Experimental investigations on effect of different materials and varying depths of one turn exhaust channel Swiss roll combustor on its thermal performance

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Abstract. More energy density of hydrocarbon fuels compared to advanced batteries available in the market demands for development of systems which will use hydrocarbon fuels at small scale to generate power in small quantity (i.e. in few watts) and device efficiency should be reasonably good, but the basic requirement is to generate heat from the fuels like methane, propane, hydrogen, LPG and converting into power. Swiss roll combustor has proved to be best combustor at small scale. Present work is carried out on one turn exhaust channel and half turn of inlet mixture channel Swiss roll combustor. Purpose of keeping exhaust channel length more than the inlet mixture channel to ensure sufficient time for heat exchange between burned and unburned gases, which is not reported in earlier studies. Experimental study mentions effects of different design parameters like materials of combustor, various depths, equivalence ratio, mass flow rates of liquefied petroleum gas (LPG), volume of combustion space and environmental conditions (with insulation and without insulation to combustors) on fuel lean limit and fuel rich limit, temperature profile obtained on all external surfaces, in the main combustion chamber, in the channel carrying unburned gas mixture and burned gas mixture, heat loss to atmosphere from all the walls of combustor, flame location. Different combustor materials tested were stainless steel, Aluminum, copper, brass, bronze, Granite. Depths considered were 22mm, 15mm, 10mm and 5mm. It was observed that flame stability inside the combustion chamber is affected by materials, depths and flow rates. Unburned mixture carrying channel was kept below quenching distance of flame to avoid flash back. Burned gas carrying channel dimension was more than the quenching distance. Considerable temperature rise was observed with insulation to combustors. But combustors with more thermal conductivity showed more heat loss to atmosphere which led to instability of flame. Keywords: Swiss roll combustor, Stable flame, heat loss, temperature profile, various materials and depths

1. Introduction
Recent innovations in the electrical energy generating devices have made it possible to generate electrical energy locally. There are regions around the globe where 24Hrs electricity is not available. New ideas for producing electrical energy would ensure generation and consumption of electricity locally. The macro energy generation is well proven in terms of distribution, performance and efficiency. Idea of producing energy from combustion of fuels is assumed to be the best way because of more energy density of the fuels containing hydrocarbons compared to more energy density
batteries available in the society [1]. Hence the development of energy generating device depends on the precise manufacturing of heat producing chamber (i.e. Combustion space/chamber). Applications of the small energy generating devices are remote sensors, micro turbines, future electronics, divert and attitude control systems, portable battle power, aerial vehicles, actuators, robots, rovers, small air conditioning devices, small space heating[8]. Major Problems associated with small scale Combustion chambers are heat loss due to [1],[3],[6],[7] decreasing ratio of volume to surface area of combustion space, sealing and fabrication of assembly [3], limit on the dimension of the flame sustaining chamber (i.e. quenching dimension)[5],[6], instability of the flame/combustion for leaner mixtures [2],[10], instability of the flame for low grade fuels, more frictional losses for internal combustion engines[1],[3],[7],[15] and because of which engine design at small scale is not possible. Fabrication difficulty, material failure, destruction of the active radicals, stability of flame only at low flow rates of reactants, problems in measurement of parameters like temperature, pressure etc. are other major issues for small scale Combustion chambers. Success of the heat generating device mainly depends on establishing or achieving a stable flame for longer duration inside the chamber. All the issues discussed above also affect formation of stable flame. The above difficulties may be overcome by utilizing: high pressures and high temperatures of incoming Air/Fuel mixture [8], reduced heat loss[9], Catalytic activation of combustion [1],[10] by increasing residence time [7], avoiding moving parts (thermoelectric, photovoltaic, pyro electric [1], piezoelectric[4]), external heating [16], inactive combustor walls[16], high grade fuels like hydrogen, combustible fuel-air mixtures, insulating the combustion space to avoid heat loss, flame speed balanced with mixture velocity, excess enthalpy burners[1],[2],[3],[5],[7],[8],[9],[10],[14],[15]. The method of excess enthalpy burners (i.e. heat recuperation from products/burned gases and using it to heat reactants/unburned gases) is effective to improve flame stability by reducing heat loss with increased heat exchange from products to reactants, reduced frictional losses using thermoelectric systems, less emissions with reduced temperatures of products, use of low grade fuels, extended flame stability limits, improved thermal efficiency with increased total enthalpy of the reactants (i.e. chemical and thermal) etc. Previously attempts were made by use of excess enthalpy to improve extinction limits by the use of catalytic combustion[1], to increase leaner stability of the flame[2], to improve low temperature stability of the flame (i.e. to get flameless mode of the combustion) [3], to study flame characteristics of counter current excess enthalpy burner for different materials and scales of the burner [5],[15] to get a sublimit flames model [6], to develop model of first principle to judge heat loss through different locations like inside reactant and product dividing walls, heat loss to atmosphere and heat transfer [7], to develop combustor as a heater and to find out flash back and blow out limits [8], to check effect of the third dimensional heat loss on the reaction[9], to study temperature profiles and extinction limits[10]. Limitations of the Swiss roll combustors as a heat producing device are not previously discussed previously. Here in the models prepared one turn exhaust channel length was more than the inlet reactants channel length. In order to study effect of Swiss roll combustor as a heat generating device, models with different materials like Stainless steel with 22mm, 10mm, 15mm and 5mm depths and Aluminum, Brass, Bronze, Copper, Granite were prepared with 20mm depth and their effect on temperature profiles inside the combustion space, Channels and on surfaces is checked. Effect of equivalence ratio on temperature profile and heat loss for a specific material and depth is discussed.

2. Swiss roll models and experimental set up

Figure 1 shows the experimental set up used during testing on models under study. Compressor of 8bar capacity used to compress the air and then it is supplied to air storage tank. LPG tank with 14 bar pressure capacity used to store LPG. But all tests conducted at ambient conditions (i.e. at 1.013bar and 300K). Pressure regulating valves were placed after tanks to step down the pressure to ambient value. Flow meters used for LPG and air were corrected for 2% of the Full scale. Y mixer placed in connection to create a uniform mixture of air and LPG. Function of the flash trapping arrangement is was to avoid back flow of flame in the pipe to avoid accident. Just before inlet of the Swiss roll combustor intake manifold was placed to ensure entry of mixture in the combustor along the depth
combustor. High speed Camera used to capture images of flame for different velocities of the mixture and to find out location of the flame in Swiss roll model of the combustor. K-type thermocouples were used to measure temperatures on external surfaces and inside the channels with 2% accuracy. All the temperatures were measured at steady state. Figure 2 shows Swiss roll model with its different dimensions and surface temperature locations and table 1 gives idea about models under test and environmental conditions used. Reactants carrying channel, products carrying channel and combustion space dimensions were 2mm, 3mm and 10 mm x 7 mm (Refer figure 2). All the models were precisely manufactured by using Wire electro discharge machining. The dimension of the reactants carrying channel was purposefully kept below quenching dimension (i.e. 2mm) of the LPG at room pressure and temperature it helps in avoiding flash back. Exhaust channel dimension was 3mm to get easy push of products out of the combustion space. Combustion space dimension was selected in Meso range (i.e. from 1mm to 10mm) because of chances of flame instability increases with reduced value of the volume to surface area ratio at this scale [8]. Top plate was made of quartz material for all the trials for optical access. Bottom plate was made of the materials under study during all the trials. Insulation was provided for all the vertical surfaces only. Top plate being quartz (For flame visibility) and bottom plate allowing passage to thermocouples could not be insulated. Two electrodes of 0.5mm diameter were inserted through beads of ceramic materials which were placed in bottom plate to create a spark. Source of 50Hz, 6KV was provided to create spark Combustor as a heat source application is satisfied by stable flame inside combustion space. Initially stable flame obtained only after preheating of the combustor. After achieving stable flame for gaseous fuel quantity, air quantity is varied to decide the leaner and richer limits of combustion for different materials and depths. Readings of temperatures in the channels and on surfaces were collected for varying equivalence ratios. Equivalence ratio is a ratio of actual air-fuel ratio to the stoichiometric air-fuel ratio. To change the equivalence ratio quantity of air was varied during the tests by keeping LPG quantity constant, which in turn changes the mean velocity of the reactants. Mean velocity of the reactants is calculated by taking ratio of mass flow rate and product of density and cross sectional area at inlet reactant carrying channel. Cross sectional area is product of depth of the combustor and reactants channel width. Stable flame inside the combustor is a result of balance between flame velocity and reactants velocity.

**Figure 1** Experimental set up. A and B – LPG and air storage tanks, C and D – LPG and air control valves, E and F – Pressure regulating and indicating gauges, G and H – LPG and Air flow meters, I – Y Mixer, J- Flash trapping arrangement, K – Manifold, L –Camera, M – Combustor model, N – Temperature data acquisition arrangement.
(a) Top view of one turn Exhaust Channel combustor with dimensions and thermocouples locations (i.e. Tc1, Tc2, Tc3, Tc4, Tc5, Tc6 and Tc7) inside the mixture carrying channel and exhaust gas carrying channel [17].

(b) 3D model of one turn exhaust channel combustor showing thermocouples Locations (Ts1, Ts2, Ts3 and Ts4) on the external surfaces S1, S2, S3 and S4 respectively.

**Figure 2** One turn exhaust channel swiss roll combustor.

**Table 1.** Swiss Roll Models Descriptions: For Different Materials and Depths with Different Environmental Conditions.

| Sr. No. | Combustor Model No. (M) | model details | Environmental conditions | Combustor Volume, mm$^3$ (Vc) |
|---------|--------------------------|---------------|--------------------------|-----------------------------|
|         |                          |               | Insulation (I)       | Without Insulation (WI)     |                             |
| 01      | M1                       | SSD22Di2De3Ds70 | Y                        | Y                           | 1540                        |
| 02      | M2                       | SSD15Di2De3Ds70 | Y                        | Y                           | 1050                        |
| 03      | M3                       | SSD10Di2De3Ds70 | Y                        | Y                           | 700                         |
| 04      | M4                       | SSD5Di2De3Ds70 | NY                       | Y                           | 350                         |
| 05      | M5                       | BrD20Di2De3Ds70 | NY                       | Y                           | 1400                        |
| 06      | M6                       | Brz D22Di2De3Ds70 | Y                        | Y                           | 1540                        |
| 07      | M7                       | Cu D20Di2De3Ds70 | Y                        | Y                           | 1400                        |
| 08      | M8                       | Al D22Di2De3Ds70 | Y                        | Y                           | 1540                        |
| 09      | M9                       | Gr D22Di2De3Ds70 | NY                       | Y                           | 1540                        |
Table 1 gives an idea about different models tested. 9 different combinations of models were made and tested by varying depths, materials and environmental conditions. Models are described as SSD2D2D2D3DcS70 where, SS – stainless steel (material), D22 – depth of combustor is 22 mm, D2 – reactants/mixture carrying channel width is 2 mm, D3 – products/Exhaust gas carrying channel width is 3 mm, DcS – Cross Sectional area of combustion space (i.e. from top view) is 70 mm\(^2\) (i.e. 10 mm X 7 mm), similarly for different materials (i.e. Br - Brass, Brz - Bronze, Cu - Copper, Al - Aluminum, Gr – Granite). Y – Test Conducted successfully, NY – Test not conducted.

3. **Findings from the experiments and discussions**

3.1. **Flame Stability Limits for Different Values of the Equivalence Ratio and Mixture Velocities**

Figure 3 shows variation of Mixture velocity with equivalence ratio for without insulating conditions of all the models and fuel less (i.e. fuel lean) and fuel more (fuel rich) limits for different models were obtained. Tests were conducted at approximately same mass flow rate. All the models tested were at higher mass flow rates (i.e. mass of LPG was 14.73 mg/s, which was more than the previously reported values of methane 0.4 mg/s, 1.04 mg/s by [10]). Amongst the nine models tested model M9 model with granite material broke during the tests. Reasons for breaking of the granite material were high brittleness resulting into failure (i.e. beyond 1100K approximately). Fuel fewer limit gives idea about how much less fuel [2] can be used to get required output at a specific air quantity and fuel more limit gives idea about how much more heat can be released without extinction of the flame inside the combustion space which is important case for isothermal applications [1]. Mixture velocity of LPG and air decides back flow (flash back limit) of flame and blow out of the flame from the combustion space. Less velocity with sufficient preheating of the mixture of LPG and air gives back flow in mixture channel and more velocity results into blow out [5] in the exhaust carrying channel (i.e. due to insufficient residence time[3]). Out of the models tested model M8 gave wider flame stability limits because of lower velocities during stable flame. Minimum velocity flame stability was obtained at 2.33 m/s velocity at 0.44 equivalence ratio. But the maximum velocity limit was 6.83 m/s at equivalence ratio of 1.35. Maximum velocity flame stability was obtained for model M4 with 11.64 m/s, which was more than previously reported in available literature maximum 2 – 3 m/s by [5] and 6 – 7 m/s by [8]. Model M5 gave narrow flame stability limit because of its more thermal conductivity results into more heat loss to surrounding.

3.2. **Flame Locations in the One Turn Exhaust Channel Combustor**

Continuous stable flame exactly at the center of combustion space of the combustor is necessary to get a uniform heat generation and distribution [1] on the top surface, which is required by thermoelectric devices. In the combustion applications location of the flame plays significant role. Flame location depends on the equivalence ratio [12], mixture velocity and dimensions of the channel. Five locations were basically found during the experiments conducted: 1. In the mixture carrying channel (i.e. Flash back condition shown in Figure 4a this occurs because of decreased flow mixture velocity [13] compared to flame speed [6], because of more dimension of channels than the quenching dimension of flame at normal conditions [5] and more heat recirculation to mixture from exhaust gases which reduces flame thickness 2. At outlet of Mixture carrying channel (i.e. about to flash back shown in figure 4b this is result of decreased flow rate [11] and will result into deterioration of edge at outlet of mixture carrying channel because of continuous chemical reaction. 3. Continuously at center of combustion space (i.e. Stable flame shown in figure 4c result of balanced flame burning speed and mixture velocity [8], sufficient residence time, balance of ratio of heat loss to surrounding to heat generation in the combustion space [6], required surface to volume ratio [3], [5], [8], [9], [10] 4. Always cling to exhaust carrying channel (i.e. about to blow out condition shown in figure 4d which
is result of high mixture velocity. In the exhaust carrying channel (i.e. blowout condition shown in figure 4e) result of large exhaust channel dimension than the quenching dimension.

**Figure 3.** Flame stability limits for different equivalence ratios and mixture velocities and for different models at approximately same LPG quantity.

3.3. **Effect of an Equivalence Ratio on Temperature Profile**

Figure 5 shows variation of external surface temperatures with equivalence ratio for model M1 when LPG was 14.73 mg/s. Locations of temperatures measured by K-type thermocouples mounted on the surfaces are shown in the figure 2. It was observed during the tests; temperatures on surface 2 measured by thermocouple Ts2 were higher at all the values of Phi and were maximum at Phi equal to unity. Surface 2 was close to combustion chamber and it was a second surface of wall separating exhaust carrying channel from the surrounding. Temperatures in descending manner were observed on Ts2, Ttop, Tbot, Ts1, Ts4 and Ts3. Highest temperature was observed at phi close to unity by Ts2 and it was 802.5 k. Model M1 has higher combustion volume which gives increased residence time [15] results into completing the chemical reaction. Results are shown for Model M1 because of higher temperature observance always on surfaces. Figure 6 shows variation of channel temperatures with equivalence ratio for model M1 and for without insulation conditions. Thermocouples placed at different locations in the channels gave maximum temperatures close to Phi equal to unity. Maximum temperatures were measured by thermocouple Te2 as it was always exposed to flame inside the combustor. In case of blowout conditions only Te1 measured maximum temperatures as it was exposed to flame directly. Maximum temperature was observed to be 1499 K at Phi equal to 1.19. On richer side of the mixture of LPG and air, proper heat exchange takes place between exhaust/ products and mixture/ reactants because of low velocity of mixture/reactants at quantity of LPG and air which give sufficient time to share heat. But for same LPG quantity as air quantity is increased mixture velocity also increases results into less time to share heat between products and reactants. As a result
of which graphs for thermocouples Tc1 and Tc6 are converging on richer mixture side and diverging on leaner mixture side.

![Graph]

**Figure 5** Variation of External surface temperatures with Equivalence ratio (Phi) for model M1 without insulation

![Graph]

**Figure 6** Channel temperatures (Tc) Vs. Equivalence ratio (Phi) for model M1 and without insulation conditions

![Graph]

**Figure 7** Combustion space temperature (Tc2) Vs equivalence ratio (Phi) for various depths for Stainless steel material

![Graph]

**Figure 8** Combustion space temperature (Tc2) Vs equivalence ratio (Phi) for different materials.

3.4. Effect of an Equivalence Ratio on Temperature Profile

Low velocity limits are decided by the ratio of heat loss to surrounding to heat generated in the combustion space [3]. Variation of combustion temperature with Phi is shown in figure 7. Maximum temperature in the combustion space was 1563 K at Phi equal to unity. Least value of temperature was observed for model M2 at Phi equal to 0.65 and was 560 K because of incomplete combustion. Minimum values were measured for model M4 approximately for all equivalence ratios which is result of decreased depth and more heat loss from the top and bottom plate. figure 8 shows variation of the combustion space temperature with equivalence ratio for different materials. It was observed that
Model M6 combustor with bronze material gave higher temperatures and model M5 with brass material gave lower temperatures. But melting problems occurred with models M5, M6 and M8 on higher temperatures in the combustors. Model M8 with Aluminum material gave wider flame stability limits. Model M7 with copper material gave temperatures less than Models M1, M6, and M8 for same equivalence ratio but were more than the brass combustor. Amongst above all model M1 was stable for higher temperatures and not melted during the tests. Top surface temperature is very important from the view point of connecting combustor to thermoelectric device. Maximum temperature on the top plate will give maximum input to the thermoelectric device [4] to get increased output in the form of electrical energy, but more temperature on the top plate is indication of more heat loss to surrounding which results into flame extinction. Figure 9 shows variation of the temperatures on the top plate with equivalence ratio for different depths of stainless steel material. Model M1 with 22 mm depth showed higher temperatures for all the equivalence ratios compared to other depths. Temperatures on top plate were found decreasing with decreased depth. Highest temperatures were observed at equivalence ratio equal unity. Figure 10 shows variation of the Temperatures on the top plate with Phi for different materials and approximately same depths. Model M1 showed more temperatures on the top plate compared to other models. Lower temperatures were observed for M8
model (i.e. for aluminium material) because of more heat loss from the combustion space to all the locations inside due to higher thermal conductivity. Temperatures were found decreasing in sequence from Model M1, M6, M7, M5 and M8.

3.5 Effect of Mixture Velocity on Heat Loss through Top Plate
Maximum heat loss was observed for Model M1 and was through top plate for all the mixture velocities. Heat loss through top quartz plate and bottom plate is important to find out how much input can be given to thermoelectric devices to generate electric energy (i.e. maximum heat loss will give maximum input to the thermoelectric devices) and on contrary to find out limit of maximum heat loss at which flame is expected to be stable inside the combustion space. Third dimensional heat loss is important on lower mixture velocities [9]. Figure 11 shows variation of the Heat loss through top plate [5], [8] and bottom plate with different mixture velocities. Maximum heat loss was found near the velocity of 4.5m/s and was high through top plate compared to bottom plate. Reference [8] used for Heat loss calculations. Figure 12 shows variation of the total heat loss variation with mixture velocity. Heat loss through all the surfaces was found to be increased because of insulation provided on all vertical surfaces. Least heat loss observed on vertical surfaces but improved heat loss through top and bottom plates resulted into increase in total heat loss. Maximum heat loss of 37.58 W was observed at 6.88 m/s for with insulation model. Consideration of adiabatic combustor is possible only with all the surfaces insulated.

3.6 Effect of Combustion Volume on total heat loss

Figure 13 Heat losses through top plate for different volumes of stainless steel material without insulation.

Figure 13 shows the variation Model M1 with more combustion volume (i.e. $V_c = 1540 \text{ mm}^3$) results into increased heat loss to surrounding. Maximum heat loss was observed close to stoichiometry for all the models. On richer side of the mixture because of incomplete combustion temperatures measured were lower and hence less heat loss. Similarly on leaner side less heat loss was found because of less heat release during the leaner combustion. Decreased heat loss was observed at leaner limit compared to richer limit.
4. Conclusion
Effects of the various depths and materials were compared to check the thermal performance of one turn exhaust channel combustor. Nine different models of the combustors were tested. Model M9 broke during the test because of brittleness and low temperature sustainability of granite material. Models M5, M6 and M8 melted during the tests on higher temperature sides. Minimum velocity at which flame stability was obtained was 2.33 m/s at 0.44 equivalence ratio. Flame was found stable at a maximum velocity of 11.64 m/s for model M4 (i.e. with 5 mm depth) and model M5 gave narrow flame stability limits (i.e. Brass can’t be used as combustor material). Maximum temperatures were always obtained in the combustion space and maximum value of the temperature was found to be 1613 K. Amongst all the surfaces, quartz material top plate surface always showed more temperatures than other surfaces. Second highest temperature was always shown by surface 2, because it was adjacent to exhaust carrying channel. Heat exchange between exhaust carrying channel and mixture carrying channel was effective and more length of the exhaust channel improves heat sharing. Higher dimension of the exhaust channel results into blowout (i.e. it should be always below quenching dimension of the flame). High heat loss was observed through top and bottom plates for all the combinations. Total heat loss was maximum for model M1 with increased depth and combustion volume. Insulation on the materials showed improved performance in terms of increased temperatures.

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