become very easy. Mainly portable power generators are targeted. Looking at the issues at the small scale of the power generator, various parameters like flame stability, material sustainability, minimum heat losses, minimum connectivity issues are focused. Present work gives idea about the precise review which is conducted on various geometries of the small scale combustors and its effect on flame quenching / flame stability and flame propagation. Out of the geometries studied suitability of the Swiss roll combustor for various small scale power generation applications is discussed as it uses regenerative preheating which helps in flame stabilization. Various parameters like equivalence ratio, flow velocity (Reynolds number), dimensions of the small scale combustor, residence time (Damkohler number), heat loss coefficient, thermal conductivity, internal radiation coefficient etc. were studied and its effect in geometry to get the stable flame inside the combustion space is precisely discussed in this review paper. Small conclusions for every point are mentioned properly. Future scope for further study is also discussed.

Keywords: ***small scale power generation, combustor geometries, parametric study***

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1. INTRODUCTION

There is continuous development going on in small capacity power generators and thus the importance of small energy source has grown. This is possible because of developments in the technologies handling fabrication / production of the components in the assembly of the power generator. Lot of progress is being done in small scale heat recirculation combustors [20, 21]. The major source of power production on macro scales in earlier days was I.C. engines. There are many moving parts in I.C. engines and hence the friction losses take place. Although these friction losses are not significant at macro scale, they become dominant in micro scale power production. So at micro scale it is necessary to use minimum no of moving parts. The Swiss Roll combustor has no moving parts hence it can be used for small scale power production. Also at small scale the implementation of I.C. engines is difficult. Use of the hydrocarbon fuels in the small scale power generation is preferred over the commercially available Li – ion batteries because hydrocarbon fuels have higher energy densities of about 45MJ/kg whereas lithium ion batteries have energy densities of 0.5MJ/kg [1,2, 23]. Thus even conversion efficiency of the 10 % is beneficial compared to Li – ion batteries as it provides almost 10 times energy conversion from thermal to electrical [3, 22]. Moreover hydrogen is one of the cleanest fuel with no carbon emissions.

For small scale combustors the effect of scale and geometry on thermal efficiency of combustors is of great importance. The combustors are categorized as macro-scale (>1.0 cm), meso-scale (1.0 cm-1.0 mm) and micro-scale (<1.0 mm). When the combustor scale decreases, the surface to volume ratio increases and flame stability decreases. Hence the effect of design parameters on the performance of the combustor is studied.

The main areas covered by the small power generators are, laptop powers, cellular powers, unmanned aerial vehicles (UAV's), Divert and altitude control systems (DACS), micro sensors, small toys, mobiles, bulbs etc.Out of the assembly of the power generators combustion chamber is very important component, because it helps in generation of the heat which is actually utilized to generate power. Flame studies in the various geometries of the combustion chamber were carried out.

Hence this review paper provides a comprehensive review on effect of various parameters like geometry, dimensions, equivalence ratio, flow velocity, heat loss etc. on quenching.

2. CHALLENGES

Combustion in small scale combustors have different characteristics when compared to large scale or conventional combustors. Surface area to volume ratio becomes a critical parameter for small size combustors. Energy released during the combustion depends or is proportional to volume of combustor and heat losses in combustor is proportional to surface area. When this ratio is greater than or equal to one, flame stabilization becomes difficult [4,5]. Flame propagation is one of the problems in small scale combustors. When the gap size is less than the excitation limit the flame does not propagate through it, this limit is also called as quenching distance [6, 7]. The quenching distance depends on rate of reaction and heat loss to the surroundings. The flame quenching results in incomplete combustion of hydrocarbon fuels.

The failure of flame propagation in the presence of combustible substances is called flame quenching. In the year 1817 Sir Humphry Davy put forth the concept of flame quenching. He observed that by using fine wire gauze the flame propagation can be stopped. A study performed on initiation of gaseous explosion by small flames by Holm, J. M. [8] shows that the flame cannot pass through gaps of less than millimeter scale.

When the heat of combustion i.e. heat generation is less than heat lost to the environment from the surrounding wall, flame extinction occurs. With the use of proper insulation on the external walls of combustor the flame extinction can be minimized to a great extent. It was found that the flame is relatively stable at the center of combustion space in the tube and unstable near the walls. At high flow rates flame gets swept out of the combustor and this phenomenon is called as blowout. On the basis of several studies many small Swiss roll geometries have been fabricated successfully [9, 25, 27].

To overcome the drawbacks in parameters affecting the flame stabilization and flame stability limits combustors of various geometries such as linear and double spiral were developed. One such device is Swiss Roll Combustor. Swiss Roll combustor works on the principle of Excess Enthalpy. A study conducted by Weinberg et. al [10] shows that extinction limits can be significantly reduced by heat recirculating combustors by recirculation of thermal energy of products of combustion to preheat the reactants as they flow parallel to each other but in opposite direction or in counter flow with each other. Thus the enthalpy of the reactants is increased due to preheating as heat is transferred by the products of combustion (total enthalpy becomes addition of chemical and thermal enthalpy). Therefore such devices are also called as ‘Excess Enthalpy Burners’. The Swiss Roll combustors as it is having a spiral geometry provides efficient heat recirculation as compared to linear heat exchangers[3, 6, 24].

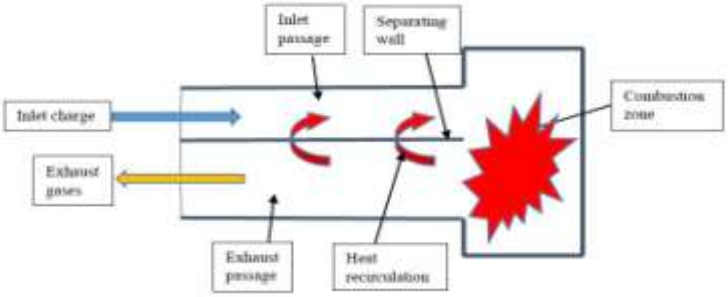

Fig-1: Heat Recirculation Principle [10]

As heat recirculation is not possible in linear combustors excess enthalpy is not generated. Thus spiral geometrics are more efficient than linear geometries. There are two types of spiral geometries: square and circular geometry [14, 26].

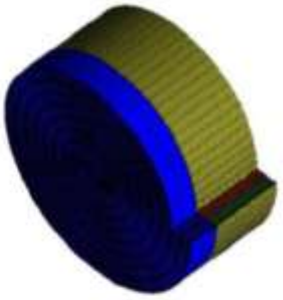

Fig-2: Square geometry [14] **Fig-3: Circular geometry [14]**

Among the square and circular combustors the square combustor is considered more important for study of flame dynamics. It is used to study the simulation results, but in case of square geometry formation of dean vortices and losses are more but travel of flame front inside the combustor is better hence widely used for simulation study. Swiss roll combustor at macro scale are used for simulation purpose and to study the effect of turbulence in the combustor and further the meso-scale arrangement is used to extract heat from the combustor so that the heat energy can be converted into electricity by using thermoelectric devices.[14]

3. EFFECT OF GEOMETRY ON FLAME QUENCHING

A study conducted by Ronney P. D. et. al. on analysis of non adiabatic heat recirculating combustor shows that at high Re extinction limits are caused due to insufficient residence time[11]. Damkohler no. is the dimensionless no. which gives us the relation of residence time. It is the ratio of residence time to reaction time. Also residence time is the ratio of diameter of center combustion chamber to the input flow speed at same Re. The residence time should be sufficiently high to give stable flame. If the input flow speed is kept same and the diameter of center combustion chamber is increased then the residence time increases. Thus at larger Da (more residence time) the large scale combustors at high Re result in better performance.

Mahbub K. Ahmed et. al. investigated that in a Swiss Roll combustor width of combustor is a more crucial parameter for flame stabilization than the length of the combustor[12]. An investigation of hydrogen fuel with air as oxidizer was carried out for different size rectangular channel meso-combustors (20mm*5mm*5 mm, 40mm*5mm*5mm and 50mm*2.75mm*5mm) and different flow configurations to check the stability of hydrogen flames. It shows that by increasing the length of meso-combusters the stability can be increased slightly whereas slight decrease in combustor width will reduce the flame stability remarkably. It can be seen that the 40mm long combustor is more stable than 20mm long combustor as its length increases whereas the 50mm long combustor is more unstable than 20mm long combustor inspite of having large length because its width decreases. As width decreases, the c/s area decreases and the flow velocity is increased as per the continuity equation. Hence blowout occurs and quenching takes place. Thus it can be seen that width is an important parameter than length for flame stabilization.

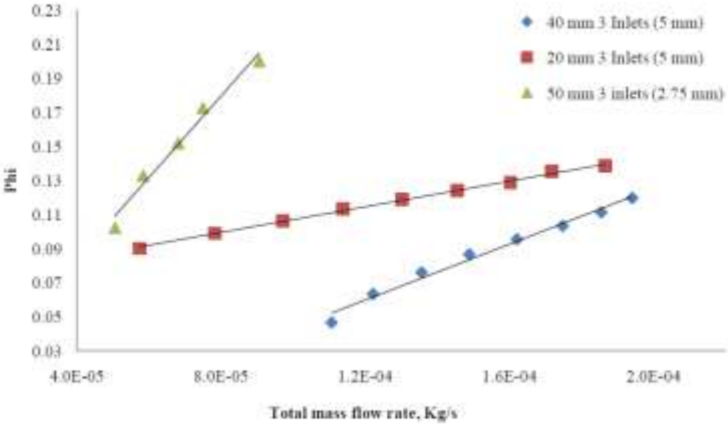

Fig-4:The lean blowout limit of hydrogen flame in different size combustors [12].

Nam ll Kim et. al. studied three types of combustors (diameters 64mm)- Shallow channel (S), Deep channel (D) and Wide combustion room (W) and also two different types of heat transfer environments for S type- Sq having a quartz cap and Si have insulation [9]. The depth of combustor (6mm and 15mm), size of combustion room (3.5mm and 12.7mm), equivalence ratio, mean flow velocity was varied. The mixture channel (1mm), exhaust channel (2mm) and wall thickness (1mm) were kept constant.

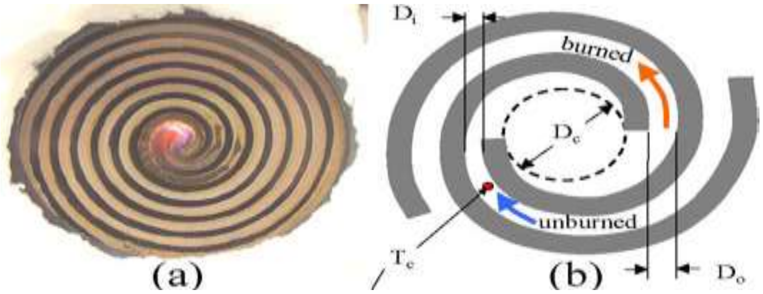

Fig-5:Configuration of the combustor [9].

The W combustor has shorter channels i.e. fewer no. of turns which reduces the temperature of unburnt mixture at the inlet of the combustion room. The wide combustion room decreases the mean flow velocity in the combustion room. As the combustion room increases heat transfer to inlet mixture during preheating decreases and thus flame stability decreases [9].

The D combustor has depth 2.5 times larger than those of other combustors. The heat loss is maximum from the upper surface of the combustor. Thus with the increase in depth of combustor heat loss from the upper surface decreases and the flammable region increases as compared to others. The flammable region for S is larger than of Sq even though quartz plate has less heat conductivity. This is because in a combustor the radiant heat transfer is dominant over the conductive heat transfer when the emissivity and temperature are sufficiently high.

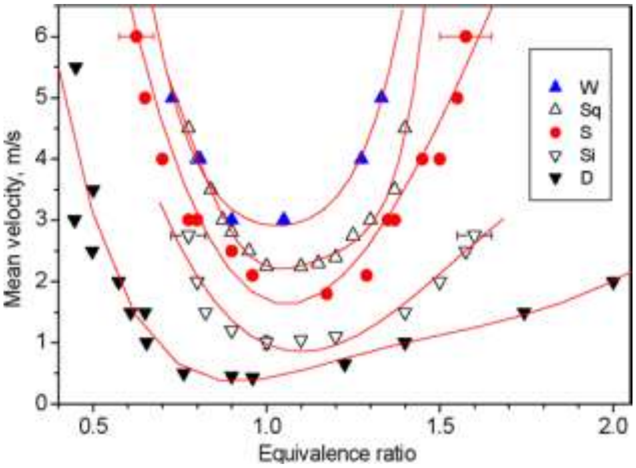

Fig-6: Flame stabilization conditions for various combustors and different heat transfer conditions [9].

4. EFFECTS OF LOSSES ON QUENCHING.

As the heat losses increase, the surface temperature will decrease and due to this the preheating of reactants will reduce. This will result in low heat generation. The chances of blowout will increase and thus quenching occurs [12].

Chien Hua Chen et. al. carried out proper analysis of Linear and Spiral counter-flow heat recirculating combustors [13, 14]. Figure shows the effect of α and N on E for spiral combustor along with detailed analysis of 3 turn spiral combustor by Targettet. al. [15]. The results are in close agreement with that of Targettet. al. [15] which indicate that the highly simplified analysis is satisfactory for the given purpose. Figure shows that at lower N, E~N i.e. Enthalpy increases in proportion to the NTU for linear combustor whereas E increases, reaches a maximum value and then decreases even for adiabatic condition. This is because for higher N i.e. lower flow rate or higher rate of heat transfer from products to reactants the recirculating heat is lost to the surroundings rather than increasing the enthalpy of reactants as discussed by Churchill et. al. [15, 16]. Thus low velocity extinction limit always exist in heat recirculating combustors. This is not the case with linear exchangers as heat transfer occurs from only one side of the outlet channel to the adjacent inlet channel. Hence for truly adiabatic system i.e. for no heat loss system linear device provide high excess enthalpy and broader extinction limits whereas for combustors with heat loss spiral exchangers provide high excess enthalpy.

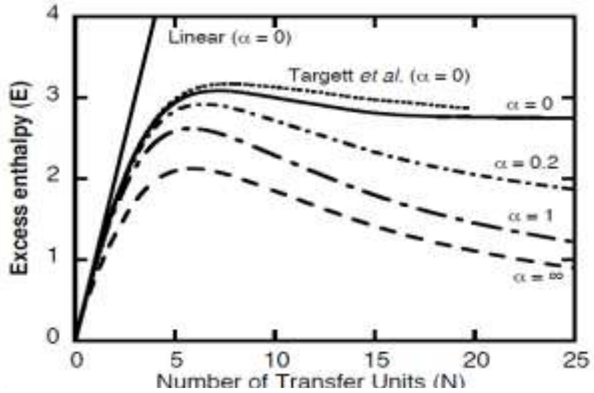

Fig-7: Dimensionless excess enthalpy (E) v/s Number of Transfer Units (N) for different heat loss coefficients (α) [13, 14, 15].

A numerical study was conducted by Chien-Hua Chen et. al. on three different scales (Full: 5 cm tall, 3.5 mm channel width; Half: 2.5 cm tall, 1.75 mm channel width; Double: 10 cm tall, 7 mm channel width.) but geometrically similar 3D Swiss Roll combustors [13]. It can be seen that all the three extinction limit curves exhibit the same U-shaped curve, but at the given Re (or Nu) the performance of the curves is not the same. At lower Re performance or extinction limit is dominated by heat losses [17, 18]. Hence for small scale combustors there is less heat loss as determined by heat loss coefficient (α) which depends on the length scale (α~d). Also the wall to wall radiation is less in small scale combustors which is determined by Internal radiation coefficient (R) which again is proportional to length scale. Thus it can be said that at smaller Re small scale combustors exhibit broader extinction limits and avoid quenching as seen from graph.

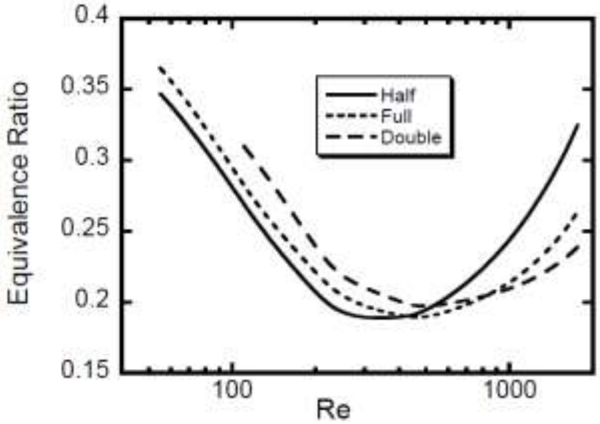

Fig-8: Computed extinction limits for Swiss roll combustors of three different sizes [13].

5. EFFECTS OF EQUIVALENCE RATIO ON FLAME QUENCHING

As mass flow rate increases the length of the flame also increases and hence blowout of the flame occurs. Equivalence ratio (Φ) and mass flow rate have a linear relationship [12].

Equivalence ratio (Φ) is calculated by dividing actual air to fuel ratio by stoichiometric air to fuel ratio. If the Equivalence ratio (Φ) is equal to 1 it denotes stoichiometric combustion, if it is less than one it denotes rich mixture (too little air) and if it greater than one it denotes lean mixture (too much air). Flame will only propagate if the equivalence ratio (Φ) is within the flammability limit of the fuel. If the mixture is too rich or too lean the flame does not propagate. When the mixture is too rich the air which is required for combustion is diluted by fuel. When the mixture is too lean the heat is lost to the surrounding and the temperature of the combustion space drops to such a level that it cannot sustain combustion.

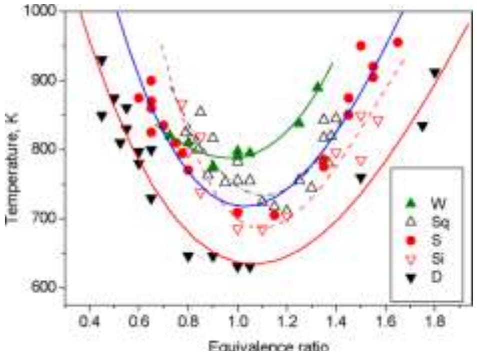

Fig-9: Measured mean temperatures as a function of equivalence ratio near the flammable limits of various combustors.[9]

For the case of D-combustor, the mean temperature obtained was smaller and the heat loss is less as compared to S and W combustors. For the case of W-combustor, the mean temperature obtained was higher and the heat loss ismore as compared to S and D combustors. For W combustor the size of combustion room was larger and the length of channels was shorter so the heat transfer by recirculation is less than that of S and D combustors. [9]

6. CONCLUSION

Heat recirculation using regenerative preheating is one of the best promising method for flame stabilization and to avoid flame quenching [10]. Swiss Roll combustors with double spiral geometries were found to be highly efficient than linear combustors as it works on the heat recirculation principle [3, 6]. Square geometry is preferred as the travel of flame front inside the combustor is better than circular geometry [14]. The scale and size of the combustors is restricted and it should be more than a certain minimum distance to avoid quenching. Thus there are difficulties in obtaining high efficiency and flame stabilization in compact Swiss Roll combustors.

To give stable flamethe residence time should be sufficiently high, thus at larger Da (more residence time) the large scale combustors at high Re gives better performance [11]. Width was found to be more crucial parameter than length for flame stabilization [12]. Heat loss from the upper surface can be reduced and the flammable region can be increased by increasing the depth of combustors. The radiant heat transfer is found to be more dominant over the conductive heat transfer at higher emissivity and temperature [9]. As the heat losses increases the blowout will increase and quenching occurs [12]. Heat losses can be significantly reduced by providing the insulation on external walls. Linear device provides high excess enthalpy and broader excitation limits if heat loss is not considered whereas spiral device provides high excess enthalpy and broader excitation limits if heat loss is considered [15]. At smaller Re small scale combustors exhibit broader extinction limits and avoid quenching [17, 18]. The flame only propagates when the equivalence ratio is within the flammability limits of the fuel. Highest temperature is obtained when the concentration is close to stoichiometric ratio [9].

Thus it can be seen that geometry and dimensions have a great effect on the overall performance of the small scale combustors. Also the equivalence ratio should lie within the flammability limit of the fuel for flame propagation.

7. FUTURE SCOPE

After flame stabilization we can use this combustor as power source for various electronic equipments which use Li-ion batteries [23]. Also it can be used as heater for heating purposes instead of electric heater. By grid formation of combustors large amount of power can be obtained which can be used for domestic purposes in rural areas.

ACKNOWLEDGEMENT

It is our privilege to express our sincerest regards to our project guide, to **Prof. Sagar B.Mane Deshmukh,** Mechanical Department, Smt. KashibaiNavale College of Engineering, for his valuable inputs, able guidance, encouragement, whole-hearted cooperation and constructive criticism throughout the duration of our review paper. We are also indebted to **Dr. A.P.Pandhare**, Head of Department (H.O.D), Mechanical Department, Smt. KashibaiNavale College of Engineering, and other staff members for encouraging and giving us valuable suggestions whenever required.

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