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DESIGN OF COMBUSTOR FOR MICRO GAS TURBINE TEST RIG AND ITS PERFORMANCE PREDICTION

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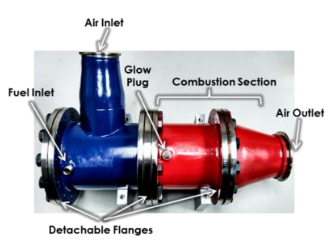
Graphical abstract



Abstract

Stringent emission rules, air pollution, fluctuation of fuel price and depletion of fossil fuel resources are driving the industry to seek for better alternative of power generation. Micro gas turbine (MGT) provides a promising potential to solve the facing problems. MGT could be used in many applications such as in range extender vehicle, auxiliary power generator, power backup system, combine heat and power system, etc. Combustor plays a very crucial role in MGT system as its performance directly affects the emission quality, power output and fuel consumption of the entire system. This paper demonstrates the literature review, design methodology and performance prediction of the combustor designed for a 14.5kW MGT test rig.

Keywords: Combustor, micro gas turbine, single can, numerical simulation

1.0 INTRODUCTION

Micro gas turbine (MGT) is a type of internal combustion engine which has the benefits of producing clean emission, has multiple fuel capability, simple and compact in design [1 - 4]. Combustor is the key element in MGT system. Inside the combustor, compressed air is mixed with fuel and burned to produce heat energy. The heat energy increases the temperature of compressed air to the desired turbine inlet temperature. The schematic diagram of MGT is demonstrated in Figure 1.

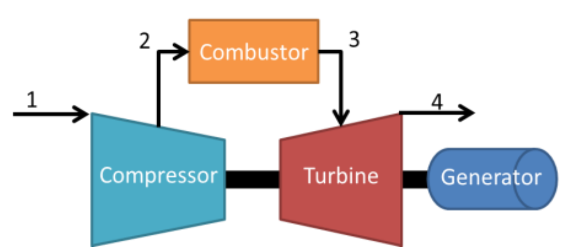


Figure 1 Micro gas tubine system

A MGT test rig has been developed in LOCARTIC, UTM using a commercial turbocharger. In the test rig, a standalone combustor is designed and built to make the system complete. The combustor design started with literature review on the current combustor technology, determination of design parameters, followed by numerical simulation for performance prediction.

2.0 LITEREATURE REVIEW

Combustors can be classified into many categories according to their flow path, geometry and method of combustion [5 - 8]. There are "straight through" and "reversed flow" type of flow path. Typically, reversed flow combustor is adapted by MGT combustor due to its much shorter geometry. However, reversed flow combustor has higher pressure drop as compared to straight through flow combustor. Combustor shape can be tubular (can), tubo-annular or annular as shown in Figure 2. Tubular combustor has the simplest design and longer life span [7].

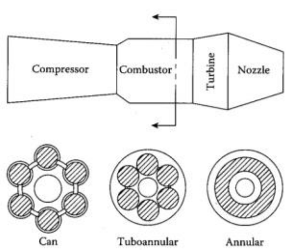


Figure 2 Combustor arrangements

To achieve better combustion efficiency, stable combustion and clean exhaust emission, many combustion models had been introduced and studied extensively. For example, there are diffusive combustor, "staged" combustor, lean premixed-prevaporized combustor, rich burn- quick mix- lean burn combustor, etc. These combustors have differences in terms of burning zones, equivalence ratio and fuel injection methodology. Catalytic combustor in which combustion of air fuel mixture occurs on catalytic reactor bed is another effort to minimize pollutants [6]. A conical wire-mesh duct burner had been designed as combustor for MGT [9]. Wire-mesh is used to provide combustion surface in the burner to enable lean burn mode with stable flame.

Despite the variation of combustor types, all combustors have three features, which are the circulation zone (primary zone), the burning zone (intermediate zone) and the dilution zone [7]. In primary zone, fuel is injected and mixed with air. Combustion begins at this zone and propagates into the intermediate zone. In the intermediate zone, more air is injected to complete the combustion. Dilution zone is the section where the remaining air is mixed with combusted air to obtain desired turbine inlet temperature.

Figure 3 shows the combustor zones and main components of a conventional combustor. Prior to the primary zone, swirler is used to create internal recirculation zone for flame to anchor. Swirler enhances the mixing of fuel with air, increases turbulence as well as creates stable and shorter flame [10]. Swirl flow in a combustor also enhance the flame blowout limits [11]. High blade angle of swirler is shown to have positive effect in reducing NOx and CO emission formation [12].

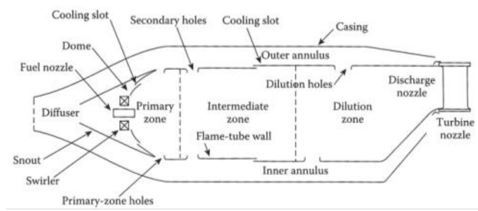


Figure 3 Main components of a conventional combustor [5]

Liner is used to contain flame within the combustion zone while separating primary air flow and dilution air flow. There are holes on the liner to enable mixing of dilution flow with the combusted air. Air flow within and outside the liner also acts as cooling agent to keep the liner temperature low [7].

Single can- swirl stabilized- straight through- diffusion type of combustor has been selected for the MGT test rig. It is due to the simplicity in its design, its low pressure drop nature and feasibility for fabrication. Table 1 shows the MGT test rig data at the design point. The data is crucial for the combustor design parameters determination.

Table 1 MGT test rig data

Parameters	Value
Mass flow rate, $\dot{m}$	0.281kg/s
Fuel flow rate, $\dot{m}_f$	4.5g/s
Combustor inlet temperature, TIC	370K
Turbine inlet temperature, TIT	1000K
Pressure Ratio, PR	2.1
Compressor outlet diameter, D_c	70mm
Turbine inlet diameter, D_t	83mm
Fuel type	Liquefied petroleum gas (30% propane, 70% butane in mole fraction)

3.0 DESIGN PARAMETERS

3.1 Reference Velocity

Reference velocity is the theoretical velocity of combustor inlet air flowing across the maximum cross section area of the combustor. It is defined as:

$$v_{ref} = \frac{\dot{m}_{in}}{\rho_{in} A_{max}} \quad (1)$$

Reference velocity is important as it affects combustion stability, ignition performance and pressure drop of the combustor [5]. In general, higher gas velocity has higher blowout limit and it needs higher energy for ignition. The designed combustor has low reference velocity of v_{ref} = 11.6m/s at design point to cater for wide flow range of the MGT test rig.

3.2 Swirl Number

Swirl number, SN is the main parameter in the swirler's design. High swirl number indicates strong swirl. To obtain practically strong swirl, swirl number should be higher than 0.6. The swirl number of the designed combustor is 0.8, with 8 x 45° vanes.

$$SN = \frac{2}{3}\frac{1-\left(D_{hub}/D_{sw}\right)^3}{1-\left(D_{hub}/D_{sw}\right)^2}\tan\theta \qquad (2)$$

3.3 Stoichiometric Ratio

The equivalence ratio of the fuel air mixture is represented by Eq.(3). MGT combustor has high overall equivalence ratio as compared to reciprocating engine. This characteristic contributes to the cleaner emission as more air is available to react with the fuel. Overall equivalence ratio for the design at the design point is 0.25. For primary combustion zone, equivalence ratio is 0.983, which is a slightly lean.

$$\phi = \frac{AF_{stoic}}{AF_{act}} \qquad (3)$$

3.4 Combustion Efficiency

Combustion efficiency is a key performance measurement for combustor. Combustor efficiency is the ratio of un-burnt fuel to the total fuel inlet as shown in Eq.(4). M_f is the mass fraction of fuel at the combustor outlet calculated by numerical simulation.

$$\eta_{comb} = \frac{M_f \times \dot{m}_{out}}{\dot{m}_{fuel}} \qquad (4)$$

3.5 Pressure Drop

Pressure drop is needed across swirler and combustor liner to generate desired flow pattern in the combustor. However, pressure drop directly impacts the turbine's power output negatively. Percentage of pressure drop is calculated using Eq. (5).

$$\%P_{drop} = \frac{P_{in} - P_{out}}{P_{in}} \times 100\% \qquad (5)$$

4.0 COMBUSTOR COMPONENTS

The designed combustor adapts components which are commonly found in the market to reduce cost and fabrication time. For example, standard stainless steel pipes and fittings are used to make the combustor body. Stainless steel 316L is used as it has high melting point (1650K), has good weldability, it has good corrosion resistance and has good thermal resistivity. All components are detachable to ensure flexibility for modification and maintenance.

The first section of combustor consists of air inlet, fuel line, fuel nozzle and swirler. Fuel nozzle is mounted in the center of swirler with 3 outlet of spray angle of 60 degree to the axial axis of combustor. There are 4 annular flow channels around the swirler to allow dilution air flow into combustion section.

Combustion occurs at the second section of combustor. In this section, a glow plug is installed near to the fuel nozzle outlet for ignition purpose. Liner is used to contain the flame with an arrangement of holes to provide cooling air within the liner.

The assembly of the combustor components is shown in Figure 4. Total length of the combustor is 465mm and the casing is 140mm in diameter.

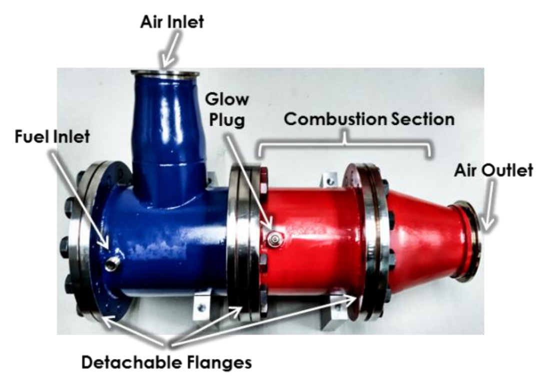


Figure 4 Combustor components

5.0 NUMERICAL SIMULATION

Performance of the designed combustor is predicted using numerical simulation approach (ANSYS Fluent). Numerical simulation has been adapted to predict the swirled flow combustion performance [13,14]. A full model of the combustor is modelled using CAD software. The model is meshed into 2.24 million elements with smaller mesh size along the complex and curvy geometry. The meshed combustor model is shown in Figure 5.

ANSYS Fluent use mass and momentum conservation equations to solve fluid flow problems [15]. In this simulation, species transport with Eddy-Dissipation model is used to represent the air fuel mixture and combustion reaction. For turbulence model, k-epsilon realizable model is used. The fluid medium's density is simulated using ideal gas equation. Pressure based coupled solver is used as the solution method.

For boundary condition setup, there are two inlet (one for air inlet, one for fuel inlet) and one outlet boundaries. All the inlet boundaries are mass inlet type and the inlet materials are set by species mole fraction. For air inlet, 0.207 mole fraction of oxygen is used as per standard atmosphere's oxygen composition. On the other hand, 0.3 mole fraction of propane and 0.7 mole fraction of butane are used for fuel inlet (refer Table 1). As for the outlet boundary, pressure-outlet type is used, with outlet pressure set to desired turbine inlet pressure.

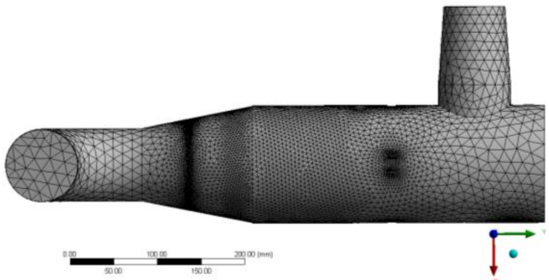


Figure 5 Combustor model meshing

Numerical simulation is carried out for four different cases. They are non-combustion case, combustion at MGT design point, combustion at low load MGT off-design point and combustion at high load MGT off-design point. The operating parameters of low and high load off-design cases are obtained from MGT thermodynamic cycle analysis and are summarized in Table 2.

Table 2 Off-design operating parameters

Parameters	Off-design (low load)	Off-design (high load)
Mass flow rate, $\dot{m}$	0.188	0.315
Fuel flow rate, $\dot{m}_f$	3.14g/s	4.72g/s
Pressure ratio, PR	1.6	2.4
Combustor inlet temperature, TIC	343K	410K
Turbine inlet temperature, TIT	1000K	1000K

6.0 RESULTS AND DISCUSSION

In the non-combustion simulation case, it is clear that a low velocity region is formed at the swirler exit (Figures 6 - 8). Diagram at the right side in the figure shows that the fluid at the low velocity region has positive sign, which is opposite to the swirler exit flow direction. Recirculation zone is formed at that region which will benefit flame anchoring and stabilization. Comparing to non-combustion case, the design point combustion simulation fluid velocity increases considerably due to fluid heating and expansion.

Combustion simulation for the three cases shows that the flame is well confined in the middle of the liner. There is cooling air flowing through liner holes forming a layer of air curtain at the inner surface of the liner preventing the flame from touching the liner. The layer of cooling air is beneficial to prevent heating of the liner.

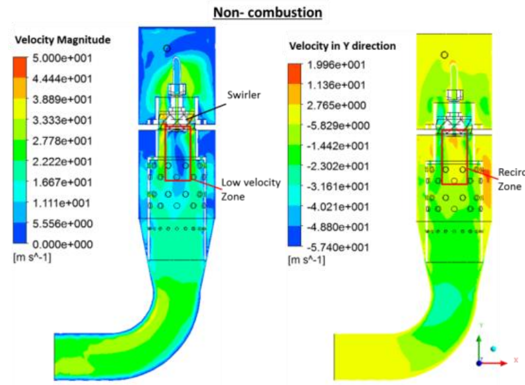


Figure 6 Non-combustion case velocity contour

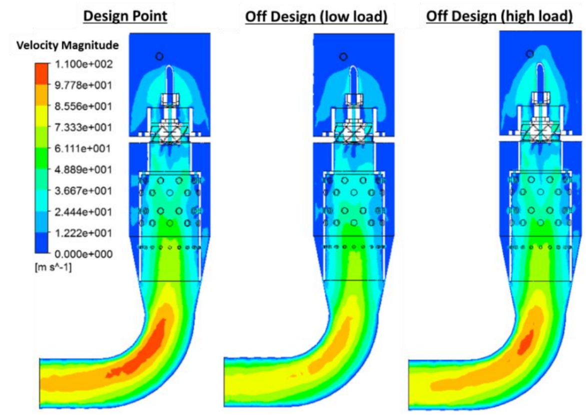


Figure 7 Combustion simulation – velocity contour

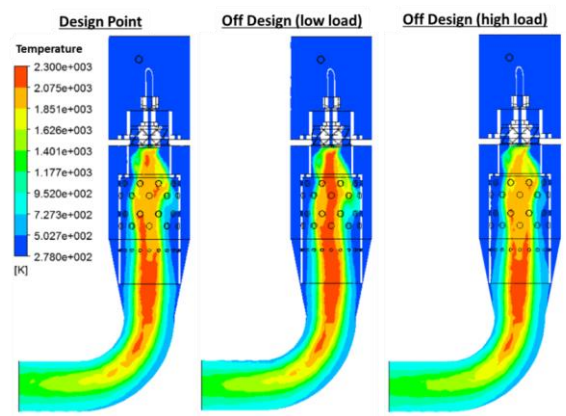


Figure 8 Combustion simulation – temperature contour

Non-combustion case simulation result shows the lowest pressure drop with $\%P_{drop}$ of 0.84%. Pressure drop of combustion cases range in between 1.37% to 1.76%. The increase $\%P_{drop}$ of combustion cases as compared to non-combustion case is mainly due to acceleration of combusted air. Nonetheless, pressure drop across the combustor for all the combustion cases are satisfying. Besides, the simulation also shows that the combustor has good combustion efficiency as shown in Table 3. Almost all the fuel is fully combusted before the exit.

Table 3 Pressure drop and combustion efficiency

Cases	$\%P_{drop}$	η_{comb}
Non- combustion	0.84%	NA
Design point	1.76%	99.9%
Off design (low load)	1.37%	99.9%
Off design (high load)	1.73%	99.9%

7.0 CONCLUSION

A single can- swirl stabilized- straight through- diffusion type combustor is designed and built for MGT test in LOCARTIC, UTM. Numerical simulation is done to study the combustor performance in four cases. The result indicates satisfying performance of the combustor with combustor efficiency of 99.9% across the cases. Pressure drop for combustion cases at off-design and design point shows good consistency (range in between 1.37% to 1.76%) and is well controlled. The next step of this project is to put the built combustor in real test to validate the simulation.

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