A REVIEW ON THE EFFECTS OF THE MATERIALISTIC PROPERTIES OF SMALL SCALE COMBUSTOR ON ITS PERFORMANCE

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ABSTRACT
High energy density of hydrocarbon fuels creates ample number of opportunities to develop small scale power generating systems to satisfy the increasing demands of portable power generating systems and localized small scale (i.e. few mW to W) power generation. Major issue associated with these devices is limitation on its size. Component which actually generates the source of power (i.e. heat) is a combustor. So precise selection of the combustor plays a significant role in the development of the small scale power generation. Decreasing scale of the combustor increases surface to volume ratio, which enhances the heat loss to the environment. Increased heat loss to the environment results into decreased flame stability which is important to generate heat at constant rate from the combustor. Flame stability at small scale of the combustor depends upon mainly geometry, materials and thermal balance in the combustor. In order to study flame stability limits with respect to the various parameters governing combustion, present review is conducted on effect of materialistic properties of the small scale combustors on its thermal performance. Parameters like material, flow velocity, equivalence ratio are focused mainly. Different materials (viz. Aluminium, Brass, Stainless steel, Copper, macor and Zirconium phosphate etc.) affecting performance of the combustor were reported in the earlier studies are discussed in detail. Effect of materials properties on flame stability is discussed in detail. Different phenomenon’s like heat loss, flammability limits, flash back and blow out, heat recirculation and peak temperature of the combustor were found to be the dominant parameters in the studies conducted. Findings of every section have included. Suggestions for future work have included.

Keywords: thermal conductivity, flame stability, reynolds number.

1. INTRODUCTION
The last few years have experienced the tremendous growth in the Small Scale power generating technologies. Varieties of the new experiments have been carried out to develop the efficient power generating device [1]. Day by day, small scale power generating technology (i.e. micro electro mechanical systems) is experiencing the new trend. One of the reasons behind this development was, less capability of the exiting power generating device [1]. Lithium -ion batteries have been used as a source power for the various devices [2]. Primary batteries available in the market (Lithium / thionyl chloride) have a specific energy of 2.6 MJ/kg (0.6 MJ/kg for an Alkaline battery) [2]. The advantage, in terms of energy per unit mass, of using liquid hydrocarbon combustion to produce power is shown graphically in Figure-1. The Increasing demands of the energy at small scale to run devices like cellular phones, laptops, unmanned aerial vehicles (UAV’s), small space heating requires the precise development of the small capacity energy or power generators [4]. Small capacity power generators use the chemical energy released by burning the hydrocarbon fuels in the combustors [5]. Swiss roll combustor design has found to be most convenient design to get a stable flame in the combustion space of the combustor, which is required to generate heat at constant rate [6]. The major problem experienced by small scale power generating device on its downsizing is increase in the combustion space surface area to combustion space volume ratio (leads to the heat loss to atmosphere) and decreases overall efficiency of Swiss roll combustor [7], [8]. Heat loss from the reaction increases problems associated with the flame stability (i.e. thermal flame quenching and radical flame quenching) [8]. Passage dimension less than the flame thickness will not allow flame to pass through the channel and suddenly it extinguishes, in the presence of low wall temperature and increased high heat loss [9]. With reduction in the size of the combustor another challenge prone in the small scale combustion is reduced time available for the completing chemical reaction [10]. Smaller combustion space volume implies that the mixture flow residence time is small and hence the mixture reactants do not get sufficient time for complete combustion and incomplete combustion results to maintain low heat at the surface [11]. In the process of extracting the heat from the hydrocarbon fuel (HC) fuels in small scale power generating devices, avoiding flame quenching and increasing residence time is important [12]. One of the best methodologies implemented to tackle this problem is regenerative preheating of the mixture reactants in the inlet channel [12]. This paper introduces the basic concept of the Swiss roll combustion chamber working on the above mentioned principle. The incoming reactant charge and the outgoing combustion products (i.e. exhaust gases) flow in the counter flow direction exchanging the heat [13]. Thus, the total enthalpy of the reactants becomes...
the chemical enthalpy plus heat enthalpy which is only chemical enthalpy initially before heat exchange [13]. Residence time available for chemical reaction is increased by flow recirculation in the combustion chamber [14]. These recirculation zones will increase the flow residence times and also recirculate the excited charge back into the combustion zone [12]. Even though the field of micro-scale power generation using combustion is new, there are currently several ongoing projects to develop micro scale combustors and power generators that are relatively well advanced [15]. Several micro combustors and chemical reactors are currently being developed, either to use in conjunction with piezoelectric and thermoelectric materials to produce power, or to use as a fuel reformers in fuel cells [16]. The main advantage of these devices is that they don’t have any moving/rotating parts (advantage is reduced frictional losses), but the problem generally lies in the low overall efficiency of the complete system [17]. An important application of small scale combustion is in the propulsion of small scale air vehicles with mass which is in few kg and thrust requirements in the range of 1-10 mN [18]. Electric driven propulsion systems currently available compete with the small scale combustion in this area [19]. The necessary requirement of the small scale combustion chamber is to get a constant stable flame to generate heat energy at fixed rate. Heat generation by burning hydrocarbon (HC) fuels can be converted into electrical energy by using thermoelectric device [20]. Electrical energy generation at constant rate is possible only by maintaining same/constant heat on surface of the combustor [20]. In order to generate constant heat, Swiss roll combustors were prepared with different materials [21]. The material selection plays an important role in the designing of the combustor [21]; this paper is mainly focused on the effect of material since heat transfer is totally depending upon the thermal conductivity and the dimensions of the materials [22] related properties of the combustor on its performance. Various materials such as Aluminium, Brass, Stainless steel, Copper, macor and Zirconium phosphate were used in the studies conducted by Zhong Bei-Jing et al. [23]. Various which are important during small scale combustor studies are equivalence ratio, mixture flow velocity, material of the combustor; dimensionless numbers are discussed in detail in the present study.

2. DISCUSSIONS AND FINDINGS

2.1 Effect of thermal conductivity on quenching distance

The quenching distance is a critical distance in passage or between two flat plates below which flame cannot propagate because of higher heat loss [24]. The main problem associated with the small scale combustor is, the limit on the dimensions of the combustor. Smaller dimensions put the limit on the critical dimensions and hence flame quenching phenomenon arises [25]. Flame quenching is always limited internal surface temperatures in the combustion space and the smaller dimensions of the combustion space or volume [25]. Flame extinction for high thermal conductivity materials near to the wall of combustion chamber is common because of high heat loss from flame (i.e. chemical reaction) to the wall [26]. The effect of the thermal conductivity of the combustor material on the quenching limit can be understood from the Figure-2. When thermal conductivity of material was greater than 100 W/m K quenching occurred within the combustion room and flame was not propagated into the channel [27]. Flame quenching depends on the high thermal conductivity of the material [28]. Temperature near the wall surface of high thermal conductivity material is lower than the low thermal conductivity material [28]. Therefore, the flame is not able to propagate and sustaining the high thermal conductive material zone [29].

Figure-1. Specific energy consumption vs different power developing source [3].
should be preferred over high thermal conductive materials [27].

2.2 Effect of thermal conductivity on the Blow Off limits of the flame

Blow off limit is significant parameter to specify parameters like Equivalence ratio, mean velocity etc. [32]. Blow off phenomenon in case of the Swiss roll combustor, can be described as the Propagation of the central zone of the combustion (i.e. chemical reaction) towards the exhaust channel or in the exhaust channel [33]. During blow off of the flame, it tends to move in the exhaust channel because of the high flame velocity and the high discharge rate of the incoming reactants (i.e. mixture of the fuel and air) [34]. Figure-3 shows the effect of thermal conductivity of the combustor on blow off limits. The figure 3 shows that, when thermal conductivity of the combustor material was less than or equal to 100 W/mK, blow off limit increased with the increase in thermal conductivity and for thermal conductivity of the material greater than or equal to 100 W/mK, blow off limit decreased [27]. For low thermal conductivity combustor materials, flames temperature becomes higher, because of reduced heat loss to the atmosphere and flame remains in the central localised region. In case of the insufficient preheating of the reactants (i.e. mixture of the fuel and air) flame is drifted in the exhaust channel [35]. At the thermal conductivity of the combustor material equal to 100 W/mK, the equilibrium is established in between the heat accumulated near the inner wall and the rate of heat recirculation to the incoming reactants from the product [27]. From the viewpoint of blow off of the flame, compromise is to be made between heat recirculation at high thermal conductivity and high flame temperature at low thermal conductivity [36]. Blow off limits of the flame were found in the wider range at equilibrium condition [27]. Hence, while selecting combustor material flame temperature and heat recirculation should be considered as important parameters.

2.3 Effect of thermal conductivity of the combustor material and mean flow velocity on the flash back limit

Flash back phenomenon in case of the Swiss roll combustor is more or less similar to the blow out with reverse reason of flow velocity and discharge rate.

This can be described as the back flow of the flame inside the inlet channel [28]. Flame flash back occurs when flow velocity is less than the flame speed and for the lean mixtures [37]. If the laminar flow velocity is less than the burning velocity, then flame may travel in the inlet channel in search of the required energy for the combustion [38]. From the fig. 4, it was found that the flame flash back limit decreased as the thermal conductivity increased from 25 W/mK to 200 W/mK [27]. Therefore laminar flow velocity should be higher than the burning speed/velocity of the flame to avoid the flame flash back. From the Figure-4, it was observed that flow mean velocity of 180 cm/s and thermal conductivity of 25 W/mK, were most favourable conditions to avoid flame flash back [27].
2.4 Effect of thermal conductivity of the combustor material on combustion space temperature distribution

Figure-5 and Figure-6 show temperature distributions inside the combustion space of the combustor for thermal conductivities equal to 5 W/mK and 100 W/mK respectively, when the mean flow velocity was 350 cm/s [39]. For lower thermal conductivity of 5 W/mK wide difference was observed between the temperatures of the reactants (fresh mixture) and products (exhaust gases). This was due the fact that, at low thermal conductivity the heat recirculation among the product and the reactant was very low. Because of the less heat recirculation heat remained accumulated near the inner side of the combustion space wall resulted into increase in the peak/maximum temperature of the combustion space up to 1700 K [39]. This showed that, there was not sufficient transfer of heat from products to reactants and expected enthalpy rise in the reactants was not seen [40]. For the higher thermal conductivity material of the combustor as shown in the Figure-6, the rate of heat recirculation from the products to reactants was impressively high causing the enthalpy rise of the reactants up to considerable level [39]. Due to higher thermal conductivity of the material of the combustor, there was less difference between the temperature of the reactants and the products [41]. Also, the peak temperature was reduced to minimize the emission of the NOx from the products [42].

As the air quantity in the fuel increases the, air available for the complete combustion increases and complete combustion occurs inside the combustion space [48]. Maximum combustion space temperature was observed for SS material for all the equivalence ratios because of its lower thermal conductivity. Minimum combustion space temperature was observed for Br material for the entire range of equivalence ratio because of its higher thermal conductivity [51]. Peak temperatures were observed at equivalence ratio of 1.068 for all the materials, this is because of excess air requirement for complete combustion in the confined chamber. Maximum temperature of 1398.50 K was observed for SS material at equivalence ratio equal to 1.068 [44]. All the temperatures were found higher for SS material compared to other materials. Higher thermal conductivity materials gave lower heat content availability.

2.5 Effect of different materials and different flow rates on flame stability in the combustor

Figure-7 explains variation of the equivalence ratio with volume flow rate for different materials. Four materials (i.e. aluminium, copper, stainless steel and brass), were tested to check combustor surface temperatures which is significant to get a conversion of heat into electricity by using thermoelectric device [43]. While testing the different materials, the equivalence ratio was varied continuously to get stable flame. It was found that the stable flame was observed for lower flow rate of
liquefied petroleum gas (LPG) equal to 0.25 LPM [44]. Richest stable flame was observed for high thermal conductive material (i.e. Aluminum) at LPG volume equal to 0.35 LPM and at equivalence ratio of 0.194 and leanest stable flame at LPG volume equal to 0.3 LPM and at equivalence ratio of 1.75 [44]. Aluminium being a high conductive material was able to sustain the rich flame. In case of high thermal conductive materials there was sufficient recirculation of heat from products to reactants, which results into increasing enthalpy of the reactants and time required to complete chemical reaction at the central zone was reduced [45]. During the tests conducted by Sagar B. Mane Deshmukh et al. [44], LPG volume flow rate equal to 0.35 LPM gave increased/wider flame stability limits for all the materials. Aluminum combustor material gave most rich and lean stable flame in the combustion space of the combustor when equivalence ratios were equal to 0.194 and 1.75 [44].

**Figure-7.** Equivalence ratio vs volume flow rate [44]

### 2.6 Effect of the thermal conductivity on the total heat transfer

The main problem associated with the small-scale power generating device was that the heat loss due to increase in the surface area to volume ratio [53]. Hence it was very important to study the consequences associated with heat flow in case of Swiss roll combustion chamber [54]. For experimentation purpose two materials macor and zirconium phosphate were studied [55]. Figure-8 shows that heat loss from the combustion chamber was lower for lower thermal conductivity materials. Combustion Chamber heat loss increased with increase in thermal conductivity rapidly in the beginning, when thermal conductivity was less than 15 W/m/K and at a lower rate for higher thermal conductivity greater than 15 W/m/K [52]. The overall heat loss also increased with increase in the thermal conductivity, but this increased at very small rate. Also, it was found that the rate of decrease in heat recirculation was higher at lower thermal conductivities and lower at higher thermal conductivities [56]. It was concluded that, for higher thermal conductivity, combustor material behaves like a lumped body, so that the conductive heat transfer inside the body is much faster than the convective heat transfer because of this heat loss from the central chamber was very high [52]. Also in the low thermal conductivity (< 15W/m/K) the material no longer behaved as a lumped body and was capable of sustaining huge thermal gradients between the central chamber and the outer walls [52]. Figure-3.7.1 shows the variation in the ratio of rate of heat recirculation to reactants through outer walls to that through the channel walls as a function of the thermal conductivity [57]. For the efficient working of the combustor and for better heat recirculation from the products to the reactants, there should be high heat transfer through the channel and low heat transfer through the outer wall [58].

**Figure-8.** Heat transfer though the combustor with different thermal conductivity [65].

It was observed that, for heat loss to heat recirculation ratio was lower than 1 for low thermal conductivity materials and increased rapidly close to 9 for a higher thermal conductivity of 202.4 W/m/K [52]. The heat recirculated through the channel walls decreased with increase in thermal conductivity of the material. These results showed that zirconium phosphate combustor was most favourable for flame stabilization from heat transfer point of view [60]. Experimentally it was found that the lower thermal conductive material showed high wall temperature and high enthalpy of the reactants due to heat transfer [52].

### 2.7 Effect of inlet Reynolds number (Inlet flow velocity) on the flame stability

Figure-9 shows effect of inlet flow velocity on flame stability. Different materials with low thermal conductivity macor (1.46 W/mK) and zirconium phosphate (0.8 W/mK) were studied for the different Reynolds numbers against the equivalent ratio [65]. Reynolds number was calculated based on the hydraulic
diameter at the inlet of the combustor (equal to 2.1mm) [52]. From the previous study, it was found that the extra lean combustion was possible for the large combustor but not for the meso scale combustor as there was limit on the inlet flow velocity [61]. For macor combustor, rich flammability limit was found to be increased with increase in Reynolds number and lean flammability limit remained constant [62]. For zirconium phosphate combustor, rich and lean flammability limits both were increased with increase in inlet Reynolds number [52]. But in the case of the Macor combustor, there was a limit for the maximum mean velocity that could be utilized to feed the reactants to the combustor and it was set by the material limitation [63]. This was observed, because for higher Reynolds number the rate of energy release was high and sometimes there were chances that the thermal stresses could exceed the limit of thermal stresses of the material [65]. To avoid the blow off and the flash back phenomenon there was always limit on the increase in the Reynolds number. Therefore, considering the above two phenomena the minimum mean velocity of flow should be higher than the burning velocity of the flame [65]. For both the cases, the minimum mean velocities were larger than the laminar burning velocity of the propane flame (i.e. 0.44 m/s) [65]. The minimum mean inlet velocity for which the flames could be sustained was found to be two times the laminar flame speed for macor combustor and four times for the zirconium phosphate combustor [52].

3. CONCLUSIONS

Precise review of effect of different materials (i.e. thermal conductivity of the material) was conducted. Dependence of the flame stability on different materials was reviewed. Higher thermally conductive materials showed lower flame stability limits, because of increased heat loss to heat generation ratio and vice versa. Maximum heat recirculation from products to reactants enhances flame stability limits. Stable flame was found to be a result of balance between flow velocity and flame speed. Flashback of the flame resulted, when flow velocity was lower than the flame speed and blow off/out was observed when flow velocity becomes higher than the flame speed. Stable flame was quenched for higher thermal conductive materials and vice-versa. Higher combustion spaces temperatures always help in maintain stable flame at the centre zone of the combustor. Higher thermal conductive material increases heat loss to the atmosphere and lower combustion space temperature.

For better thermal performance of the combustor, low thermally conductive materials which sustains under higher temperatures in the combustors should be preferred.

NOMENCLATURE

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<td>Ks</td>
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<td>HL_cc</td>
<td>Rate of Heat loss in combustion chamber</td>
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<td>HL_tot</td>
<td>Rate of total heat loss from the combustor</td>
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<td>HR_cw</td>
<td>Rate of heat recirculation to the reactants through the channel walls</td>
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