EFFECT OF MIXTURE VELOCITY FOR GIVEN EQUIVALENCE RATIO ON FLAME DEVELOPMENT IN SWISS ROLL COMBUSTOR

by

Sagar MANE DESHMUKH[a], Krishnamoorthy ARUNAGIRI[b*], and Virendra BHOJWANI[c]

[a] Sathyabama Institute of Science and Technology, Chennai, Tamilnadu, India
[b] Department of Mechanical Engineering,
Sathyabama Institute of Science and Technology, Chennai, Tamilnadu, India
[c] Department of Mechanical Engineering, JSPM's,
Jayawantrao Sawant College of Engineering, Hadapsar, Pune, Maharashtra, India

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Small-scale power generation using heat energy from hydrocarbon fuels is a proven technology. In this study, we analyzed 2-D flame development in meso-scale Swiss roll combustor. A mixture of 60% butane and 40% propane was used (0.25–0.55 L per minute). During all the analyses, equivalence ratio (1.1) was kept constant by adjusting air quantity against fuel quantity. The effect of increase in the mixture velocity on the development of flame shapes/patterns was monitored. We found different patterns of flame, e. g., planar, concave, and conical, with the increase in mixture velocity. Increase in combustion chamber temperature was also noted. No flashback was observed and blowout was observed with very high mixture velocity. Combustion chamber temperatures were found to be increasing with the increase in mixture velocity at the same equivalence ratio. Elongation of the flame was observed because of the increased flow velocity. Heat re-circulation to the reactants enhances flame characteristics.

Key words: *flame, flame patterns, combustion space temperature, meso-scale, Swiss roll combustor*

Introduction

Scope to develop small-scale mechanical systems running on small-scale power is growing because of the recent precise developments in the technologies, *e. g*. micro-electro-mechanical systems. Current small-scale systems are run on Li-ion batteries available in the market. The main problem associated with batteries is its lower energy density. Hydrocarbon fuels have high energy density, and thus energy production by burning the hydrocarbon fuels is said to be the best option [1]. Energy produced in the small scale can be utilized to run various devices viz. laptops, small space heating, small fans, micro-aerial vehicles, small-scale portable power generating devices, small-scale thrusters, sensors, small chemical reactors *etc.* [2]. But decreasing the size of the power generator increases problems in its production (fabrication of the component, assembly, *etc.*). The main component of the small-scale power generator is combustor.

* Corresponding author, e-mail: akrish61@gmail.com

As the scale of the combustor decreases, surface area-to-volume ratio increases which increases heat loss-to-heat generation ratio resulting into flame instability [3]. Flame instability is a major problem and main cause of micro-power generator failure.

Flame stability issues can be resolved by following ways:
– use of catalyst to enhance combustion characteristics [4],
– uniform heating of the micro-combustor during initiation of combustion reaction [5],
– ensuring operation of combustor for mixtures within flame stability limits, and
– use of excess enthalpy due to heat re-circulation from products to preheat the reactants for burning very lean or very rich mixtures [6, 7].

Excess enthalpy provided by the products to the reactants is supplied by the products resulting from combustion by manufacturing exhaust and inlet channels side by side in the Swiss roll combustor. This idea was first put forth by Lloyd and Weinberg in 1974 [7].

Later on, excess enthalpy concept was implemented and tested exhaustively for:
– improving flame stability limits [8],
– achieving improved flame patterns [9-12],
– better flame development,
– increasing heat capacity of the combustor, and
– reducing exhaust emissions, *etc.*

Flame-pattern formations in the radial micro-channels were experimentally investigated by Fan *et al.* [13]. Fixed temperature gradients were maintained on the surface of the combustors/channels. During their study, Pelton wheel-like flame (rotary) and travelling flames with kink-like structures were observed for the first time. The present research focuses on one of the aforementoned important aspects, *i. e.*, the flame development in the central combustion space (combustion chamber) of the meso-scale Swiss roll combustor. Flame development plays significant role in the performance of combustors. Experiments conducted investigated the effect of increase in the mixture velocity on the development of the flame inside the combustion chamber. The details of the flame development are shown in fig. 3. Combustion-chamber temperatures along with flame colors corresponding to different flame patterns were recorded.

Experimental set-up details

Schematic layout of the experimental set-up is shown in fig. 1. The set-up includes arrangement for supplying air from compressor and LPG in required proportion (40% propane and 60% butane). Air and LPG were transferred to the combustor through pneumatic hoses. Pressure gages were used to monitor the pressure of air and LPG flowing through the pneumatic hoses. Pressure of air and LPG was kept close to atmospheric value by setting it using pressure regulators. Initially air and LPG streams were carried through separate pneumatic hoses and then these were mixed by using Y-shaped tube (*i. e.* mixer). Homogeneous mixture of the LPG and air through the inlet of the Swiss roll combustor is then supplied to the reactants channel. The LPG flow meter with range of 0.23-2.3 L per minute and air-flow meter with range of 0-25 L per minute with an accuracy of ±2% of the full scale were used to prepare exact mixture concentration. Flashback arrester was used for safety purpose before the inlet of the combustor. Combustion space (also called as combustion chamber) temperature was measured using *K*-type thermal sensor with an accuracy of ±5 K. Flame development was monitored by high-speed camera with 30 fps recording speed and shutter speed of 1/50 seconds. Data-acquisition system along with personal computer was used to record and store temperatures of the combustion space. The data presented in the paper are for the steady-state. Concentration of the mixture was varied by keeping LPG flow constant and by varying the flow of the air (to maintain constant equivalence ratio). Details of the various instruments used and their accuracies are mentioned in tab.1.

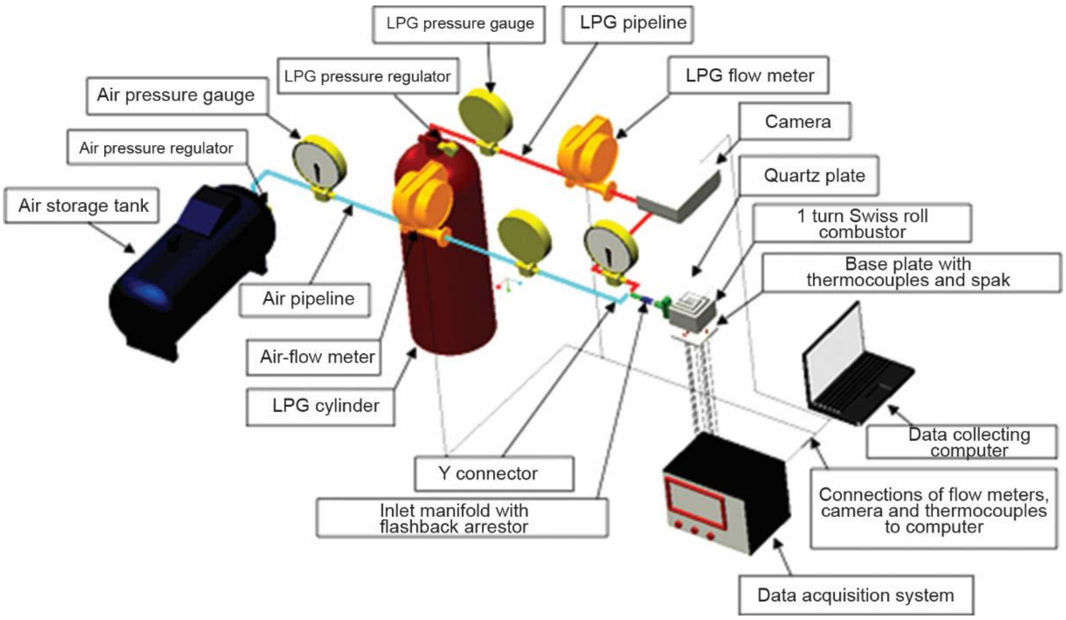


Figure 1. Schematic layout of the experimental set-up

Table 1. Details of the instruments used in the experimental set-up

Sr. no.	Instrument	Range/capacity of instrument	Accuracy
01	Flow meter – LPG	0.23-2.3 L per minute	±2% of the full scale
02	Flow meter – Air	0-25 L per minute	±2% of the full scale
03	*K*-type temperature sensor	0-1350 °C	±5 K of the actual value
04	Ignition device (spark plug)	6 kV, 50 Hz	Not applicable
05	High-speed camera	30 fps recording speed and shutter speed of 1/50 s	Not applicable
06	DAQ	SCADA software (to monitor temperatures)	±5 K of the actual value

Swiss roll combustor with stainless steel material was tested in the present study. The details of the dimensions of the Swiss roll combustor, top plate, and bottom plate are mentioned in tab. 2. To visualize the flame from inside the actual combustion space, top plate of the combustor was prepared with a transparent material (quartz).

All the dimensional details and various passages (inlet mixture channel, exhaust gas channel, combustion chamber, inlet of the combustion space, exit of the combustion space, *etc.*) are shown in fig. 2. Different channel passages and spaces in the combustor are shown by different colors: the inlet mixture channel is shown by blue color, combustion space by red color, and exhaust gas channel by orange color (as shown in fig. 3).

Table 2. Geometrical dimensions/details of the meso-scale Swiss roll combustor

Sr. no.	Description of the part/component	Material	Dimensions of the part
01	Reactants channel	Stainless steel	2 mm (width)
02	Products channel	Stainless steel	3 mm (width)
03	Depth of the combustor	Stainless steel	5 mm (depth)
04	Actual combustion space	Stainless steel	10 mm × 7 mm
05	Bottom plate	Stainless steel	5 mm (thickness)
06	Top plate	Quartz	3 mm (thickness)

*Note: 10 mm dimension of the actual combustion space is in the direction of the flow of the mixture in the actual combustion space, and 7 mm in the direction transverse to the flow.

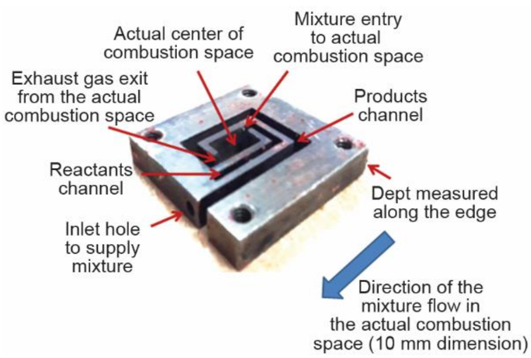


Figure 2. Meso-scale Swiss roll combustor

Results and discussion

Flame-pattern development in the center combustion space of the Swiss roll combustor

Preliminary observations

Preliminary studies were carried out to understand and classify different flame propagation modes observed in the present research. Effect of the increasing flow of the LPG and the air at same equivalence ratio (1.1) on the development of the flame inside the combustion chamber is observed. Experimental investigations were carried out for the LPG in the range between 0.25-0. 55 L per minute. The flow of the LPG was increased in the steps of 0.05 L per minute and air quantity was adjusted accordingly to keep the equivalence ratio of 1.1.

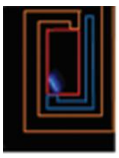
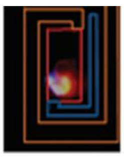
a	b	c	d	e	f	g
0.25 Lpm	0.3 Lpm	0.35 Lpm	0.4 Lpm	0.45 Lpm	0.5 Lpm	0.55 Lpm
13.9 m/s	16.68 m/s	19.47 m/s	22.23 m/s	25.02 m/s	27.18 m/s	30.58 m/s
Planar	Planar	U-shaped	Conical with large base and less height	Conical with medium base and medium height	Conical with small base and more height	Conical with small base and more height
						

Figure 3. Flame-pattern development in the combustion chamber of Swiss roll combustor for equivalence ratio Φ = 1.1 and for different volume flow rates of the LPG

Mixture velocities are increasing, when flow of LPG and air is increased. Mixture velocity, V_{mix}, was calculated by diving total flow rate of the mixture, Q_{mix}, by cross sectional area at the inlet of the reactants channel, A_r. Area of the A_r is the product of the width, W, and the depth of the channel, D. Total flow rate of the mixture is sum of the volume flow rate of the LPG, V_{LPG}, and volume flow rate of the air, V_{air}. Equivalence ratio is the ratio of $(A/F)_{act}$ to the $(A/F)_{st}$. The value of the $(A/F)_{st}$ was taken 15.5. Mass of the LPG and the mass of the air used to calculate $(A/F)_{act}$ were calculated from the basic formulae of the density. Density of the LPG and air were taken 2.21 kg/m^3 and 1.1644 kg/m^3, respectively, at atmospheric conditions.

All the mixtures were ignited by placing spark plug at the center of the combustion chamber. All the flames were generated at the center first because of the placement of the spark plug and then the reaction was travelled to the inlet of combustion chamber. Flame was observed at inlet of the combustion chamber for equivalence ratio of 1.1 for all the flow rates of the LPG. The change in the shape of the flame is observed because of the changes in the flow rate [13]. Flame was observed at the inlet of the combustion chamber for equivalence ratio of 1.1 for all the flow rates of the LPG. Following different types of flames were observed during the experiments: planar flames, U-shaped flames, and conical flames.

The red hot zone which is observed in the actual combustion chamber of the combustor in the fig. 3(c)-3(f) is the portion of the bottom plate (actual flame is observed just above that). All the flames were found to be starting from inlet of the combustion chamber, because of the expansion of the flow when mixture comes out from the reactants channel. All the flames were stable in nature.

Planar flame

Figure 3(a) shows thin planar flames observed for 0.25 L per minute for LPG. Planar flame was found to be the smallest flame among all the types of the flame. During the occurrence of this type of flame, there was continuous flame spread phenomenon (unstable nature as mentioned by Kumar *et al.* [14]. Temperatures observed during this type of flame pattern were always lower compared to other types. Reason behind this was the lowest flow rate of the mixture of LPG and air. Because of the lower flow rates, even after providing the spark in the mixture at the center of combustion chamber, flame was shifted to the inlet of the combustion chamber and was trying to flashback in the reactants channel.

Kinks were observed with this type of the flame because of low temperature oxidation phenomenon mentioned by Fan *et al.* [13]. Thick planar flame is shown in fig. 3(b) and it was observed for 0.3 L per minute flow rate of LPG. This flame was also observed with kinks and was always observed at the inlet of the combustion chamber. Temperature measured during this type of flame was higher compared to thin flame, but lower compared to the other types of flame patterns. The planar flame at 0.25 L per minute was observed with uniform luminosity, and non-uniformity in luminosity was observed for planar flame observed at 0.3 L per minute.

U-shaped flames

The U-shaped flame is shown in fig. 3(c) and it was observed for V_{LPG} corresponding to 0.35 L per minute. Temperature observed is higher compared to planar flame, but lower compared to other types. Flames were bigger in size compared to planar flames. The U-shaped flame was formed because of flow-detachment phenomenon mentioned by Fan *et al.* [13]. Flow detachment is a result of the increased size of the combustion chamber (7 mm) compared to the size of the reactants channel (2 mm). The planar flame with increased thickness was developed into U-shaped flames. The upper part of the flame which is not continuous is a result of local extinction. The local extinction in the flame occurs because of imbalance between heat losses from the combustion chamber to the heat release rate in the combustion chamber [14, 15].

Conical flames

Further increase in the fuel flow rates resulted in the development of conical-shaped flames at V_{LPG} of 0.4 L per minute, V_{LPG} of 0.45, 0.50, and 0.55 L per minute as shown in figs. 3(d)-3(g), respectively. Beyond V_{LPG} of 0.55 L per minute, the flame was extinguished. The reason is that with the increase in the mixture velocity, the heat loss from the structure of the combustor increases, and hence, the temperature of the structure/walls is not sufficient to support a flame which will remain stable at the required location in the combustion chamber (reduced residence time due to increased mixture velocity compared with the increased chemical reaction time due to the decreased wall temperature). This increases heat losses from the stable flame, and thus, will lead to flame extinction in the combustor [14]. The conical flames were observed with increasing the height because of the elongation of the flame with the increasing mixture velocity. Flame was stable and hence less chances of presence of the hydrocarbons in the products of the combustion [16]. The shape of the flame was partially conical at V_{LPG} of 0.55 L per minute. It was observed that for same equivalence ratio and depth, with the increase in the volume flow rate of the gas, flame start location remained the same, but the flame shape changed continuously and the richness in the flame also increased. Existence of the flame in the combustion space at higher mixture flow rates was observed because of the higher wall temperatures which were used to get a balance of flame speed with the mixture flow velocity.

Flame color variation with the increase in the mixture velocity

Colors of the flames were found to be changing with the increase in the mixture velocity. Flames observed with different colors for different mixture velocities are listed in the tab. 3.

Table 3. Flames with different colors for different mixture velocities

Sr. no.	LPG [Lpm]	Flame pattern developed	Color
01	0.25	Planar	Combination of white and blue
02	0.30	Planar with increased thickness	Combination of white and blue
03	0.35	U-shaped	Combination of white and red
04	0.40	Conical with large base and less height	Combination of white and red
05	0.45	Conical with medium base and medium height	Combination of white and red
06	0.50	Conical with small base and more height	Combination of white and red
07	0.55	Conical with small base and more height	Combination of white and green

Variations of combustion chamber temperature for different quantities of the combustor

Figure 4 shows the variations of the combustion chamber temperature with varying quantities of LPG for the same equivalence ratio. Combustion chamber temperatures were found to be increasing with the increase in the quantity of the LPG. The reason behind the increased temperatures was the increase in flow rate due to the increasing LPG and air quantities. Flames were not observed for the LPG flow rate of more than 0.55 L per minute, because of imbalance in the flame speed and mixture velocity.

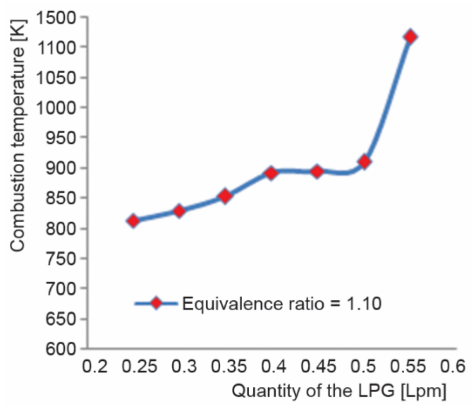


Figure 4. Variations of the combustion chamber temperature with different quantities of LPG

Heat re-circulation effect on flame pattern development

Figure 5 shows variation of the temperature difference in the reactants channel and the products channel with the quantity of the LPG for the same equivalence (1.1) in SW5. Temperature difference in the reactants and products channel was found to be increasing with the volume flow rate of the LPG, because of tendency of high heat releasing with increased LPG quantity. The temperature difference observed in the reactants channel was higher compared to the products channel, because heat shared to the reactants from products and combustion space (reactants channel was close to actual combustion space). Differences between ΔT_{react} and ΔT_{prod} was found to be decreasing with increasing quantity of the LPG, because of testing the combustor (with high thermal conductivity) under non-adiabatic conditions. For non-adiabatic conditions heat loss to the atmosphere from the combustor increases with increasing heat released in the combustor because of the increased quantity of the LPG, which helps in reaching state of the combustor with almost same temperature difference in the reactants and products channel. Heat re-circulation from the products channel to the reactants channel helped in the increasing the combustion space temperatures, which helps in the enhancing the flame characteristics. It has been observed that, with increase in the quantity of the LPG (keeping same equivalence ratio) temperatures of the reactants at the inlet of actual combustion space increases, which helps in increasing size of the flame and temperature in the combustion space for lower depth models.

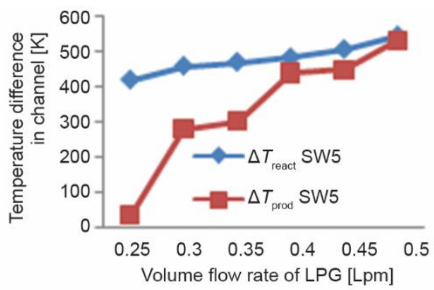


Figure 5. Variation of the temperature difference in the reactants channel and products channel with quantity of the LPG

Conclusion

The present experimental study was conducted on meso-scale Swiss roll combustor. The effect of variation in the mixture velocity for the same equivalence ratio (*i. e.* 1.1) on the flame-pattern development was discussed. Flame was found to be developing into various patterns, *viz*. planar, planar with increased thickness, U-shaped, conical with large base and less height, conical with medium base and medium height, conical with small base and more height. Flame was observed sticking to the inlet of combustion chamber during all the flame patterns and for all the mixture velocities. Combustion chamber temperatures were found to be increasing with the increase in the mixture velocities. No flame was observed beyond 0.55 L per minute LPG, because of imbalance between the flame speed and mixture velocity. Developed flame patterns were found with three combinations of the colors: white and blue for planar (LPG = 0.25 and 0.30 L per minute), white and red for conical (LPG = 0.35-0.50 L per minute), and white and green for conical (LPG = 0.55 L per minute). Excess enthalpy provided to the reactants helps in enhancing flame characteristics.

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Nomenclature

A_r – area of the reactants channel, [m^2]
$(A/F)_{act}$ – actual air to fuel ratio based on mass of air and the fuel, respectively
$(A/F)_{st}$ – stoichiometric air to fuel ratio based on mass of air and the fuel, respectively
D – depth of the reactants channel, [m]
ΔT_{react} – temperature difference in the reactants channel, [K]
ΔT_{prod} – temperature difference in the products channel, [K]
Q_{mix} – total flow rate of the mixture, [Lpm]
SW5 – Swiss roll combustor with depth 5 mm
T_c – temperature measured in the central combustion space, [K]
V_{air} – volume flow rate of air, [Lpm]
V_{mix} – velocity of the mixture obtained at the inlet of the reactants channel, [ms^{-1}]
V_{LPG} – volume flow rate of LPG, [Lpm]
W – Width of the reactants channel, [m]
Φ – equivalence ratio

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