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Materials Today: ProceedingsXX (2016) XXX–XXX

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PMME 2016

EXPERIMENTAL RESEARCH ON THE EFFECT OF MATERIALS OF ONE TURN SWISS ROLL COMBUSTOR ON IT'S THERMAL PERFORMANCE AS A HEAT GENERATING DEVICE☆

Sagar B. Mane Deshmukh [a]☆, A. Krishnamoorthy [b] , V. K. Bhojwani [c]

[a] *Research Scholar of Sathyabama University,Chennai 600119,Tamilnadu,India. manedeshmukh_sagar@yahoo.co.in*
[b] *Professor & Head, Deptatment of Mechanical Engineering, Sathyabama University, Chennai 600 119,Tamilnadu,India. akrish61@gmail.com*
[c] *Professor, Department of Mechanical Engineering, JSPM's, Jayawantrao Sawant College of Engg., Hadapsar,Pune 411028,Maharashtra,India.bhojwanivk@gmail.com*

Abstract

Looking at the present need of small scale power generation to run devices like small thrusters, cellular phones, laptops etc. attempts were made to develop small scale power generating devices. But issues increases with downsizing of the small scale power generators. Present work mainly focuses on the experimental investigations carried out on different materials (i.e. Aluminum, copper, stainless steel and brass) which were manufactured as one turn Swiss roll combustor. Studies were carried out on the Swiss roll combustor for fixed depth of 20 mm. Reactants channel dimension and Products channel dimensions were 2mm and 3mm respectively. During the experiments conducted parameters varied were equivalence ratio and materials of the combustor. Parameters measured during the experiments were flame stability limits, external surface temperatures, combustion space/room temperatures. External surface heat loss to atmosphere was calculated for different values of equivalence ratio. Flame was observed stable successfully during all the experiments conducted. Heat transferred on all the external surfaces from the combustion space can be used as heat input to thermal electric devices. Higher heat content values were observed for SS material and lower values for Br material. Equivalence ratio equal to 1.068 was found to be the best at which maximum temperatures and heat content observed for all the materials. Maximum total heat content of 39.21 W was observed for SS material. Lean limit temperatures were observed to be higher compared to rich limit temperatures.

* Corresponding author. Tel.: +91-8007773358; fax: +20-24354938.
E-mail address: manedeshmukh_sagar@yahoo.co.in

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

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Keywords: One turn; Swiss roll combustor; Meso scale; materials; heat loss.

1. Introduction

Increasing demands of the energy/power at small scale to run devices like cellular phones, laptops, unmanned aerial vehicles (UAV's), small space heating etc. calls for the precise development of the small capacity energy or power generators and that is possible with Micro electro mechanical system (MEMS). Small capacity power generators use the chemical energy released by burning the hydrocarbon fuels in the combustors. Benefit of using the hydrocarbon fuels to generate energy is the higher energy density of the hydrocarbon fuels (i.e. 100 folds more [1]) compared to the commercially available lithium-ion batteries. But the major issue at the small scale of the combustor is to achieve stable and sustainable combustion. Combustion is sustainable generally at a dimension of combustor which is more than the quenching dimension of the flame for a particular fuel. Combustion in the small scale combustors is lost because of increased heat loss to surrounding which is result of increased surface to volume ratio at small scale. Swiss roll combustor design is found to be most convenient design to get a continuous stable flame at its center which is required to generate heat at constant rate on the top plate. Various ways implemented to improve sustainable combustion (i.e. stable flame conditions) viz. use excess enthalpy principle [3] in which products (i.e. exhaust gases) enthalpy is used to preheat the reactants (i.e. mixture of the air and fuel) to increase total heat content of the reactants, use of high pressures, temperature and minimizing heat loss [4 - 5], use of catalysts [6], lower flow velocity (provided heat loss to heat generation ratio should be maintained) [7], minimizing third dimensional heat loss, wall to wall radiative heat transfer [8], proper selection of material and insulation on the combustor [9], providing external thermal environment to the combustor walls [10] etc. Continuous stable flame is requirement to generate heat at constant rate. Heat generated can be converted into electrical energy by using thermal electrical materials. Continuous and constant electrical energy generation is possible with the support of constant heat generated by combustor. In order to generate constant heat, one turn Swiss roll combustors were prepared with different materials (i.e. Aluminum, copper, stainless steel and brass). Channel dimensions and combustion cross sectional area dimensions were selected same like [2]. Various parameters varied during the tests were equivalence ratio, flow velocity and materials and their effect on channel temperatures, surface temperatures and heat loss to surrounding was observed.

Nomenclature

LPG	liquefied petroleum gas
VLPG	volume flow rate of LPG, LPM
Ts1	temperature on surface 1, K
Ts2	temperature on surface 2, K
Ts3	temperature on surface 3, K
Ts4	temperature on surface 4, K
Tp	top plate temperature, K
Tb	bottom plate temperature, K
Tcs	combustion space temperature, K
Qt	total heat loss through all external surfaces including top and bottom plate heat loss, W

2. Experimental set up and models of combustor

Experimental set up used by S. B. Mane-Deshmukh et. al. [2] was used to conduct experiments. In the experimental Set up LPG storage tank and air storage tank were used to store LPG and air. Through proper pipelines

LPG and air was carried to inlet of one turn Swiss roll combustor. Pressure and temperature of LPG and air during all the tests conducted were equal to 1.013 bar and 300 K respectively. To get a continuous stable flame in the combustion space, initially rich mixture was supplied to the combustor and it was ignited by spark plug of capacity 6 KV and 50Hz. Spark plug was placed through bottom plate in the center combustion space of combustor. Once the stable flame was established in the combustion space near to stoichiometric conditions (i.e. at chemically correct combination of air and fuel quantities at which complete combustion occurs), by keeping the VLPG constant air quantity was varied below and above the stoichiometric conditions to decide rich and lean limits. Air quantity higher than the stoichiometric condition gives lean limit and lower than stoichiometric condition gives rich limit. Experiments were repeated for different VLPG. Temperatures in the combustion space and on all the external surfaces were measured for different values of equivalence ratios (i.e. ratio of actual air-fuel ratio to the stoichiometric air-fuel ratio [4]). For lean mixture equivalence ratio is more than one and for rich mixture equivalence ratio is less than one. Similar tests were conducted for different materials. Figure 1 shows one turn Swiss roll combustor model used during tests. Dimensions of the combustors for all the materials were kept same during all the tests conducted. Figure 1a shows all the important dimensions. Reactants channel was 2 mm wide, products channel was 3 mm wide, combustion space was 10 mm X 7 mm in cross section and depth was 20 mm. Figure 1b shows locations of the surfaces and their temperatures. To check stable flame conditions inside the combustion space, quartz plate was used on top of all the combustors. K-type thermocouples were used to measure temperatures in the combustion space and on all external surfaces. Bottom plates were prepared in materials of the combustors. High speed camera was used to capture flame images.

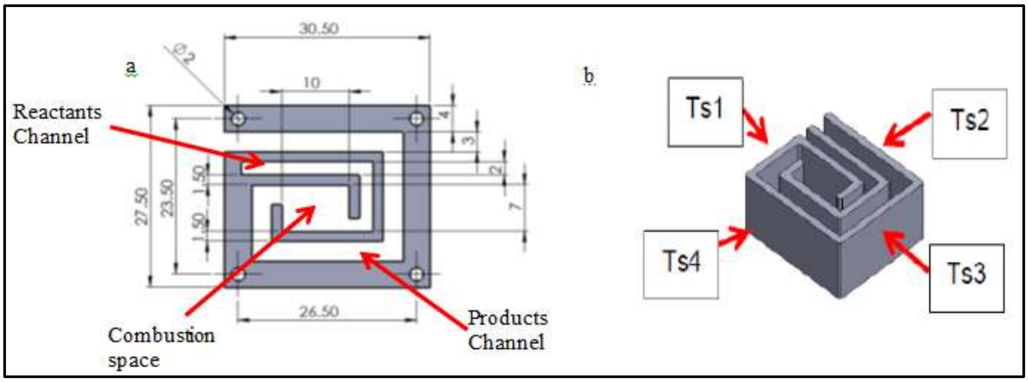

Fig. 1. Model of one turn Swiss roll combustor (a) dimensional details of channels and combustion space; (b) surface temperatures on surfaces 1 through 4 in sequence [2]

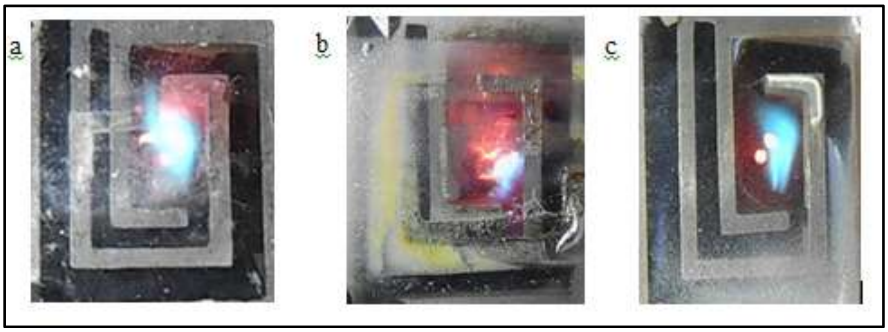

Fig. 2. Stable flames were observed at center of the one turn Swiss roll combustors for different materials at 20 mm depth (a) Stainless steel; (b) Aluminum; (c) Brass

Figure 2 shows that stable flames were observed in the combustion space of the one turn Swiss roll combustor for all the materials and that is the main requirement to transfer heat from combustion space to top plate at constant rate which is required by the thermal electrical devices.

3. Findings and discussions

During the tests conducted Flame stability limits were determined for four materials (i.e. Cu, Br, Al and SS). Continuous stable flame at the center of the one turn Swiss roll combustor was result of balance between flame speed and flow velocity [5]. Continuous stable flame at the center of the Swiss roll combustor ensures constant heat transferred to the top plate and bottom plate of the combustor from the combustion space. This is used as input to the thermal electric materials to generate electrical energy. Figure 3 shows stable flame conditions for the different materials at various flow rates of the LPG. Stable flame conditions were observed between VLPG of 0.25 - 0.5 LPM. Tests were always started with VLPG equal to 0.25 LPM and air quantity was varied to change the equivalence ratio. After achieving the stable flame at the center of the combustor for VLPG equal to 0.25 LPM next value of the VLPG was chosen and similar procedure was continued. Same experiments were conducted on all the materials. After so many experiments it was observed that most rich stable flame was observed for Aluminum material at VLPG equal to 0.35 LPM and at equivalence ratio of 0.194 and most lean stable flame at VLPG equal to 0.3 LPM and equivalence ratio of 1.75. For all the materials stable flame range was observed to be narrowing on higher and lower VLPG (i.e. here at VLPG equal to 0.25 LPM and 0.5 LPM). For all the materials there exist a specific VLPG at which wider stable flame range can be observed. During the present work VLPG equal to 0.35 LPM gave wider flame stability range for all the materials and hence was selected as a decision making parameter for further analysis. Lean limit decides at how much less quantity of fuel required energy output is obtained (i.e. helps in improvement of thermal efficiency [3]). Rich limit gives an idea about maximum heat released by burning of hydrocarbon fuels without affecting flame stability (but on rich side of the mixture thermal efficiency is always compromised because of incomplete combustion). Lean and rich limits can be extended by exchanging heat from products to reactants [8].

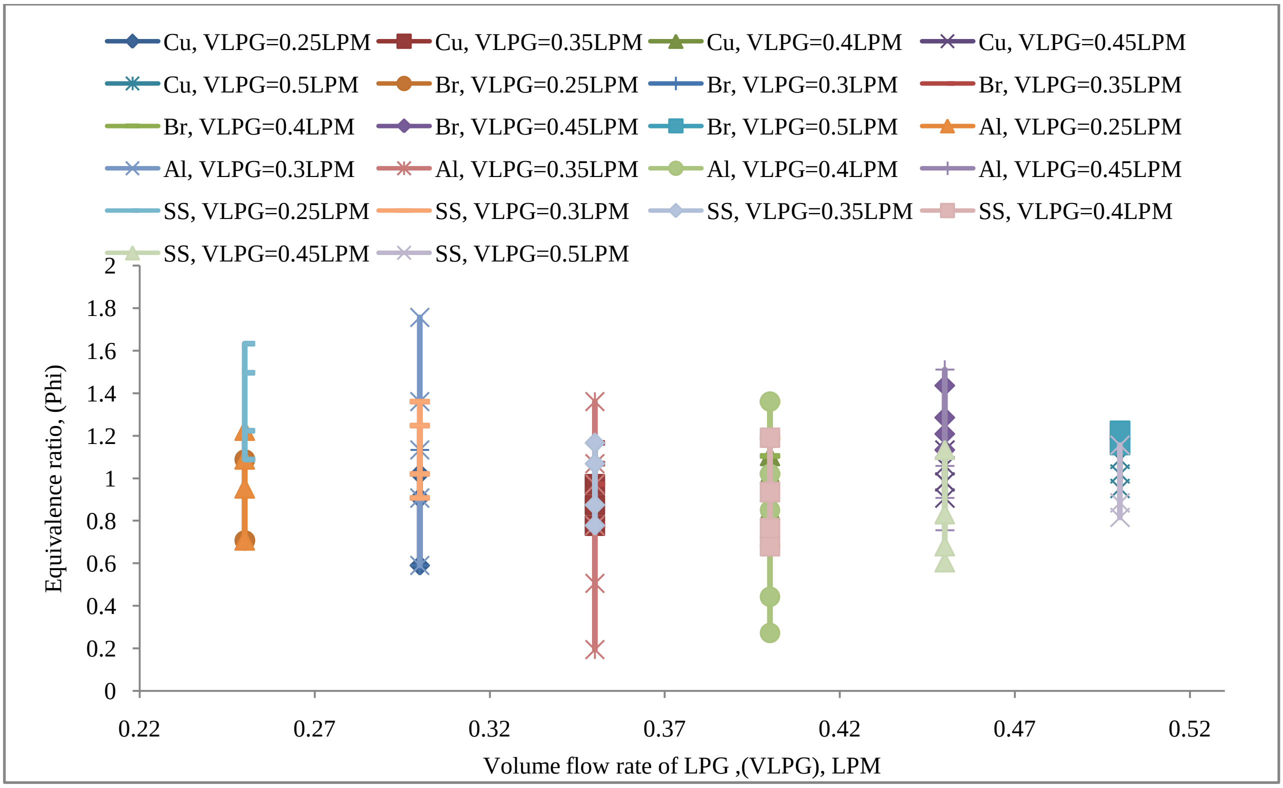

Fig.3 Flame stability range for different Volume flow rate (VLPG) of LPG and for different materials

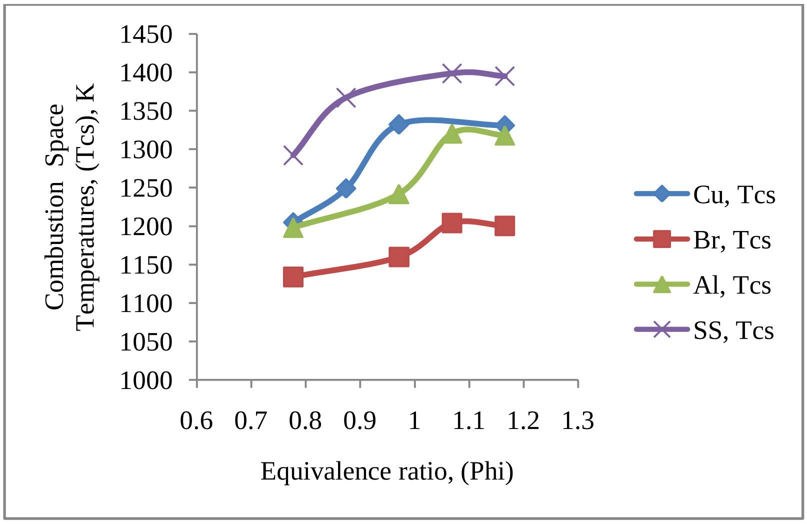

Fig. 4 Combustion space temperatures Vs Equivalence ratio at 20mm depth and VLPG = 0.35 LPM for different materials

Combustion space temperature is important parameter to find out heat generation in the combustion space. Temperatures inside the combustion space were monitored continuously by K-type thermocouples. Temperatures were found increasing with increase in the equivalence ratio for all the materials up to equivalence equal to 1.068 and then decreased with further increase in equivalence ratio. For the same VLPG equal to 0.35 LPM when air quantity was increased gradually, equivalence ratio and flow velocity of the mixture were increased. This resulted into fast heat released after combustion in the combustion space, because of more air availability. But beyond particular value of the equivalence ratio mixture becomes leaner and heat released decreases, results into decreased temperatures in the combustion space. Figure 4 shows variation of the combustion space temperature with equivalence ratio for different materials. Higher thermal conductivity of material distributes heat through all the surfaces at fast rate compared to lower thermal conductivity materials. Maximum combustion space temperature was observed for SS material for all the equivalence ratios because of its lower thermal conductivity [9] and minimum combustion space temperature was observed for Br material for the entire range of equivalence ratio because of its higher thermal conductivity. 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. Lower temperatures were observed on rich limit compared to lean limit because of incomplete combustion [3]. Maximum temperature of 1398.50 K was observed for SS material at equivalence ratio equal to 1.068. More temperature variation was observed at equivalence ratio equal to one compared to either side of stoichiometric conditions for all the materials. Thermal electric devices are run on constant heat generated by combustors. Present Swiss roll combustor generates more heat on the top plate of the combustor compared to all other surfaces of combustor. Variation of the top plate temperature with equivalence ratio is shown in the Fig. 5. As top plate was always in contact with the flame in the combustion space, it showed higher temperatures compared to other surfaces. Maximum temperatures were observed at equivalence ratio equal to 1.068 for all the materials. Top plate temperatures also showed same trends which were observed for combustion space temperature. SS material showed higher temperatures and Br material showed lower temperatures for all the equivalence ratios. SS showed maximum temperature of 775.03 K at equivalence ratio equal of 1.068 and Br showed minimum temperature of 615.34 K at equivalence ratio of 0.77. Maximum temperature difference between the SS material (showing higher temperatures) and Br materials (showing lower temperatures) were below 130 K. Figure 6 shows variation of bottom plate temperatures with equivalence ratio for different materials. Large values of the temperatures were observed for SS material compared to other materials. Cu, Br and Al bottom plate temperatures were found to be converging on rich and lean limit side because of their higher thermal conductivity (i.e. because heat released on rich side or lean side is lower compared to heat released close to stoichiometric conditions). More separation of temperature was observed near stoichiometric conditions and very less temperature variation was observed at rich limit and lean limit for both top and bottom plate.

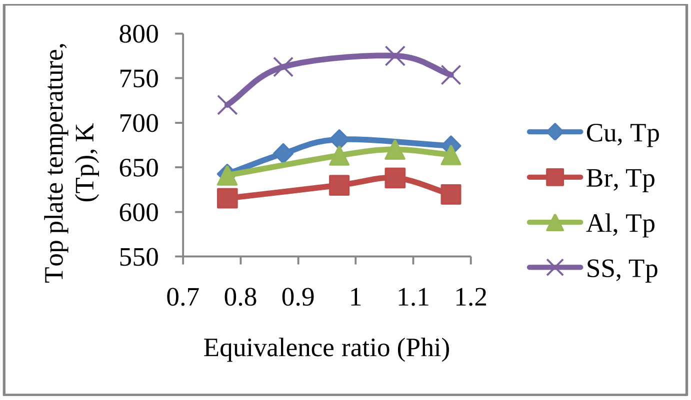

Fig. 5. Top plate temperatures Vs Equivalence ratio at 20 mm depth and VLPG = 0.35 LPM for different materials

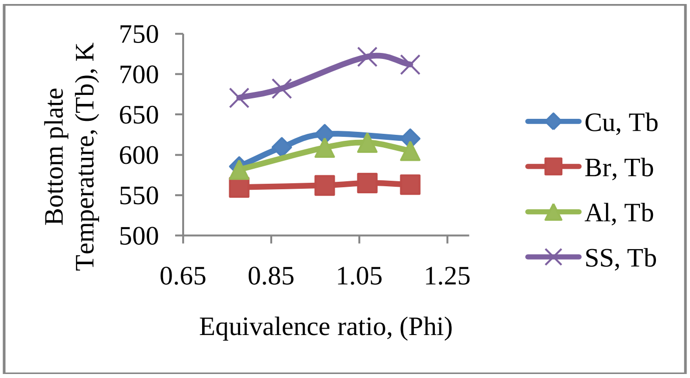

Fig. 6. Bottom plate temperature Vs Equivalence ratio at 20 mm depth and VLPG = 0.35 LPM for different materials

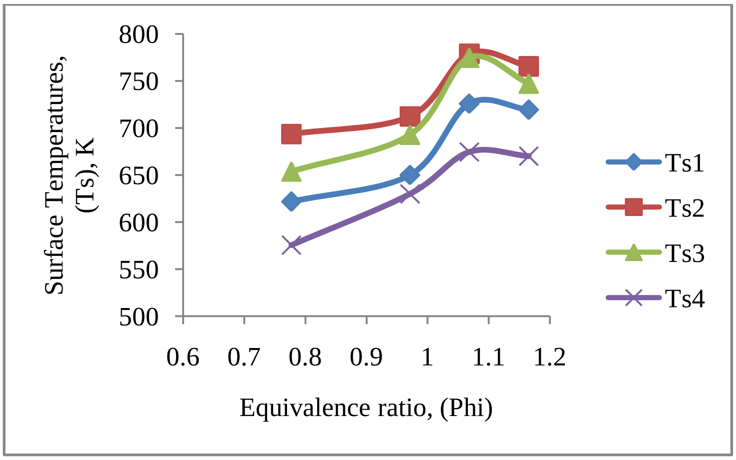

Fig. 7. Surface temperatures Vs Equivalence ratio for Aluminum material and at 20 mm depth

Figure 7 shows variation of surface temperatures with equivalence ratio for Al material. All the surface temperatures were found increasing up to equivalence ratio equal to 1.068 and then decreased. All materials followed the same trends for external surface temperatures. Surface 2 always showed higher temperatures compared to other surfaces because it was close to combustion space and there was earlier and fast heat transfer. Temperatures were found in the decreasing manner on the surfaces as Ts2, Ts3, Ts1 and Ts4. Maximum value of temperature was observed on surface 2 and it was 778.80 K at equivalence ratio equal to 1.068 and least value of temperature was observed for Ts4 and it was 575.60 K at equivalence ratio equal to 0.77. Lean limit temperatures were higher compared to rich limit temperatures. Maximum variation of the temperature was observed at rich limit (i.e. at equivalence ratio equal to 0.77) between Ts2 and Ts4 and it was 118.00 K.

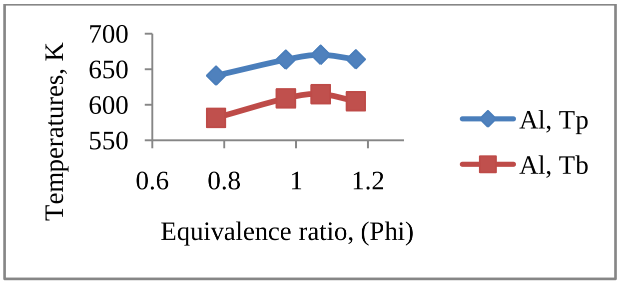

Fig. 8. Temperatures Vs Equivalence ratio for Aluminum material and at 20 mm depth

Figure 8 shows variation of the temperatures on top and bottom plate of Al with equivalence ratio. Top plate temperatures were found higher for all the equivalence ratios compared to bottom plate temperatures [5]. Maximum temperatures were observed at equivalence ratio equal to 1.068 on top and bottom plate. Maximum variation in the temperature on top and bottom plate was below 70 K (same was the case with other materials also). Heat transferred from combustion space to top plate (i.e. here for this application it is heat loss from top plate to atmosphere) is estimated by using natural convection correlations used by [5]. Total heat available is the sum of heat available on all the external surfaces (i.e. surface 1 through 4, top surface and bottom surface). Heat calculated on the SS material top surface was found to be higher compared to other materials. Maximum value of total heat content available was 39.21 W which was observed for SS material at equivalence ratio of 1.068. Heat content values were found increasing with equivalence ratio up to equivalence ratio equal to 1.068 and decreased beyond that because of less heat released on leaner side [7]. Lower heat content values were observed on rich limit compared to lean limit because of incomplete combustion. Heat content values for higher thermal conductivity materials (i.e. Cu, Br and Al) were found close to each other at all the equivalence ratio. But more separation of heat content values was observed for SS material compared to other materials for all the equivalence ratios. Higher thermal conductivity ensures fast heat transfer through material in all the directions (i.e. through all the internal surfaces and external surfaces). That is why values of heat content were same/converged on rich and lean limits for higher thermal conductivity materials. It is clear from Fig. 9 that SS material is most suitable for thermal electrical applications as it is having higher total heat content available on top plate.

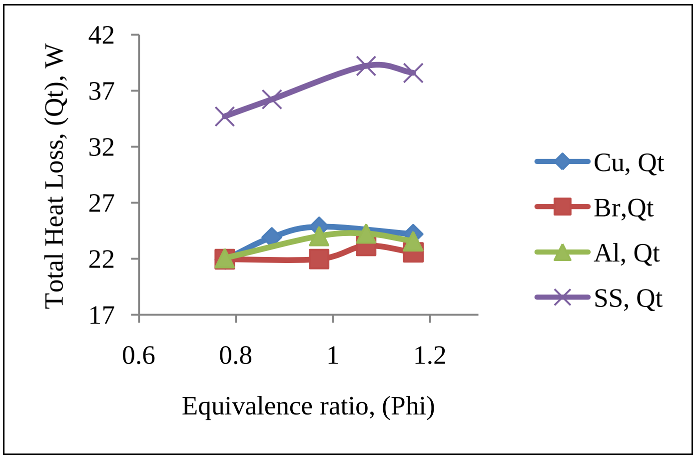

Fig. 9. Total heat loss VS Equivalence ratio for different materials and at 20mm depth

4. Conclusions

One turn Swiss roll combustors with different materials (i.e. Al, Cu, Br and SS) at fixed channel dimensions and combustion space dimension were fabricated and tested successfully to get a continuous stable flame at the centre of the combustor. Flame stability limits were determined for different VLPG and for different materials. Narrower flame stability limits were observed at VLPG equal to 0.25 LPM and 0.5 LPM for all the materials. VLPG equal to 0.35 LPM gave wider flame stability limits for all the materials. Aluminum material gave most rich and lean flame stable flame in the combustion space at equivalence ratio equal to 0.194 and 1.75 respectively. Combustion space temperatures, surface temperatures, top plate temperatures and bottom plate temperatures were varied with equivalence ratios. Equivalence ratio equal to 1.068 was found a critical where all the temperatures were maximum. Maximum combustion space temperature was 1398.5 K for SS material at equivalence ratio equal to 1.068. Temperature increases with increase in the equivalence ratio up to 1.068 because of increased flow velocity which leads to fast heat transfer. But with further increase in the equivalence ratio, leanness in the mixture increases, which results into decrease in heat released during combustion and temperatures. Lean limit temperatures were observed higher than the rich limit temperatures because of more air availability in the combustion space for complete combustion on leaner side. Top plates showed higher temperatures compared to all other external surfaces because of direct contact of flame and combustion space. All the temperatures were found higher for SS material compared to other materials. Higher thermal conductivity materials gave lower heat content availability. SS material showed maximum total heat content of 39.21 W at equivalence ratio equal to 1.068 and Lower total heat content 21.95 W was observed for Br material at equivalence ratio of 0.77.

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