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THERMODYNAMIC ANALYSIS OF A MINIATURE GAS TURBINE MOTOR

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ABSTRACT

In the current day, the utilization of power is expanding because of the proliferation of compact electronic gadgets. The upgrade of a minimally expensive gas turbine motor is expected for its tirelessness in producing power. It is another age of disseminated innovation utilized for fixed power. A specific type of ignition turbine produces both intensity and power at a low level. This research focuses on the development of low-cost, mini gas turbine engines using turbochargers in small trucks and assesses the thermal efficiency of the developed micro gas turbines. In general, the test engine bench was built using a Mitsubishi Stradra std-4D56T automotive turbocharger, which consists of a compressor and a common shaft-mounted turbine assembly. The performance of the adapted mini gas turbine was experimentally analyzed with an increased compressor speed of 5,000 rpm. The turbine speed was limited to 34,000 rpm, and the system was only allowed to operate at a maximum temperature of 701 °C, thermal efficiency of the system is 18%.

KEYWORDS: Mini gas turbine motor; Combustion process; LPG fuels; Exhaust gases temperature; Fuel consumption.

INTRODUCTION

One of the advantageous apparatuses with non-sustainable parts is the miniature turbine. Overall, a microturbine is a small turbine, like a jet engine, that is capable of operating on dissimilar gases and liquefied fuels. This small turbine is connected to a generator. The arrangement of microturbines and generators in power electronics and control devices is well known as a micro turbine.[1] High-speed gas vented from the furnace drives the microturbine. The microturbine compressor and generator are installed on the same shaft of the turbine. Figure 1 shows an illustration of a microturbine schematic diagram. A microturbine is a combustion turbine technology for producing both heat and electricity on a relatively small scale. According to the process of formation, they can be divided into two types: non-convalescent and convalescent. In the non-rehabilitated microturbine, compressed air is combined with the fuel and burned under constant pressure during normal cycles. The recuperated microturbine uses a plate-metal heat exchanger. It can recover some heat from the exhaust stream and transfer it to the incoming air stream to improve the temperature of the air stream supplied to the combustion. Additional exhaust heat recovery in the cogeneration process is advantageous because, although unrestrained microturbines have approximately 15% lower efficiency, they have lower capital costs. With higher reliability and heat for cogeneration than any other technology, the efficiency of the recovered technology is in the range of 20%–30%. This research aims to construct a low-cost micro-gas turbine based on an automotive turbocharger that is capable of generating electricity or applying mechanical energy. The test was carried out in order to evaluate the performance of the micro gas turbine; therefore, from the assessment, further wide-ranging enhancement will progress.

BRAYTON CYCLE: THE IDEAL CYCLE FOR GAS-TURBINE MOTOR

In 1870, George Brayton proposed the Brayton cycle for use in the responding oil-copying motor. Today, it is utilized for gas turbines, where both the pressure and extension processes occur in turning hardware. Gas turbines typically operate on an open cycle, as displayed in Figure 1.

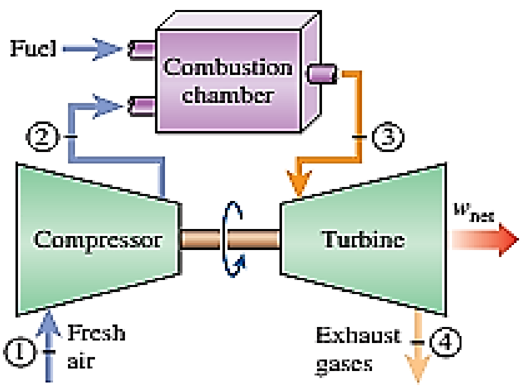

Figure 1: An open-cycle gas-turbine motor.

Air from the climate is drawn into the air compressor, where the temperature and pressure will increase. High-pressure compressed air flows into the combustion chamber, where the fuel is burned at a constant pressure. The subsequent high-temperature gas enters the turbine, which expands to atmospheric pressure while producing energy. The exhaust gases from the turbine are expelled. (non-circulating) causes the cycle to be classified as an open cycle. The recently described open gas turbine cycle can be modeled as a closed cycle, as shown in Figure 2, using the standard air assumption. Here, the compression and expansion processes remain the same. But the combustion process was replaced by a constant-pressure heating process from an external source. As well, the exhaust process is replaced by a constant-pressure heat rejection process into the ambient air. The ideal cycle that the working fluid goes through in this closed circuit is the Brayton cycle, which consists of four reverse processes:

1-2 Isentropic compression (in a compressor)

2-3 Constant-pressure heat addition

3-4 Isentropic expansion (in a turbine)

4-1 Constant-pressure heat rejection

The T-s and P-v diagrams of an ideal Brayton cycle are shown in Figure 2.

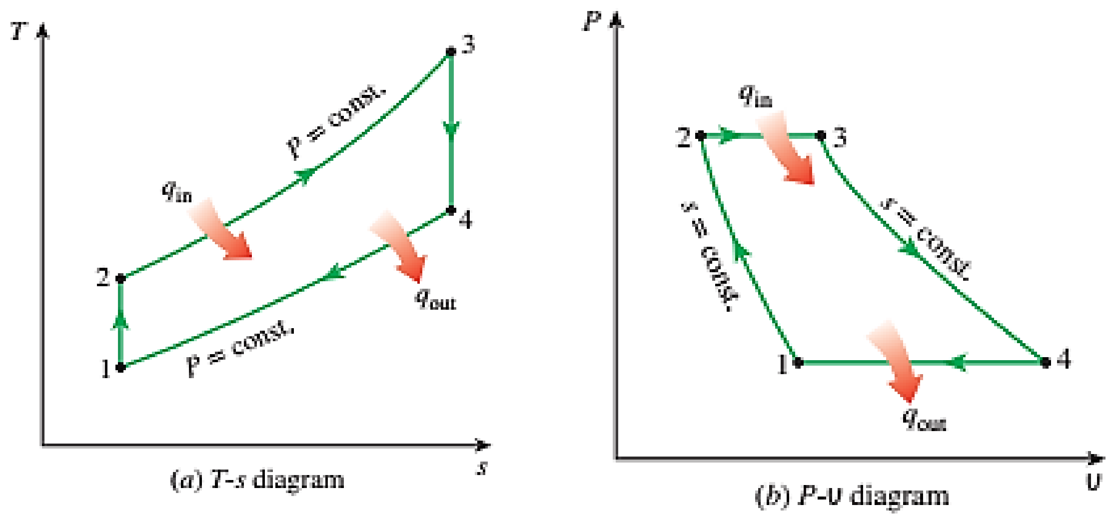

Figure 2: T-s and P-v diagrams for the ideal Brayton cycle.[2]

Notice that all four processes of the Brayton cycle are implemented in steady-flow devices; thus, they should be evaluated as steady-flow processes. When the variations in kinetic and potential energies are neglected, the energy balance for a steady-flow process can be expressed, on a unit-mass basis as

$$(q_{in}-q_{out})+(w_{in}-w_{out})=h_{exit}-h_{inlet} \quad (1)$$

Therefore, heat transfers to and from the working fluid are

$$(q_{in})=h_3-h_2=c_p(T_3-T_2) \quad (2)$$

and

$$(q_{out})=h_4-h_1=c_p(T_4-T_1) \quad (3)$$

$$\eta_{th,Brayton}=\frac{w_{net}}{q_{in}}=1-\frac{q_{out}}{q_{in}}=1-\frac{c_p(T_4-T_1)}{c_p(T_3-T_1)}=1-\frac{T_1(T_4/T_1-1)}{T_2(T_3/T_2-1)} \quad (4)$$

Process 1-2 and 3-4 are isentropic, and $P_2 = P_3$ and $P_4 = P_1$. Thus,

$$\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{(k-1)/k}=\left(\frac{P_3}{P_4}\right)^{(k-1)/k}=\frac{T_3}{T_4} \quad (5)$$

Substituting these equations into the thermal efficiency relation and simplifying give,

$$\eta_{th,Brayton}=1-\frac{1}{r_p^{(k-1)/k}} \quad (6)$$

Where $r_p=\frac{P_2}{P_1}$ (7)

P_2/P_1 is the pressure ratio, and k is the specific heat ratio. Equation 6 shows that, under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle depends on the pressure ratio of the gas turbine and the specific heat ratio of the working fluid. The thermal efficiency increases with both of these parameters, which is also the case for actual gas turbines. A plot of thermal efficiency versus the pressure ratio is given in Fig. 2 for k = 1.4, which is the specific-heat-ratio value of air at room temperature. The highest temperature in the cycle occurs at the end of the combustion process (state 3), and it is limited by the maximum temperature that the turbine blades can withstand. This also limits the pressure ratios that can be used in the cycle. For a fixed turbine inlet temperature T_3, the net work output per cycle increases with the pressure ratio, reaches a maximum, and then starts to decrease, as shown in Fig. 2. Therefore, there should be a compromise between the pressure ratio (thus the thermal efficiency) and the net work output. With less work output per cycle, a larger mass flow rate (thus a larger system) is needed to maintain the same power output, which may not be economical. In most common designs, the pressure ratio of gas turbines ranges from around 11 to 16.

Consequently, the present paper focuses on gas turbines.[3–7] The gas turbine efficiency depends primarily on the compressor pressure ratio and the uppermost temperature in the cycle, which is the combustor outlet temperature (COT). Today, most manufacturers use a

COT of 1500 ◦C. Only one of the leading producers presented the COT at a level of 1600 ◦C, and conducted research towards the use of 1700◦C.[8,9]

EXPERIMENTAL SET-UP

This experiment developed a mini-gas turbine motor adapted from an automotive turbo charger. The assembly was finally completed, and the output testing began. The performance of the mini gas turbine motor was evaluated by conducting performance tests. The air temperature throughout the experiment was measured and recorded, as well as the exhaust gas temperature. The temperatures at the four points and the room temperature were measured as well. The K-type thermocouples are attached to the combustion chamber on both the inlet and outlet sides. An ambient temperature was collected by a data logger at all six points, as shown in Figure 3. Then, for each tested point and time (temp-time of day), plot the temperature relationship. The performance and the overall thermal efficiency of the mini gas turbine were calculated by equation 6.

Specifications of miniature gas turbine motor are as follow:

Motor Length	160	mm
Diameter	75	mm
Engine Weight	4.0	kg
Maximum Speed	34,000	rpm
Exhaust gas temperature	701	°C
Fuel	LPG	

The experimental setup consists of a mini gas turbine motor adapted from an automotive turbo charger, five points of K-type thermocouple, a tachometer for engine speed measurement, and a data logger for recording temperature, as shown in Figures 3–4.

Figure 3: Mini Gas Turbine Motor experimental study.

Temperatures were recorded using a GRAPTEC GL 820 data logger, as shown in Figure 3. LPG fuel consumption measurement was carried out as shown in Figure 4.

Figure 4: LPG fuel consumption measurement.

PERFORMANCE TEST OF A MINI GAS TURBINE MOTOR

The small gas turbine demonstration unit consists of a water tank and an oil tank with 12-volt DC pumps. The pumps operate with a battery and a cooling fan by running the car's radiator while the engine is running to cool the combustion chamber and the turbocharger. The system is equipped with an electrical distribution unit to ignite the air-fuel mixture in the combustion chamber and provides aeration with a blower. Open the gas valve from the 10.4 kg LPG cylinder to allow the gas to flow through the pipe into the combustion chamber to keep the engine running. The measuring tools installation consists of four K-type thermocouples measured at room temperature. The compressed air temperatures at the combustion chamber and the exhaust pipe were recorded. Combustion chamber pressure data was collected. Weigh the gas tank on a digital scale to determine the fuel consumption rate. Start the engine, and then speed up the blower to increase the engine speed. Adjust the gas flow rate to 5, 10, 15, 18, and 20 liters per minute using a stopwatch and record the data in the table sheets. The duration of the test was about 15 minutes at a time to protect the engine from overheating, regardless of whether it is furnished with a radiator and electric fan.

RESULTS AND DISCUSSION

The graph shows the temperature at the measurement point of a mini gas turbine motor using LPG as fuel. The relations between the temperatures and time are shown in Figure 5.

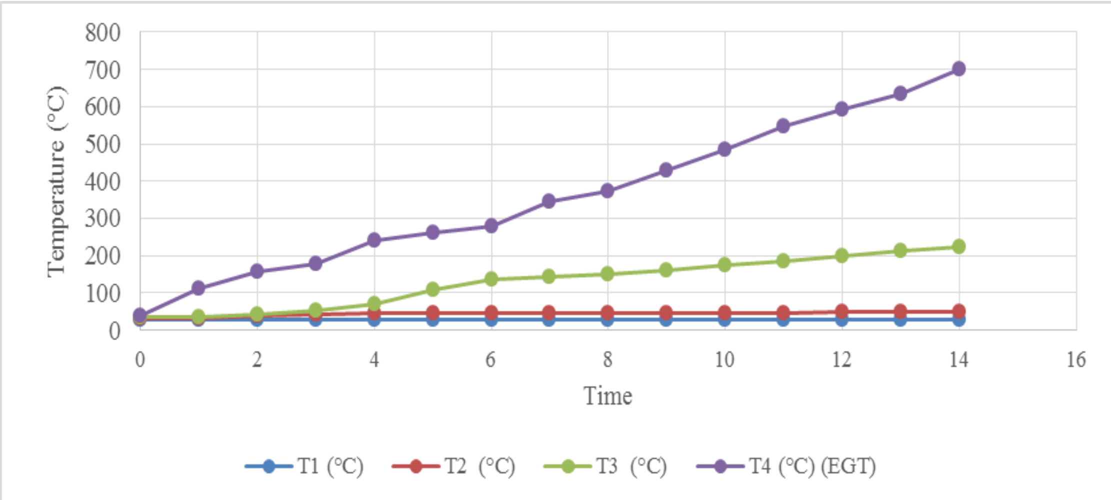

Figure 5: Temperature measurement at various times.

From the graph, it is found that, the motor start temperature is 31.4 °C and the exhaust pipe temperature is 111.8 °C with increasing air volume. The temperature of the combustion chamber rises quickly to 109.8 °C in 5 minutes and reaches a maximum of 224 °C in 14 minutes, as shown in Figure 6. The exhaust pipe temperature increases with motor speed and reaches a maximum of 701 °C. The fuel consumption was 270 grams per 14 minutes, or 19.286 g/min.

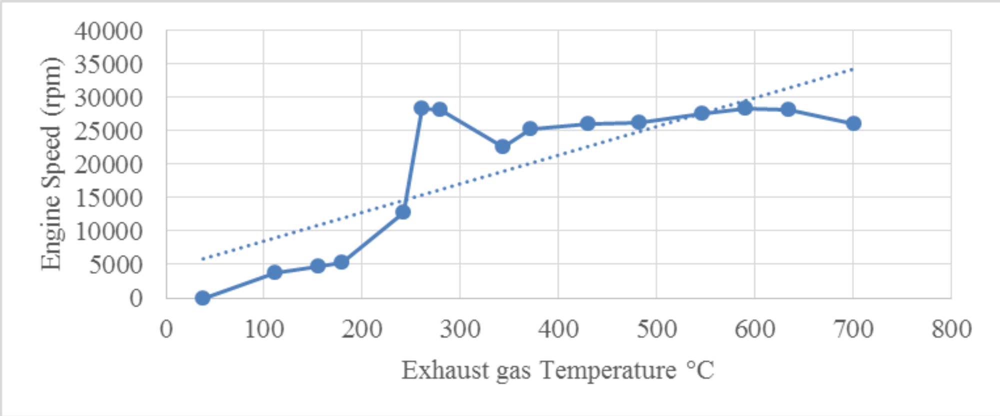

Figure 6: Motorspeed versus exhaust gas temperature data measurement.

To avoid failure of turbocharger bearings and other components, performance parameters such as inlet temperature, compressor temperature, exhaust gas temperature, and fuel and air mixture flow rate must be monitored. The data was manually assessed by computation. According to the testing results, the speed of the turbine can reach 34,000 rpm and produce 16.24 kW of mechanical power.

Miniature gas turbine efficiency calculation

The miniature gas turbine efficiency in other word Brayton turbine thermal efficiency calculation was executed by using Microsoft excel created by John R Andrew, 2010 as shown below.

GAS TURBINE IDEAL EFFICIENCY	Input		
Air enters the compressor at temperature, tA =	30	deg C	
Air enters the compressor at pressure, PA =	101.3	kPa	
Gas turbine maximum temperature, tC =	585	deg C	
Exhaust to atmos pressure ratio, r =	2	Expansion pressure ratio	
	Calculate		
Air enters the compressor at temp., TA =	tA + 273		
=	303	deg K	
Gas turbine absolute max temperature, TC =	tC + 273		
=	858	deg K	
k =	1.4		
Compressor discharge temperature, TB =	TA*(PB / PA)^(k-1)/k		
=	TA*(r)^(k-1)/k		
=	369.4	deg K	
Turbine discharge temperature, TD =	TC*(1 / r)^((k-1)/k)		
=	704.0	deg K	
Back work ratio, BWr =	Cp*(TB - TA) / (Cp*(TC - TD)		
BWr =	(TB - TA) / (TC - TD)		
=	0.430		
=	43.0%		
Brayton turbine thermal efficiency, ηth =	1 - r^(1-k)/k		
=	0.180		
=	18.0%		

Figure 7: The miniature gas turbine efficiency calculation.

CONCLUSION AND FUTURE SCOPE

In this research, the design and construction of a mini gas turbine engine demonstration unit were performed. For design and calculation, Brayton's cycle theory was the main theory used. A gas turbine is an internal combustion engine cycle that undergoes both heat gain and heat release through a constant pressure process. It is compressed and expanded in an isentropic process, which is suitable for gas turbine engines because the system of a gas turbine engine is a system that has a continuous flow of media and can be designed for continuous combustion at constant pressure. In the design of this small gas turbine engine, the Mitsubishi Stradra std-4D56T was used as the main component in the design and construction of turbocharger parts. It consists of a compressor unit and a turbine unit. Testing of small gas turbine engines designed and built in stages resulted in the conclusion that this engine is still not fully functional on its own, based on temperature measurements at various points and at the exhaust pipe, and thrust test. The mini gas turbine is able to work at idle speed, but it is possible to improve the engine's ability to maintain engine speed and produce more power. From the results obtained from the experiment, several conclusions can be drawn. The developed mini gas turbine engine has a mechanical power output of only 16.24 kW. The turbocharger's efficiency has not reached its maximum level. Because the operating speed has not reached its maximum value due to interference in the tachometer while measuring, small gas turbine engines designed and built to provide the engine can achieve a maximum speed of 34,000 rpm with an exhaust temperature of 701 °C. The thermal efficiency was 18 % with a pressure ratio of 2:1.

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