Review of effect of meso scale combustor wall material, Catalytic material, & Porous media on flame Stabilization

Gajanan Z. Jadhav¹, Dr. K K Gupta²
SVKM’S, NMIMS, MPSTME, Shirpur, Maharashtra, India 425405.
gajanan.jadhav@nmims.edu

Abstract. In recent trends demand of energy for portable devices like notebook, microsatellite, laptops, UAV are increasing at high rate, a high energy density hydrocarbon fuel creates opportunity to alternate chemical Li-ion batteries with micro combustion based power generation system. Mainly, this review focus on experimental, mathematical modelling techniques, and numerical simulation performed on heat recirculating combustor to find the effect of combustor wall material, catalytic material and porous media. It also summarizes the electricity generation possibilities with micro combustor turbine, thermo electric material & thermo-photovolatic combustion system. The effect of combustor wall material, catalytic material, and porous media on flame stabilization are enlisted with its summary.

Keywords: - Combustion, Wall conductivity, Catalysis, Thermoelectric

1. Introduction

The recent development in manufacturing technology, MEMS (micro electro mechanical system), & rapid prototyping, minimization of portable devices have accelerated. Because of this rapid growth of portable devices like cell phone, notebook, video cameras are dramatically increased. With this development demand of energy are increased currently chemical batteries are used in this devices, but this battery having low energy density about 0.2KWh/Kg [1].

This chemical battery with low energy density as compared to hydrocarbon fuel require more time recharge and it continues for few hours. It also had limited number of recharging cycle limitations. As well as its disposal creates environmental pollution which is not desirable. Moreover, new devices like 4G cellular phone, laptops require high energy and minimum recharging time, with this view in mind increase in the operational life time of power devices, the energy density fuel & the energy conversion system need to be re-examined. Fig.1 displays judgement of energy densities of different fuels. It is seen that most progressive Li-ion batteries having one sixteenth energy density of hydrocarbon fuels. Several researchers took the advantages of this high energy density of hydrocarbon fuel to generate power at small scale.

At macro scale conventional power plant were more efficient but at micro scale it difficult to fabricate, still at MIT micro gas turbine, Wrankle Engine at [FernandezPello], HCCI by [Aichlmajr et al], IC Engine by Dahm et al] were developed and tested for power generation. Table-1 shows list of micro engine developed at micro scale with its capacity. As it had moving parts which leads to friction subsequent causes less efficiency as well as manufacturing cost at microscale increases therefore this research leads to the development of non-moving part combustion system for power generation and propulsion system.

Several approaches were used to developed combustor based power generation system at micro scale level. Firstly, Thermoelectric, Thermophotovolatic, Thermoelectromagnetic material to convert heat energy into the electric energy. But at micro and meso level the flame stabilization problem were found. To tackle this problem researcher used excess enthalpy concept with number of techniques likewise
change of combustor wall material, use of catalyst, use of porous media and its effect are revisited in this paper.

### Table 1. Micro Engine with its capacity

| Researcher       | Engine Type   | Capacity | Fuel               |
|------------------|---------------|----------|--------------------|
| FernadezPello    | Wankel Engine | 4W       | Hydrogen/ Air      |
| Aichlmajr et al  | HCCI          | 10W      | n Heptane/ Air     |
| Dahm et al       | Micro I C Engine Swing | 20W | Butane Fuel       |

**Figure 1.** “Comparison of specific energy densities of lithium ion batteries with hydrocarbon and oxygenated hydrocarbon fuels as well as different engines” [1].

1.1 *Decision parameters for sizing of micro/meso combustor:*

During last decades’ development of micro devices like engines, thrusters & reactors uses different reference scale. It leads to confusion regarding micro scale & meso scale size. Table -2 shows three different lengths have been used in previous studies one length are physical dimensioning of combustor. When the size of the combustor is less than 1 mm is referred as microscale combustor whereas size of the combustor is in between 1 mm to 1 cm is referred as meso scale combustor. This definition mostly used in micro engines [2].

Secondly length of flame is used to define size of the combustor if combustor size is smaller than quenching diameter. Thirdly relative length scale is used. In this the size of the combustor are compared with conventional large size combustor for example size of combustor for micro satellite would be (1 to 10 Kg) compared to large satellite of 1000 Kg and above. Micro combustion process depends on chemical kinetics & physical process such as gas phase & surface reaction, radiation, transport, convection, mass diffusion.

### Table 2 Sizing of micro- meso scale combustion using different length scales [5]

| Sizing based on | Combustion regime | Length scale | Applications |
|-----------------|-------------------|--------------|--------------|

2
2. Experimental and Numerical Studies:

Several experimental numerical studies conducted over meso and micro scale combustor. It was observed that flame instability in pre-mixed, non-pre-mixed, non-equilibrium, catalyst combustion system. But when combustion occurs at small scale surface area to volume ratio increases and thermal characteristic inertia time also reduced which subsequently leads to the heat loss from combustor wall, flameless combustion, and flame instabilities. To reduce this flame instability different techniques were reported, likewise use of excess enthalpy concept by using heat recirculation. With heat recirculation combustor wall material conductivity affects flame stability. These effect of Combustor wall material are revisited in this study. Also this study focuses on use of catalyst, porous media on flame stabilization.

2.1 Effect of use of catalytic material:

The large surface area to volume ratio has concern with higher heat loss tend itself use of catalytic material for low temperature combustion. The use of catalytic allows combustion of fuel at low temperature. (~55˚C minimum temperature observed [12] and this also enables low level power production without any waste. Ronney et al [5] demonstrated 3W of thermal energy release with near complete combustion fuel (propane). This low temperature combustion allows use of plastics and polymers combustion that can manufacture in different geometries with rapid prototyping and CNC machining.

Lee & Kin, [12] studied effect of catalytic material on combustion of methane. Platinum were good catalytic material for combustion. The oxygen: methane feed ratio, particle size, support nature, loading of precious metal affects the catalytic combustion.

P D Ronney [6] performed experimental study on Swiss roll burner to evaluate extinction limits of flame with use of catalyst. Effect of catalyst with Re number were evaluated. With use of catalyst combustion of Propane-air at lean stoichiometric ratio were observed. Gas phase combustion occurred in “Flameless mode”, with high Re, Stoichiometric combustion didn’t require heat recirculation but it occur out of the centre, to centre it catalyst were used. It was concluded by the researcher that with use of catalyst in heat recirculating burner with low Re greatly benefited by selecting proper mixture. Figure -2 shows Extinction limit map for gas phase combustion on Swiss Roll Combustor. Kim et al [7] in a flat type counter current combustor and Pt type catalysis arise largely same conclusion i.e. flame rich extinction regime increases & flame lean extinction regime lone marginally.
Figure 2. “Extinction limit map for catalytic and gas phase combustion in the Inconel Swiss-Roll” [6].

Teresa A. Wierzbicki et al [11] compared the performance of meso scale heat recirculator combustor with and without Platinum & Rhodium catalysing material. The result showed that addition of catalyst greatly increased stability and extinction limits. It also observed that Propane with Rh had rich stoichiometric ratio, whereas propane with Pt had leaner stoichiometric ratio.

Junwei et al reported experiments results on N-Heptane fuel used in micro combustor. This experiment results shows the effect of inlet reynold number and mass flow rate on flame shape, combustor wall material temperature and outlet temperature. Whereas other studies which [14] evaluates energy efficiency of micro combustor by comparing heat recuperation micro combustor with non-heat recuperation micro combustor. They performed numerical simulation with SIMPLE algorithm. It had been observing that average wall temperature, emitter efficiency notably improved with the incorporation of heat recuperator. Junjie Chen et al performed CFD analysis to observe combustor wall material conductivity, feed composition, and flow rate effect on thermal uniformity during exothermic catalyst reaction. With H2-air, equivalence ratio of 0.9, 25.8% improvement of total radiation power and 30.6% emitter efficiency were observed.

Yei Chinchao et al [3] performed theoretical, experimental analysis as well as numerical simulation which indicates as the size of tube decreases, which results in shift of flame from low velocity region to high velocity region.

Summary:- Different investigator performance Numerical and experimental evaluation of catalyst with heat recirculation techniques in combustor with varying inlet velocity, mass flow rate, Equivalence ratio on flame stabilization. It had been observed that use of catalyst likewise Platinum, Rhodium had positive effect over flame stabilization as compared to without catalyst combustion. Catalytic extended the rich extinction intensely and lean extinction only slightly. It is applicable only when gas phase combustion cannot be achieved.

2.2 Effect of thermal conductivity of combustor wall material:
At small / meso scale level combustion affects because of large surface to volume ratio, the researchers examine the effect of combustor wall material with different thermal conductivity on flame stabilization. It was observed that material with high thermal conductivity with heat recirculation geometry supports to flame stabilization V Vijayan performed experimental and numerical simulation on heat recirculating combustor, which shows thermal conductivity of wall material plays significant roll to stabilize the flame. With low thermal conductivity material, it was found that amount of heat recirculation increased while heat loss decreases. Also investigate the lowest thermal conductivity material.
Figure 3. “Effect of thermal conductivity on heat transfer rates for a heat load of 29W.” [13]

Aiwu Fan et al. [10] performed numerical investigation on Swiss roll combustor made of Steel, Silicon Carbide, and Quartz with bluff body. Heat loss play important role in flame blow off limits for this newly designed combustor with bluff body. This study summarizes the effect of heat loss, heat recirculation and flow recirculation zone on SS, SiC, Quartz combustor, which causes largest blow off limit in SS, Smallest blow off limit in SiC, and Medium blow off limit in Quartz.

Junjie et al [15] performed CFD and experimental analysis which shows with low thermal conductivity wall material shows flame stability as well as for the heat recirculation inlet, outlet stream temperature equal to room temperature and exhibits high thermal and combustor efficiency.

Upendra Taywade et al [16] find the effect of mixture velocity, equivalence ratio and heat recirculation on the wall temperature. It had been observed that for high velocity >4m/s wall temperature is lower. It also reported that for rich equivalence ratio high wall temperature obtained.

**Summary:** Several researchers conducted experimental and numerical study on material of combustor wall like SS, Sic, and Quartz etc. to found its effect on flame stabilization with heat recirculation techniques. It had been observed from above discussion that material with thermal conductivity helps to stabilize the flame inside combustor. Fig.-3 notable indicates Effect of combustor wall material thermal conductivity on heat transfer rates for a heat load of 29W.

2.3 Flame Dynamics and instability:
Junjie Chen et al [15] compare the flame stability of single pass combustor with respect to heat loss coefficient and total power loss in between CFD and single channel combustor.
It had been observed that heat recirculation affect blows out limits but had minimal effect over extinction.
Upendra W taywade [16] et al made numerical and experimental investigation three step combustor to find effect of heat recirculation on flame stability. It was observed by the researcher that heat recirculation is function of cup dimension, material of cup and flow velocity and equivalence ratio for the cylindrical shape heat recirculating combustor. Thermal outputs of 2.2W for 0.5 equivalence ratio were observed with stable flame. This study was also reported the variation in position of flame with respect to mixture inlet flow velocity.
V Vijayan et al [17] performed experimentation, acoustic emission incorporation with high speed flame imaging diagnostic. It had been observed that stable self-sustained combustion at high mean velocity in meso scale combustor. The reactant preheat temperature of 700K-1000K range were observed. Tradition FREI was absent. Uttam rana et al [18] performed thermodynamic model to evaluate exergy transfer. It were reported that flame stabilization by heat recirculation were justified from energy quality preservation perspective.
Chien Hua et al [19] performed numerical and experimental study on Swiss roll burner. It were reported that thermal management of 3D swiss roll combustor were satisfied double spiral burner. Effect of third dimension heat loss on extinction compared numerically as well as experimentally. Aiwu et al [10] carried out investigation for flame blow out limits on swiss roll heat recirculating combustor with bluff body. It were concluded with numerical simulation and experimentation that bluff body helps to stabilize the flame and the position of bluff body affects inlet and outlet velocity.

**Summary:** The extinction of flame greatly depending on the thermal characteristic of combustion geometry. Increase in heat recirculation channel length of combustor allows combustion of lean mixture. As researcher tried to vary the heat recirculation geometry which causes pre-heating of reactant leads to significant flame dynamics under the correct conditions. It notably indicates that combustor of high thermal conductivity material had positive response as compared to material with low thermal conductivity.

2.4 Porous Media Material Effect:
Daoguan Wing et al [20] mesotubes of 4, 5.6mm in diameter Y shaped combustor were developed. The effects of adding fibrous porous media on flame stabilization, ignition temperature were systematically investigated. Jonwei Li et al [21] performed experimentation on n-heptane air combustion with porous media in meso scale burner.

3. Micro-power Generation

It were easy to convert heat energy into electric energy or kinetic energy at macro scale but at micro scale level it’s challenging task. Researcher developed combustor at meso /micro level to generate power and thrust force. This section discussion about the power generation with combustor.

Some of the researcher tried miniaturization of macro scale power generation system like wise Fernandez Pello developed “Wankle” engine, Aichlmayr et al. designed HCCI engine with a power of 10W. But because of moving parts its fabrication are difficult and costly as well as friction between moving parts leads to loss of efficiency. Therefore, most researchers focused on micro level power generation with solid conversion system instead of moving parts likewise conventional macro level power plant. Most of the researcher preferred thermoelectric and thermophotovoltaic material based conversion system over the other.

3.1 Electricity Generation

The conversion of heat energy into electrical energy has two scenarios. Firstly, conversion of shaft power into electric energy through dynamo. Secondly conversion of electrical energy through Seebeck & Peltier Effect as well as thermophotovoltaic conversion (TPV) Thermoelectric system consist of major four components:

i) Combustor  
ii) Thermal Spreader  
iii) Thermoelectric Material  
iv) Heat sink

The thermoelectric material are of P type and N type semiconductor. As because of heat electrons tends to flow from n type of semiconductor material toward cooling region, whereas holes from p type semiconductor flows toward power load. It is reported that power output of the TE material are proportional to square of temperature gradient, but it has to operate at 300 °c. This limiting the application of combustor with catalyst which operates comparatively at lower temperature. Fig-4 describes working of conversion of heat energy into electrical energy by using thermoelectric materials.
Tanuj Singh [24] et al. developed a novel combustor and optimized it to obtain stable enclosed premixed flame. This study found that the relationship between ambient temperature and thermoelectric power generation was established through environmental control chamber experiments. They observed that the blow-out limit first decreases with an increase in plate length. The largest blow-out limit was found at Lb=1.0mm. Another solid power conversion system, such as the use of thermophotovoltaic materials to absorb thermal radiation from heat sources and convert it into electrical energy, was also investigated by different researchers. Figure 5 shows the working of the thermophotovoltaic (TPV) based power conversion system.

Roman Fursenko, et al. [26] performed numerical and experimental studies in a multichannel system for flame penetration and its propagation. Varying mixture flow rates, equivalence ratios, and channel sizes resulted in different combustion regimes. Y.-C. Chao, [27] reported the results of experimental and numerical analysis of a reverse tube TPV combustor with a porous media. It was observed that the use of emitter material in a swirling combustor improved flame structure and uniformity in illumination by the flame.

4. Conclusion
Effect of combustor wall material as interpreted by most researchers indicates that wall materials with high thermal conductivity have a better effect on flame stabilization.
Similarly, the use of catalyst and porous media also helps to stabilize the flame inside the meso-scale combustor. Thermal conversion of electric energy through shaft work, thermoelectric or thermophotovoltaic, is still in its infancy if modest efficiency is reported.
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