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Investigation of Different Validation Parameters of Micro Gas Turbine for Range Extender Electric Truck

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P A P E R I N F O

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A B S T R A C T

Nowadays the demand for reducing pollutant emissions and fuel consumption have paved the way of developing more fuel-efficient power generation system for transportation sector. Micro gas turbine (MGT) system can be an alternative to internal combustion reciprocating engine due to its light-weight and less fuel consumption. In this paper, some major running and operating characteristics of MGT are evaluated for the validation of the system for range extender electric truck. First noise characteristic of the system are investigated, then performance at high ambient temperature and variation of electrical output with and without the use of air filtration are investigated. The noise characteristics of MGT are different from diesel engine. At lower rpm and lower operating temperature, the electrical output of the system increases rapidly. All the found results are either compared with other systems or validated by comparing with the data provided by the manufacturer where necessary. The emission characteristics of MGT are different from other reciprocating engines. With the increase of power output the emissions of MGT reduces significantly. Finally, some noise reduction methods are recommended.

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1. INTRODUCTION

In view of solving the problem of range anxiety in electric vehicles, several companies have begun to explore the business model of recharging electric batteries in automotive vehicles with a parallel turbine engine driving as generator-coined under the term “micro turbine range extender”. MGT is a small combustion engine with output of 25 to 500 kW and approximately one-third of the size of equivalent diesel engine [1-5]. It can run on several types of fuels including hydrogen, alcohol, kerosene, recycled oil and vegetable oil. The most noteworthy speed MGT is about 50000-120000 rpm. Normally the system has an efficiency of 15-20%. However, the use of heat recovery system tends to increase the efficiency up to 46% in single cycle and 44% in combined cycle [2]. The MGT runs in the principle that the compressor and the electric generator are mounted on the same power shaft. The combustor is fitted with the fuel compressor and the gas compressor. Before feeding the combustor, the compressed air is preheated using the waste heat of the flue gas, which is done by the recuperator. The recuperator works as a heat exchanger in the system. This increases the overall efficiency of the cycle. The range extender working cycle is shown in Figure 1. Several works have been done on characteristics and parameters of MGT based range extending electric vehicles (REEV) [6-22]. An analytical and experimental study of MGT for electric vehicles in Asian cities is discussed in the literature [7].

In this paper, vehicle model is developed for analyzing the impact of driving conditions and sizing the range extender for Malaysian urban drive cycle.The driving range of the vehicle is greatly reduced when operating in that specific cycle. Karvountzis-Kontakiotis et al. [8] have built and evaluated the performances of a REEV model using MATLAB software. The calculated performance in terms of fuel consumption and pollutant emissions are compared with other conventional systems. In another research [9] a liquid fuel combustor based on the FLOX MGT burner concept for range extender is discussed for next generation cars. The CFD simulation for two phase flow is done by ANSYS 16.1

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software. The combustor characterization is performed at high pressure optical test rig. Experiment was conducted while focusing on the analysis of fuel combustion and different compressor and turbine parameters to obtain high efficiency of the device [10]. Brayton external combustion gas turbine system is evaluated in literature [11] for determining the fuel saving potential of REEV. In that paper; an exergo-technological explicit analysis is conducted to identify the best system configuration. The research showed that the downstream intercooled reheat external combustion gas turbine system shows much higher efficiency. Several industrial MGT system studies were found in literature [12-15] focused on finding appropriate and accurate compromise between maximizing the system efficiency and power density, where reducing the weight is not a major concern.

Several works have been done on performance, compressor and turbine efficiency of MGT for REEV vehicle. But still the performance due to the variation of ambient temperature and emission characteristics need to be considered and examined since literature on these topics are very rare. In this paper, noise and vibration of an 80 kW MGT for range extender electric vehicle is analyzed and compared with diesel engine having the same power. Along with this, several running and operating conditions like efficiencies at high ambient temperatures, electrical output with and without air filtration and emission characteristics were numerically analyzed. For all these investigations same sort of model was used with slight necessary modification for each model. All of the results are discussed in details and finally some recommendations are given.

2. MATERIALS AND METHOD

2. 1. Noise Characteristics Determination The powertrain of the vehicle for which different parameters are determined is shown in Figure 2. For REEV the powertrain combines a thermal power train and an electrical powertrain, as illustrated in Figure 2. An energy converter and an electric generator is associated with the thermal powertrain called auxiliary power unit (APU).

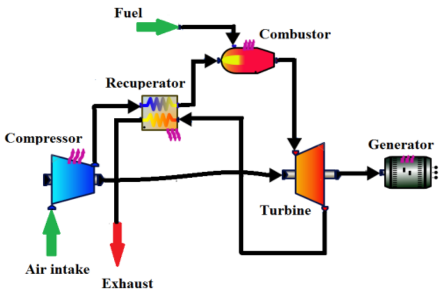

Figure 1. Range extender working cycle

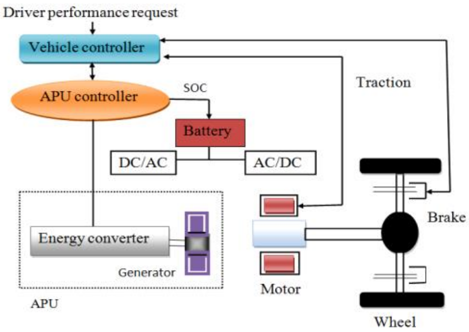

Figure 2. Power train configuration of MGT based range extender vehicle

Once the battery is depleted APU is used to recharge the battery and the necessary power to overcome the driving load is provided by the electric powertrain. The APU operating speed is kinematically decoupled from the vehicle velocity and the energy converter operating point is easily controllable to meet its best efficiency. Different parameters of the 80 kW MGT which were tested in this research are mentioned in Table 1. Different parts of the MGT produce noise. The turbulence mixing of the exhaust from the micro gas turbine engine produces a relatively higher intensity of noise as compared to the other sources of noise, the devices like compressor, fan also produce noise which cannot be ignored. Some major sources of noise from a micro gas turbine engine are shown below in Figure 3. The noise determination technique was first introduced by famous researcher Sarradj, et al. [22]. The authors used DIN EN ISO 3741 with a handheld sound level meter. Only steady, broadband and narrow-band sound can be measured by ISO 3741 method.

In this paper, to determine the sound power level in decibel (dB) a DIN EB ISO 3743-1 with a handled sound power meter including IEC 61672-1 Class-1 microphones and cables, IEC 60942 Class-1 calibrator according to ISO 11204: 2010 (en) are used and reference sound source was taken as ISO 6926 [23]. At first the microphone is attached to the noise source and the sound level meter is set up. The function of microphone is to count the air disturbance resulting from the noise source and to send the data to the digital display. The sound level meter shows the level in decibel (dB) by filtering the signal and then amplifying. Following Equation 1 expresses the sound power level:

$$SL = 10\, log_{10}(P/P_0)\; dB \qquad (1)$$

where, SL = Sound power level; P = I.A (Intensity (I) in watt/meter square and Area (A) in meter square); P_0= Absolute power level (taken as 10-12 watt). To determine the frequency of the noise source a digital 12.4 GHz digital frequency meter is attached to the source of noise (HP- Model 5240 A, range 10 Hz to 12.5 MHz).

TABLE 1. Data sheet of the MGT

Compressor type	**Centrifugal**
Turbine type	Radial, single stage
Number of combustion chamber	1 chamber
Number of shaft	1 Shaft
Rotational speed	50000-120000 rpm
Turbine inlet temperature	950 ˚C approximately
Frequency output	420/230 V (AC)
Voltage output	400 V (AC)
Required fuel pressure*	.02-0.5 bar
Required fuel temperature	0-60 ˚C
Consumption**	32 Nm^3/h
Electrical output	(80 ± 4) kWe
Electrical efficiency	(32 ± 2) %
Exhaust gas flow	.75 kg/s
Exhaust gas temperature	260-280 ˚C
NOx	<15 ppm(v)= 31 mg/Nm^3 (at 15% O_2)
CO	<15 ppm(v)= 19 mg/Nm^3 (at 15% O_2)

* natural gas compressor device (booster) installed inside the micro turbine cabinet
** depending on natural gas LHV

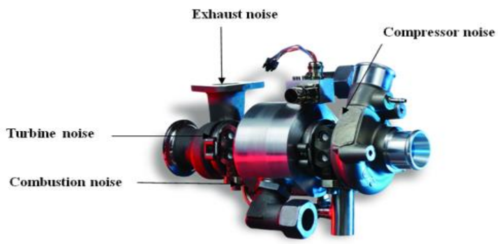

Figure 3. Sources of noise of MGT

The noise meter works in such a way that the noise frequency is conditioned and then divided into small data bits using a temperature compensated crystal oscillator having a pre-scalar set up. Using the main gate flip-flop, the signal is transferred to the main gate where it meets the original signal. Then the frequency is counted by a counting register and displayed in a digital display. Figure 4 shows the block diagram of the whole procedure. The Following expression 2 shows the mathematical representation of frequency in Hertz (Hz).

$$f = 1/T\ Hz \quad (2)$$

where, T is the time period to complete an event.

The measurement procedure is "Engineering method (Grade-2)" procedure, which gives very accurate results. In this type of measurement the source type and acoustic environment type is taken into account. The uncertainties of the group 3740 is calculated in accordance with the ISO/IEC grade 98-3. In case of ISO 3743-1, it is not necessary to account for Standard deviation of the uncertainty due to instability of the operating and mounting conditions. The uncertainty of the ISO 3743-1 is 3.2 dB.

2. 2. Performance at High Ambient Temperature

The performance of the vehicle is affected by the ambient temperature as micro gas turbine is greatly affected by the ambient temperature. Both the efficiency and output power of the system decreases as the ambient temperature increases. As the ambient temperature increases the density of the air decreases which causes a reduction in inlet air and fuel mass flow rate. In this section, a 80 kW micro gas turbine is investigated and the MGT is fueled with natural gas. First, the MGT was run at a constant output power by setting a specific ambient temperature, and then the net electrical output power was checked by varying the ambient temperature from 22 ˚C.

2. 3. Electrical Output with Air-Filter

The performance with air-filter was first experimented by RMRA Shah et al. [20]. In this investigation, the MGT is used capable of producing 80 kW at 100000 rpm. The mass flow rate was 620 g/s. Since at higher rpm the noise and vibration of MGT is small, that is why no vibration reducer was necessary. The power electronics are modeled in such a way that they give accurate results. Two filters are used one is primary and other is secondary. The test is done at normal atmospheric pressure and temperature. The electrical output is first measured with filter and then without filter. Filters specifications according to European Normalization standards are shown in Table 2.

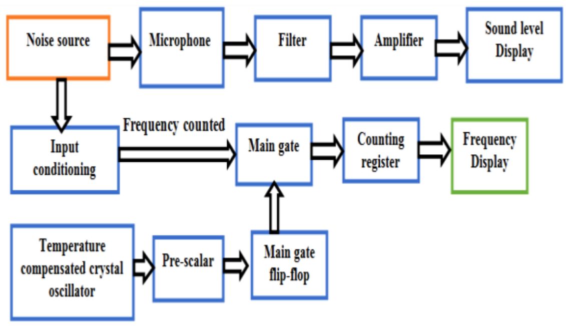

Figure 4. Block diagram of noise measurement procedure

TABLE 2. Specifications of filters

Usage	**Class**	**Performance (%)**	**Particulate size**	**Test standard**
Primary	G4	90	>5 µm	BS EN779
Secondary	F9	95	>1 µm	BS EN779

3. RESULTS AND DISCUSSION

3. 1. Noise Characteristics Figure 5 shows the comparison between 50 kW MGT and diesel engine at partial load and Figure 6 shows 80 kW at full load. From both the graph, it is seen that at low frequency the noise level of MGT is very low compared to diesel engine of the same power. However, as the frequency increases the noise level rapidly increases. Up to 1 kHz, the noise level of MGT is very low compared to diesel engine. Nevertheless, above one kHz (medium to high frequency) frequency, the noise level increases. The very high tonal sound at the range of 9 kHz is due to the generator cooling which come out at the time of exhaust. Therefore, in terms of REEV, when noise is considered for medium to high frequency, use of diesel engine is more advantageous than micro gas turbine.

3. 2. Performance at Different Ambient Temperature, With Air-Filter and Emission Characteristics Figure 7 shows the output power of the MGT at constant 32 ˚C. The output power is much affected by the ambient temperature but the electrical efficiency is not greatly affected. From Figure 8, it is seen that, for a temperature of 23 ˚C the electrical output is 73 kW but as the temperature increases the electrical output significantly drops.

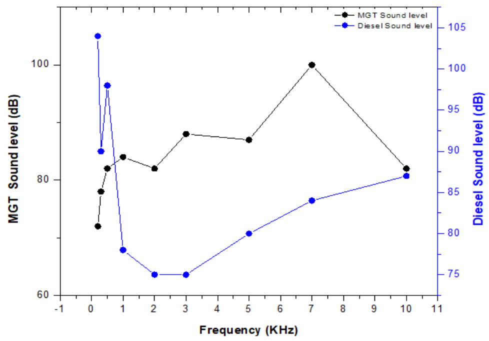

Figure 5. Comparison of measured sound power of 50 kW - MGT and Diesel engine

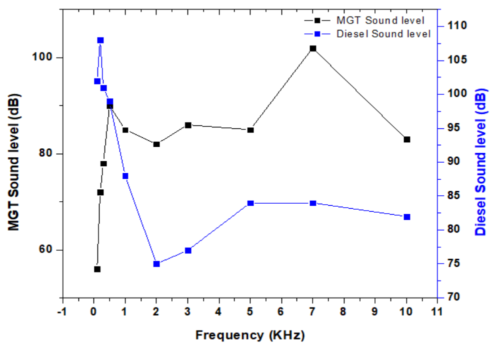

Figure 6. Comparison of measured sound power of 80 kW - MGT and Diesel engine

For an ambient temperature of 30 ˚C the net electric power output reduces to 69 kW. This is because a colder air charge going into the MGT is denser and contains more oxygen than its warmer counterpart contains. From the investigation the most suitable temperature for MGT is obtained 22 ˚C.

Form Figure 9, it is seen that at lower rpm the effect of using filter is not noticeable because the output is quite same as without filter. However, as the rpm increases, the effect of filter is visible. At higher speed, the electrical output increases almost 2 kW than the normal output. As the electrical output is increased, the fuel consumption is significantly reduced. During the investigation, the pressure drop was relatively small and no compressor surge was detected.

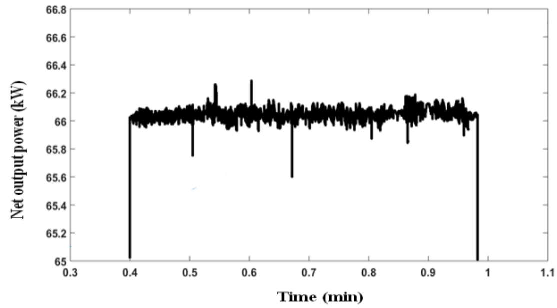

Figure 7. Net output power at 32 ˚C

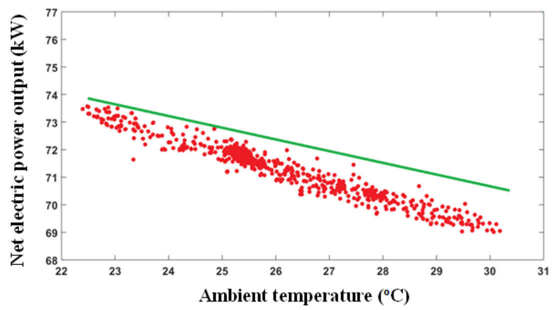

Figure 8. Net electric power output as a function of ambient temperature (red-investigated; green-manufacturer)

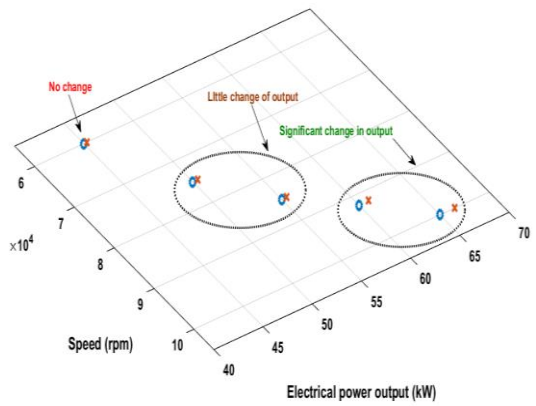

Figure 9. Electrical output of the MGT (x-with filter and O-without filter)

CO and NOx emissions at different power output for the micro gas turbine is shown in Figure 10. The combustion occurs in three different steps. The first step is start-up to 5 kW, then second step is from 5 kW to 20 kW and the third is the rest. In the first two steps CO formation decreases and NOx formation increases and in last step lean-premix condition occurs and NOx formation tends to decrease. Both the emissions of CO and NOx experienced a downward trend while power output crosses the value of 20 kW.

4. NOISE REDUCTION METHODS

4. 1. Active Noise Control System The schematic representation of the exhaust noise control system is shown in Figure 11. The primary noise source is the unwanted source of noise (exhaust gas noise) whose frequency is detected by a detector. To send 180-degree phase and same amplitude sound wave the primary noise data is sent to the controller. Controller then analyzes the signal and commands the secondary source to supply required sound wave to produce cancellation at the point of observer. The feedback control structure is described below and the block diagram is shown in Figure 12. Where, $L_1(s)$ = Transfer function of distance L_1; $L_2(s)$ = Transfer function of distance L_2; $L_3(s)$ = Transfer function of distance L_3; $L_4(s)$ = Transfer function of distance L_4; S(s) = Transfer function of secondary source; D(s) = Transfer function of detector; C(s) =Transfer function of controller; E(s) = Transfer function of exhaust noise source i.e., the primary source. The primary signal and the secondary signal are equal in magnitude and opposite in phase i.e. 180 degree apart in phase.

Now from the control structure, we have:

$$E_o(s) = -S_o(s) \quad (3)$$

$$E_o(s) = L_3(s)\, E(s) \quad (4)$$

$$S_o(s) = L_4(s) = \frac{D(s)C(s)S\,(s)L_1(s)}{1-D(s)C(s)S\,(s)L_2(s)} \quad (5)$$

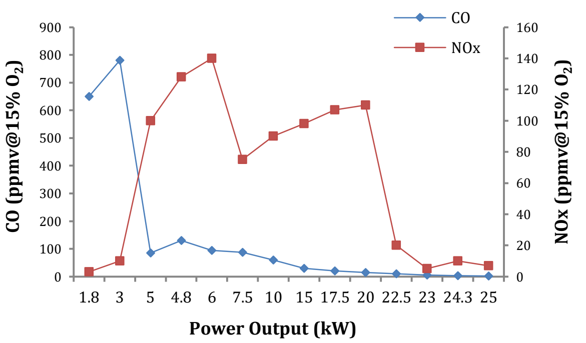

Figure 10. CO and NOx Emissions of the MGT

Using this Equations (4) and (5) from Equation (3),

$$L_3(s)\, E(s) = -L_4(s)\frac{D(s)C(s)S\,(s)L_1(s)}{1-D(s)C(s)S\,(s)L_3(s)} \quad (6)$$

$L_3(s)$ E(s) − $L_3(s)$ E(s) D(s) C(s) S(s) $L_2(s)$ = − $L_4(s)$ D(s) C(s) S(s) $L_1(s)$; $L_3(s)$ E(s) = $L_3(s)$ E(s) D(s) C(s) S(s) $L_2(s)$ − $L_4(s)$ D(s) C(s) S(s) $L_1(s)$ (7)

$$C(s) = \frac{L_3(s)[L_3(s)L_2(s)-L_1(s)L_4(s)]}{D(s)S(s)} \quad (8)$$

Equation (6) represents the final controller transfer function to have cancellation at the observer point. The feasibility of this type of control system has been confirmed by [24], where they have done their experiment using motorcycle exhaust. To control the other types of noises coming out from a gas turbine engine like compressor fan noise, broadband noise or tonal noise acoustic methods may be used.

4. 2. Acoustic Control System Acoustic liners can be used at the inlet of the fan duct to reduce the tonal noise. Tonal noise (single frequency noise) is one type of fan noise which forms due to pressure fluctuation (distortion). If the fan nozzle area increases then the noise significantly reduces. Chevron nozzles are the nozzles having seen toothed patterns at the backside of the engine which reduces the exhaust noise by mixing the core and bypass air flow. This method has been used successfully in aviation gas turbine engines and can be used for medium heavy vehicle engines.

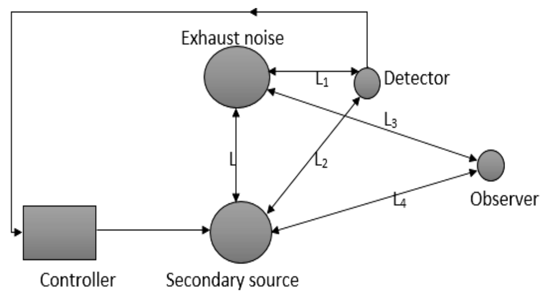

Figure 11. Schematic representation of exhaust noise control structure

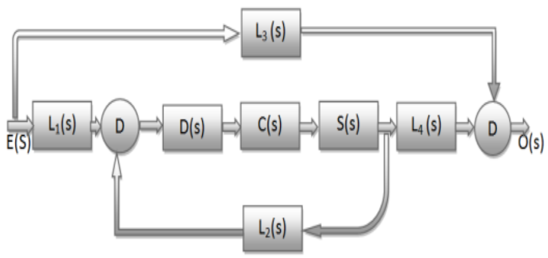

Figure 12. Feedbacks exhaust noise control structure

5. CONCLUSIONS

In this paper, overall four running and operating conditions of MGT for range extender electric truck are investigated. These results are very important for validating the MGT system for range extender electric vehicle. Some of the results were compared with the data provided by the manufacturer where necessary. The production of noise of MGT system is less at lower rpm compared to same size of diesel engine. A high pitch thudding noise is observed at every cycle which is caused by the generator exhaust. From test two, it is found that with the increase of ambient temperature the electrical output of MGT reduces. The best effective temperature was found 20 to 22 ˚C for getting maximum output. Use of air filter is very effective when it is necessary to run the vehicle at higher speeds. With the increase of power output the emissions of MGT are greatly reduced. When the power output exceeds 30 kW the formation of CO tremendously reduces. In fine, it is interesting to mention some future developments of the discussed methods and the research work:

1. The emissions due to the use of air filter should be reduced, but it is not determined in this paper, which should be a future consideration.
2. The performance at temperature below 20 ˚C need to be taken under consideration in future.
3. The MGT performances need to be checked using the recommended noise control method.

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Air Filtration

چکیده

امروزه تقاضا برای کاهش انتشار آلاینده‌ها و مصرف سوخت، راه را برای توسعه سیستم‌های تولید انرژی بالاتر برای بخش حمل و نقل به ارمغان آورده است. سیستم توربین گاز میکرو (MGT) می‌تواند جایگزین موتور مجزا احتراق داخلی با توجه به وزن سبک و کم مصرف سوخت آن باشد. در این مقاله، برخی از ویژگی‌های اصلی در حال اجرا و عملیاتی MGT برای اعتبارسنجی سیستم برای کامیون الکتریکی محدوده وسیله‌ای اندازه‌گیری می‌شود. اولین نویز ویژگی سیستم مورد بررسی قرار گرفته و سپس عملکرد در محیط دمای بالا و تغییر خروجی برق با استفاده از و بدون استفاده از تصفیه هوا مورد بررسی قرار می‌گیرد. ویژگی‌های نویز MGT متفاوت از موتور دیزل است. در رمپ کمتر و درجه حرارت پایین‌تر، خروجی الکتریکی سیستم به سرعت افزایش می‌یابد. تمام نتایج یافته شده در مقایسه با سایر سیستم‌ها یا با مقایسه با داده‌های ارائه شده توسط سازنده در صورت لزوم معتبر هستند. ویژگی‌های انتشار MGT متفاوت از سایر موتورهای مجاور است. با افزایش تولید برق، انتشار گاز MGT به طور قابل توجهی کاهش می‌یابد. در نهایت، برخی از روش‌های کاهش نویز توصیه می‌شود.

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