Effects of Fuel and Nozzle Characteristics on Micro Gas Turbine System: A Review

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Abstract. For many decades, gas turbines have been used widely in the internal combustion engine industry. Due to the deficiency of fossil fuel and the concern of global warming, the used of bio-gas have been recognized as one of most clean fuels in the application of engine to improve performance of lean combustion and minimize the production of NO_X and PM. This review paper is to understand the combustion performance using dual-fuel nozzle for a micro gas turbine that was basically designed as a natural gas fuelled engine, the nozzle characteristics of the micro gas turbine has been modelled and the effect of multi-fuel used were investigated. The used of biogas (hydrogen) as substitute for liquid fuel (methane) at constant fuel injection velocity, the flame temperature is increased, but the fuel low rate reduced. Applying the blended fuel at constant fuel rate will increased the flame temperature as the hydrogen percentages increased. Micro gas turbines which shows the uniformity of the flow distribution that can be improved without the increase of the pressure drop by applying the variable nozzle diameters into the fuel supply nozzle design. It also identifies the combustion efficiency, better fuel mixing in combustion chamber using duel fuel nozzle with the largest potential for the future. This paper can also be used as a reference source that summarizes the research and development activities on micro gas turbines.

1. Introduction

This review paper is discussed on the effects of dual-fuel nozzle of fuel injector on the fuel air mixing in the combustion chamber of micro-gas turbine system fuelled by biogas and investigation of the mixture formation during earliest stage of burning process of bio-gas combustion. It also discussed on the sufficient flow mixing mechanism of biogas on combustion process which strongly affects the reduction of NO_X emissions. The output of this review paper will be the combustion performance and the emissions of the Carbon Monoxide (CO), Nitrogen Oxide (NO_X) and Hydro-Carbons (HC).

Gas turbine engines fuelled by hydrocarbon fuels sources have been used widely in power production for many decades. Due to the depletion of fossil energy and increasing concerns of global warming, hydrogen or hydrogen blended fuels have been considered as one of the most promising clean fuels in order to improve the lean combustion, performance and to reduce pollutant emissions [1-4]. Frenillot *et. al.* [1] had showed adding hydrogen in hydrocarbon fuels could allow stable lean burn at a lower temperature. The used of fuel in internal combustion engine has already been applied since the engine existed. The chemical combination of fuel with the oxygen produce

heat that been converts into mechanical energy by the engine. There are many different type of fuel can be operated in the internal combustion engine such as solid fuel, gaseous fuel and liquid fuel. The use of different fuel is significantly influence the design of engine. Thus, the design of engine is accordingly depending on the type of fuel [5-7].

Natural Gas - Natural gas is the cleanest and most hydrogen rich of all hydrocarbon energy sources, and it has high energy conversion efficiencies for power generation. Of more significance is that gas resources discovered but as yet untapped remain plentiful. The sector is poised for considerable growth over the next two decades, and some believe that it may even overtake oil as the prime fuel between 2020 and 2030 [8-10]. The trend towards natural gas becoming the premium fuel of the world economy is not now easily reversible. The key and the challenge for the energy industry is how the transition is to be managed. Natural gas consists of a high percentage of methane (generally above 85 percent) and varying amounts of ethane, propane, butane, and inerts (typically nitrogen, carbon dioxide, and helium) [11]. The average gross heating value of natural gas is approximately 1,020 British thermal units per standard cubic foot (Btu/scf), usually varying from 950 to 1,050 Btu/scf. Table 1 shows the general properties of natural gas [12].

Table 1: Properties of natural gas [12].

Physical and Chemical Properties of Natural Gas	
Molecular formula	CH_4
Molecular weight of mixture	18,2
Boiling point at 1 atmosphere	-160.0 °C
Melting point	-180.0 °C
Vapour density (Air =1) at 15.5	0,61
Liquid density (Water=1) at 0°/4 °C	0,554
Expansion ratio	1 litre of liquid becomes 600 litres of gas
Water solubility at 20 °C	Slightly soluble (0.1 to 1.0%)
Appearance and colour	Colourless and tasteless

Biogas - Biogas covers a wide and difficult to manage range, starting from forest and farming wastes (including fermented liquid manure) through sewage sludge to municipal wastes. Its field of application includes combustion engines, burners as well as gas turbines for electricity generation and cogeneration of heat and power [13]. Biogas can be further enhanced from low-quality to natural gas quality before it is fed in the public gas grid. Table 2 below shows basic parameters of typical biogas.

Table 2: Physical properties of biogas and its component [14].

Physical properties		Biogas components				Biogas (60CH$_4$, 40%CO$_2$)
		CH_4	CO_2	H_2	H_2S	
Volume Fraction	%	55-70	27-44	1	3	100
Calorific Value	MJ/m$_3$	35,8	-	10,8	22,3	21,5
Flash-Point	^{o}C	650-750	-	583	-	650-750
Critical Pressure	MPa	4,7	7,5	1,3	89	7,5-8,9
Critical Temperature	^{o}C	-82,5	31	-	100	-82,5
Normal Density	g/cm^3	0,72	1,98	0,09	1,54	1,2
Critical Density	g/cm^3	162	468	31	349	320
Density Ratio of Air	[-]	0,55	2,5	0,07	1,2	0,83

Biogas can be gained in an anaerobic digestion process from different organic substances, e.g. from energy crops, agricultural waste or municipal organic waste. It is produced from organic wastes by concerned action of various groups of anaerobic bacteria through anaerobic decomposition. In

comparison with natural gas, biogas has significant benefits for the environment [15]. One important cycle necessary to understand the biogas is the cycle of matter. From the production of feedstock to the application of digestate as fertiliser, the biogas provides a closed nutrient and carbon cycle. Carbon dioxide (CO_2) is re-up taken by vegetation during photosynthesis [16].

2. Thermodynamics Analysis

The basic operation of a micro gas turbine is similar to that of a steam power plant, except that is used instead of water. The fact that all type of gas turbines is a mass flow machines and the thermodynamically process are totally the same does not change its name based on the size of a gas turbine [17]. The tips to maximize the output power of a gas turbine are to turn its rotor close to the speed of sound. Thus, the smaller the radius of the turbine, the required speed to maximize the output power of gas turbine is higher [18]. Micro gas turbine is a device that involved thermodynamic process that converts thermal energy to mechanical one which is possible only by means of a thermodynamic cycle. It also can be defined as a cycle of thermodynamic processes which finally returns to its initial state after the working fluid undergoes a series of state changes [19].

Thermodynamic processes can be represented on a pressure–volume diagram and on a temperature–entropy diagram. Figure 1 shows an example of an isothermal expansion process in the thermodynamically processes in micro gas turbine, where the temperature of the gas remains constant during the thermodynamic process. The areas shown in the pressure–volume and temperature–entropy diagrams correspond to the work and heat transfers, respectively [20].
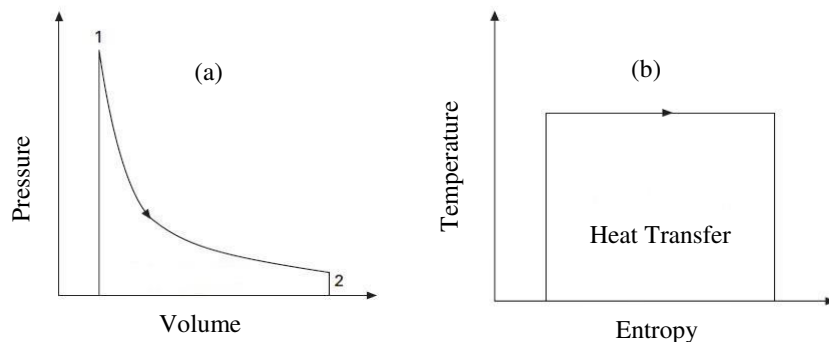

Figure 1: Work and heat transfers on (a) pressure – volume and
(b) temperature – entropy diagrams [21].

The increment in entropy during the expansion process on the temperature–entropy diagram is important. Many thermodynamic processes that exist in the gas turbine, the reversible and adiabatic processes, which are also known as isentropic processes is such an ideal process which both the heat transfer and the entropy changes are zero.
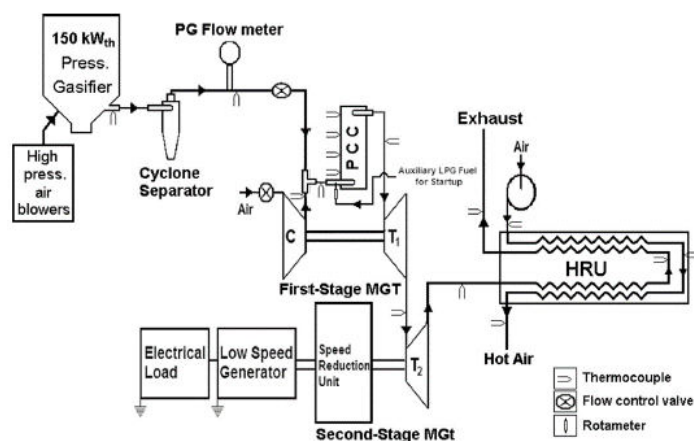

Figure 2: Schematic drawing of the micro-gas turbine system for PG single-fuel mode [23].

3. Micro gas turbine system

Micro gas turbine system example can be obtained in several research papers. Researcher Al-attab K.A and Zainal Z.A used two-staged micro-gas turbine with a small-scale design based on small turbocharger in its research on performance of biomass fueled two-stage micro gas turbine system hot air production heat recovery unit as shown in the Figure 2 [22]. In earlier development of MGT, a small turbocharger, IHI-RHB32 with turbine wheel diameter of 36 mm was used for the first-stage based on the air flow rate that the compressor could provide to match the PCC design. For the second-stage MGT, a larger turbocharger: HOLSET-H1C with turbine wheel diameter of 70 mm was used.

4. Injector Nozzle Characteristics

In injection system, fuels directly impinge on the chamber walls, thus preventing the mixture being well-stratified. Furthermore, more complex design was required to improve the mixture formation process and is associated with higher emissions [24]. If fuel is well distributed to the combustion chamber through each nozzle, thrust can be adequately developed and the design lifetime of hot section components can be maintained. In the contrary, incomplete combustion due to uneven fuel distribution results in disproportionate fuel consumption, and poor exhaust emission, which significantly impacts on the long-term reliability of the components in the system. Thus, the flow distribution of the fuel supply nozzle in the annular combustor plays an important role in development of the micro gas turbine.
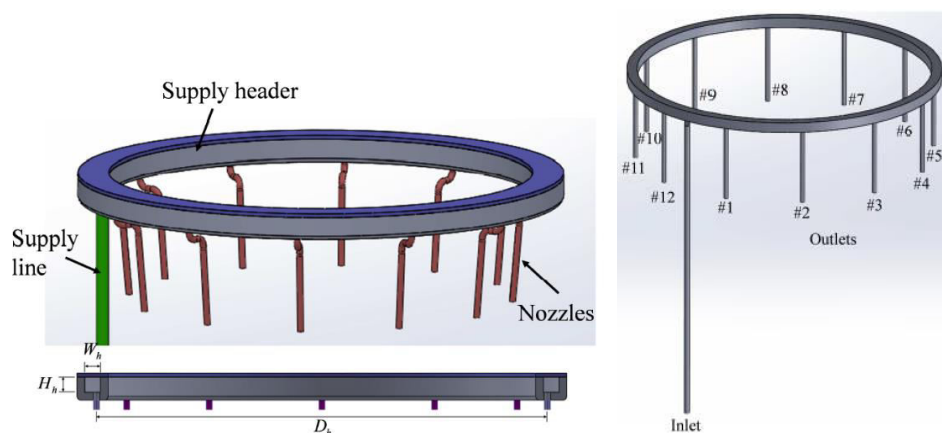

Figure 3: Fuel supply nozzle [25].

Several previous researchers had not considered the distribution flow of the nozzles in the combustor when they designed the micro gas turbines. Researcher Dessomes *et. al.* [26] conducted a study on advances in the development of a microturbine engine. They found that when the nozzle diameter is less than 500 mm, the corresponding non-uniformity parameter is less than 2%, which means the maximum deviation of the normalized mass flow rates to be less than 5%. Moreover, they also found that the flow distribution of the fuel nozzle in the annular combustor of a micro gas turbine hardly affect by the fuel temperature and different types of fuel. In the aspect of the uniform flow distribution as well as the lower power consumption of the pump, we concluded that all nozzles with 500 mm in diameter were appropriate for the fuel supply nozzle of the micro gas turbine developed in this study [26]. Figure 3 shows fuel supply nozzle used in the investigation on flow distribution of the fuel supply nozzle [27].

5. Fuel Spray Characteristics

This section discusses the fuel spray characteristics used injected into combustion chamber. All practical sprays are comprised of drops of a variety of sizes. There are many different ways in which the droplet size distribution can be characterized. One way in which the droplet size characterized is

by use of the Sauter Mean Diameter (SMD). The SMD is the diameter of a drop that has the same surface-to-volume ratio as the entire spray for engine work [28-29].

Swirl spray - A standard technique used in automotive industries is by surround the fuel spray by a swirling co-flow to generates a recirculation zone which to confine the droplets which to stabilize the flame and to control its length [30]. This method is useful to avoid the flame from reaching the opposite combustor wall in the particular case of gas turbine combustion chambers. Besides, it also can prevent potential damage to the heat exchanger tubes [31-32]. There are essentially three types of fuel injector which is swirl injectors, multi-hole injectors and outwardly opening injectors. Each injector shows different spray pattern. Figure 4 shows different fuel spray pattern from different injector [33].

Furthermore, a temperature reduction in the reaction zone can contribute to flame extinction due to physical contact of the flame to the comparatively combustion chamber cold walls. When temperatures are critically lower in rich or lean mixtures, these phenomena can occur [34]. There are some researcher attempts by conducting experiment about the effect of swirl on the flow and flame dynamics in combustion systems. Tangirala *et al*. [35] studied on the influence of swirl and heat release on the flame properties and flow structures in a non-premixed swirl burner. They discovered that the increasing in number of swirl to approximately unity can improve the fuel mixing and flame stability. In addition, they also discovered that turbulence level and flame stability can be reducing further by increasing the swirl number. Stone and Menon [36] investigate about a swirl stabilized combustor flow and they focused on the impact of varying swirl and equivalence ratio on flame dynamics. In addition, Wang *et al.* [37] conducted an examination about the vortical flow dynamics in a swirl injector with radial entry. Various flow instability mechanisms, such as the Kelvin–Helmholtz, helical, and centrifugal instabilities, as well as their mutual interactions, were investigated in detail.
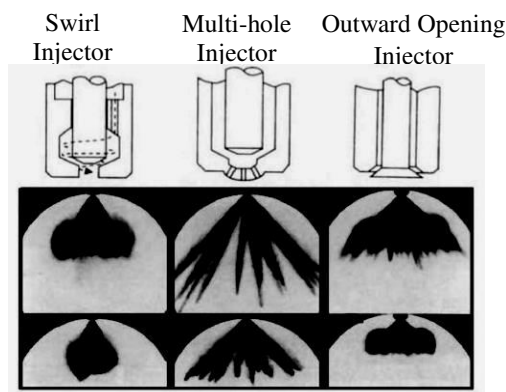

Figure 4: Fuel spray pattern from each different fuel injector at 1 bar (upper images) and 6 bar (lower images) with reduced space penetration [33]

Fractal Spray - Fractal are the geometric shapes with self-similar for certain similar structure which can be observed at different levels of magnification. The grids are usually located at upstream of the flame with a distance of several characteristic mesh sizes to ensure a well-developed velocity field. Turbulence will decay quickly with downstream distance although the grids can generate high levels of turbulence intensity [38, 39]. Basic research for the dependence of the turbulence characteristics is convenient to use grids generating turbulence such as perforated plates or meshes.
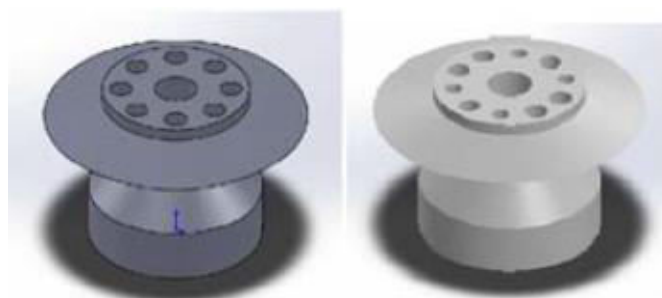

Figure 5: Fractal regular grid and fractal grid design [41].

The fractal grids can produce more than approximately 30% higher turbulence intensities than regular grids even both grids have the same blockage ratio [40]. Several previous researches have been done on fractal grids in various sectors to use the turbulence generating for multipurpose researches. Ronny Yii and A. Khalid [41] conducted a comparison between the fractal and swirl injector of diesel spray characteristics in the burner system. Figure 5 shows the fractal design used in the research. A. Khalid and M. Bukhari [42] conducted a numerical investigation about the circle grids fractal flow conditioner for orifice plate flowmeters. They successfully discovered that the fractal grids could remove the flow distortions and produced the fully developed flow. Besides, M. Fahmi *et al.* [43] also studied numerically about the circle fractal grid perforated plate as a turbulent generator in combustion chamber. They investigated that the fractal grids showed good perceptivity in generating turbulence and the fractal flow physics. Other than that, they found also the turbulent intensity can be increased by a grid with higher blockage ratio.

6. Performance of Micro-Gas Turbine

The environmental concerns on burning hydrocarbon fuels and the strict emissions performance standards for gas turbines, along with the strategic need for energy security, are the reasons that motivate researchers and manufacturers to explore novel combustion technologies. Such technologies would burn different fuels, maintain an efficient thermal energy conversion, and emit less of pollutants.

Emission - The goal of the micro gas turbine is to develop leaner combustion systems applicable for both stationary and aeronautical engines. These systems must be eco-friendly; by offering lower fuel consumption and producing less NO_x and CO emissions to cope with the strict regulations. For example, depending on the type and load of a combustion system, the Environmental Protection Agency (EPA) of the USA would regulate the maximum NO_x emissions limitto15ppm (at 15% O_2), and that of CO emission to 130 ppm (at 3% O_2) [44]. With a stricter futuristic projection for regulations, aircrafts are planned to produce 90% less NO_x by the year 2050 [45]. Since it's introduced by Wünning [46], the flameless combustion mode has demonstrated low emission levels and it is seriously considered as an interesting option to implement in different applications.

Nitrogen Oxide - Nitrogen oxides must be divided into two classes according to their mechanism of formation as in equation 1.0. Nitrogen oxides formed from the oxidation of the free nitrogen in the combustion air or fuel is called "thermal NO_X." They are mainly a function of the stoichiometric adiabatic flame temperature of the fuel, which is the temperature reached by burning a theoretically correct mixture of fuel and air in an insulated vessel.
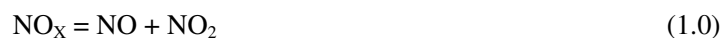
$$NO_X = NO + NO_2 \tag{1.0}$$

Table 3: Relative thermal NO_X emissions [37].

Fuel	Stoichiometric Flame Temp.	NO_X (ppmvd/ppmvw-Methane) 963 ^{o}C-1104 ^{o}C Firing Time	NO_X (ppmvd/ppmvw-Methane) @ 15% O_2, 963 ^{o}C-1104 ^{o}C Firing Time
Methane	1.000	1.000/1.000	1.000/1.000
Propane	1.300	1.555/1.606	1.569/1.632
Butane	1.280	1.608/1.661	1.621/1.686
Hydrogen	2.067	3.966/4.029	5.237/5.299
Carbon Monoxide	2.067	3.835/3.928	4.128/0.529
Methanol	0.417-0.617	0.489/0.501	0.516/0.529
No. 2 Oil	1.667	.567/1.647	1.524/1.614

Gaseous fuels are generally classified according to their volumetric heating value. This value is useful in computing flow rates needed for a given heat input, as well as sizing fuel nozzles, combustion chambers, and the like. However, the stoichiometric adiabatic flame temperature is a more important parameter for characterizing NO_X emission. Table 3 shows relative thermal NO_X production for the same combustor burning different types of fuel. This table shows the NO_X relative to the methane NO_X based on adiabatic stoichiometric flame temperature. The gas turbine is controlled to approximate constant firing temperature and the products of combustion for different fuels affect the reported NO_X correction factors [47]. Therefore, Table 3 also shows columns for relative NO_X values calculated for different fuels for the same combustor and constant firing temperature relative to the NO_X for methane.NO_X emission is the most headed in gas turbine. Literally, the development of different combustor design sand technologies is aimed towards the simultaneous reduction of the emission. That concern may beat tribute to their effects and indications [48].

Unburned hydrocarbon - Unburned hydrocarbons (UHC), like carbon monoxide, are associated with combustion inefficiency. When plotted versus firing temperature, the emissions from heavy-duty gas turbine combustors show the same type of hyperbolic curve as carbon monoxide. At all but very low loads, the UHC emission levels for No. 2 distillate and natural gas are less than 7 ppm (parts per million by volume wet) as shown in Figure 6 [47].
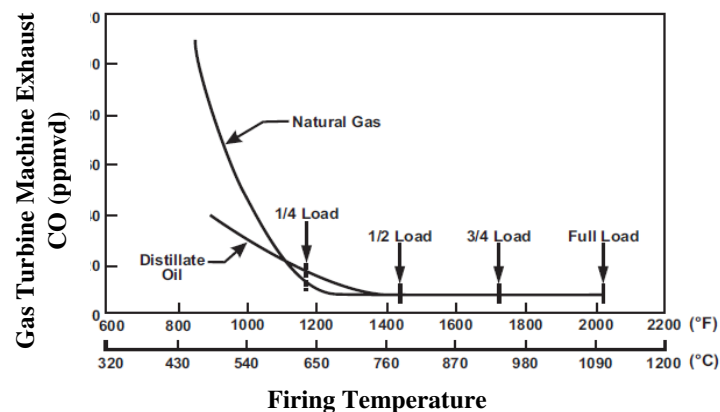

Figure 6: UHC emissions for MS7001EA [37].

Hydrocarbon emissions are occurred due to the air-fuel ratio is non-stoichiometric. Based on Figure 6, it shows hydrocarbon emission levels are a strong function of equivalence ratio. The shortage of oxygen to reacts with all the fuel-rich mixture, thus producing in high levels of hydrocarbon and carbon monoxide in the exhaust production. If air-fuel ratio is too lean, the combustion becomes poorer, resulting in hydrocarbon emissions.
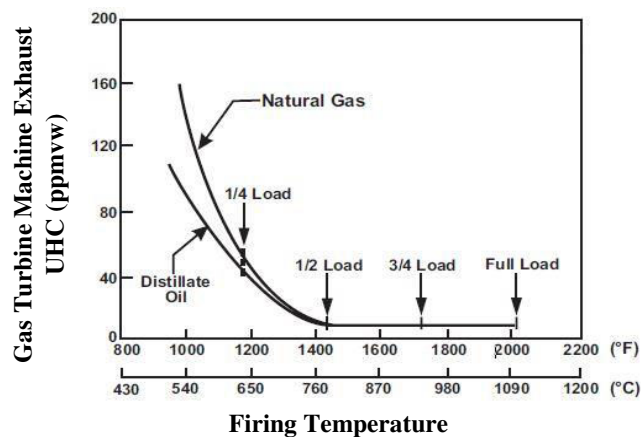
Figure 7: CO emissions for MS7001EA [37].

Carbon Monoxide - Carbon monoxide (CO) emissions from a conventional gas turbine combustion system are less than 10 ppmvd (parts per million by volume dry) at all but very low loads for steady state operation. During ignition and acceleration, there may be transient emission levels higher than those presented here. Because of the very short loading sequence of gas turbines, these levels make a negligible contribution to the integrated emissions. Figure 7 shows typical CO emissions from a MS7001EA, plotted versus firing temperature [47]. As firing temperature is reduced below about 1500°F/816°C, the carbon monoxide emissions increase quickly. This characteristic curve is typical of all heavy-duty machine series.

Combustion Flame
The power production of micro gas turbine is restrained by the heat input which used burning fuel in the combustion chamber and using air from the discharge of compressor to be generated. The use of liquid fuels such as kerosene, and gaseous fuels such as natural gas and biogas, is becoming increasingly frequent in the gas turbine industry. The amount of heat input generally indicated to as the net thermal input. There are several previous researchers have been done on combustion flame characteristics in micro gas turbine system. A. Hayakawa *et. al* [47] conducted an experimental investigation of stabilization and emission characteristics of ammonia/air premixed flames in a swirl combustor. They found that the ammonia/air premixed flame can be stabilized for various equivalence ratios and inlet velocity conditions. The lean and rich blow-off limits are close to the flammability limit of ammonia flame. There is a minimum limitation for mixture inlet velocity of flame stabilization. The blow-off limits were affecting by the swirl number and burner geometry, but the liner length does not affect the flame stability characteristics. Figure 8 shows ammonia/air flame stabilized in the burner with a cylindrical liner in a gas turbine [48].
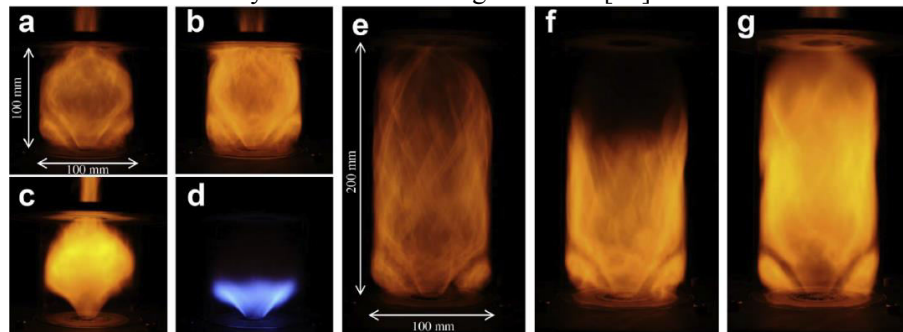

Figure 8: Flames stabilized in the different swirl burner with cylindrical liners [41].

Combustion Efficiency - The term of combustion efficiency can be defined as the ratio of the actual heat released to the maximum heat released of the combustion process. This transcribe to the theoretical fuel-air ratio for a given combustion temperature rise to the actual fuel-air ratio for the same temperature rise. Researcher S. Yuasa *et. al.* [49] conducted experiment on the concept of

combustion characteristics of ultra-micro combustor with premixed flame. They found that the heat loss to the nozzle had little effect on the flat-flame combustion on the porous plate itself, causing a temperature decrease in the exhausted gas after complete combustion. They also found that the flame zone becomes thicker and as the equivalence ratio decreases and combustion reactions would be inhabited by the heat loss to the nozzle.

7. Conclusions

In this review paper, a several number of papers discussing different micro gas turbines have been summarized. Although significant progress has been achieved, the development of micro gas turbine is still at the early stage. There is still a lot of work needs to be done before its application in practice. The main thermodynamic conclusions of the review are micro-gas turbines have a thermodynamic potential of efficiencies similar to, or higher than, combined cycle efficiencies. The development of dual-fuel nozzle is still in early stage in the micro-gas turbine system and need improvement.

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