Micro Gas Turbine Range Extender - Validation Techniques for Automotive Applications

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Abstract

A Micro Gas Turbine (MGT) can be considered as an alternative to the internal combustion engine as a range extender for electric vehicles. The MGT produces less raw exhaust gaseous emissions such as HC and CO in aerospace and static applications compared to the internal combustion engine. In addition, the MGT weight is less than an equivalent internal combustion engine and potentially can reduce the level of CO_2 further in a vehicle application. However, the use of the MGT in an automotive domain has some unique technical and commercial requirements that will require new validation approaches. An air filtration system is known to be one of the important elements to characterise the performance and the emissions of the MGT. In the past, most of the efforts on MGT were focused on the vehicle development and packaging studies, where the technical requirements of the test standards for the air filtration system were not considered. Furthermore, the validation techniques of the air filtration system for automotive applications have different requirements to those of a large scale turbine for aerospace use. A test method has been developed to investigate the effect of the automotive air filtration system on the MGT's characteristics in terms of the electrical power output and potentially the gaseous emissions. The outcomes of the research have provided good understanding of the MGT validation process in the automotive applications. It addresses the potential challenges that may hamper the MGT range extender for hybrid electric vehicle development processes.

1 Introduction

The MGT has the potential source to be an alternative power plant for the range extender in Hybrid Electric Vehicle (HEV) application. The clean combustion of the MGT theoretically contributes to the low vehicle emissions when operating in range extender mode compared to the internal combustion engine due to the continuous and complete combustion process of the air-fuel mixture [1-3]. However, the low gaseous emission such as NOx, CO and HC may deteriorate if the quality of the air mass flow is reduced such as in hot climate and high altitude areas [4-6]. In addition, the untreated air leaves deposits on the compressor and changes the aerodynamics profile of the air mass flow; and subsequently degrades the performance of the MGT over time [7, 8]. The fouled compressor can change the natural frequency of the rotating components and reduces its reliability and other rotating components [9].

The operating speed of the MGT is typically in the range of 100,000 revolutions per minute (rpm) and operates with a high temperature combustion process. The use of conventional bearings and magnetic bearings are not suitable for these types of design parameters. The implementation of air bearing offers a good solution to the most of the technical requirements of the MGT [10-12]. The air supplied to the air bearing must be free from any debris or particles that may damage or seize the rotating shaft. The schematic diagram of the MGT is shown in Figure 1.

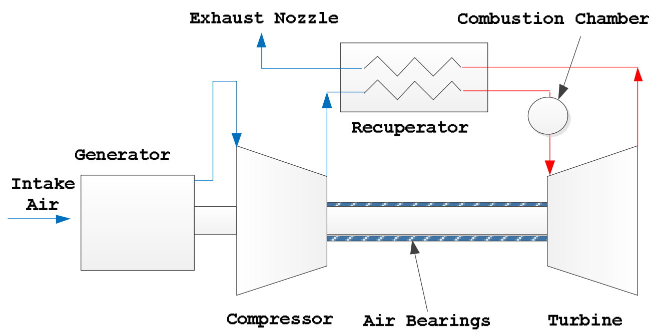

Figure 1: Schematic diagram of MGT with power generation (generator)

Most of the MGT designs come with a recuperator system to increase the thermal efficiency. The heat from the exhaust gas is transferred to the compressed air through the heat exchanger passages. The design of the heat exchanger comprises of multiple small passages to improve the heat transfer rate. One of the design criteria of the recuperator is to minimise the pressure drop across these passages, where a large pressure drop can cause a reduction in thermal efficiency and subsequently reduces the MGT performance [13].

The requirement for a clean air supply for the MGT can be achieved with the introduction of an air filtration system. However, in an automotive application, this would be constraint by costs and different specifications. The air filtration system for MGT applications is typically tested against various aerospace test standard such as BS EN 1822-2:2009 and ASHRAE Standard 52.2-2007 [14, 15]. For automotive applications, the air filtration system is tested against ISO 5011 test protocol [16]. As a result, the air filter can cause several potential issues that affect the performance and the reliability of the MGT. For example, a pressure drop across the air filtration system can potentially create a compressor surge and damage the MGT [17]. The air density can also be reduced quite significantly and consequently reduces the performance of the MGT [18-21].

In this paper, we present a study to analyse the effects of an automotive air filtration system fitted on the MGT in terms of the pressure drop and the overall performance. The other parameters such as the air fuel ratio (AFR) and turbine exit temperature (TET) will be monitored in order to understand the effect of the design change. An automotive exhaust system will not be coupled with the MGT to simplify the test procedures and the gaseous emission will not be monitored in this paper. This is also to allow the isolation of the effects of air filtration.

2 Vehicle Energy Requirements

In order to associate the MGT's performance requirement with the air filtration system, a vehicle has been simulated based on New European Drive Cycle (NEDC) using a mathematical model built in Microsoft Excel. The vehicle parameters are shown in Table 1. A combination of energy from the batteries and the MGT is used to compensate the energy required to drive the vehicle on NEDC as shown in Figure 2. The 28 kW MGT is sufficient to sustain the battery's charging characteristics at urban cycle. In the extra urban cycle, it can be seen that the batteries charging rate is reduced due to the higher energy demand by the vehicle and the vehicle resistance at high speed. Subsequently, when the vehicle is coasting down (under vehicle braking), the batteries charging rate is observed to be the same as in urban cycle due to the low vehicle energy demand and the excess power supplied from the regenerative braking of the hybrid component.

The vehicle has also been simulated at different operating points to identify the minimal power requirement for the battery's charging characteristics. It can be noticed that the vehicle can only allow for a maximum of 15 kW power reductions in order to sustain the battery's charging characteristics.

Vehicle Mass	2000 kg
Drag co-efficient	0.3
Frontal Area	3 m^2
Air density	1.2 kg/m^2
Tyre rolling resistance	0.01
Vehicle maximum power	100 kW
Vehicle energy requirement	10 kWh
MGT power	28 kW
Regenerative fraction captured	70%
Regenerative power limit	50kW

Table 1: Vehicle Data for simulation in NEDC

In summary, the simulation result can be used to determine the performance requirement for the automotive air filtration system i.e. no performance drop of the MGT is allowed at different operating conditions.

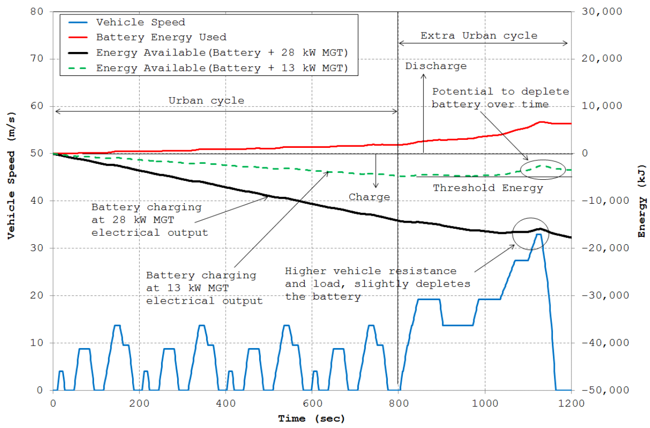

Figure 2: Vehicle energy requirements in NEDC with the energies supplied by the batteries and the 28kW MGT at minimum state-of-charge

3 MGT Test Set-up

The MGT used in the experiment is capable of producing 28 kW electrical power at a maximum speed of 96,000 rpm and 25% net efficiency measured at 18 °C and 1.013 bar atmospheric pressure based on Diesel fuel (ASTM D975-07b Grade Low Sulfur No. 1-D, 2-D). The mass flow rate designed for the MGT is 310 g/sec. The MGT is supplied in one whole unit with the power electronics and control harnesses as shown in Figure 3. The MGT is mounted on a steel plate and attached to the steel frame. No bushes are required as the vibration of the MGT is small. The power electronics are mounted to the steel frame using steel brackets and located below the gas turbine. The controller for the MGT is based on a black box unit and cannot be accessed in order for any strategy change requirements in the input/output parameters.

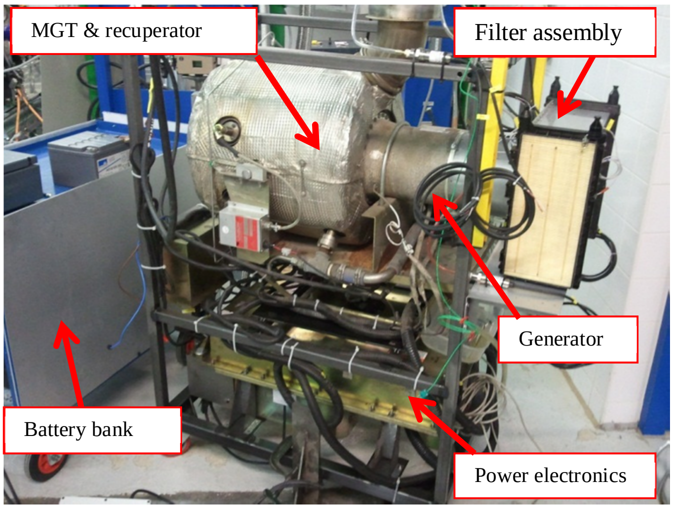

Figure 3: Automotive air filtration system test rig for 28 kW MGT

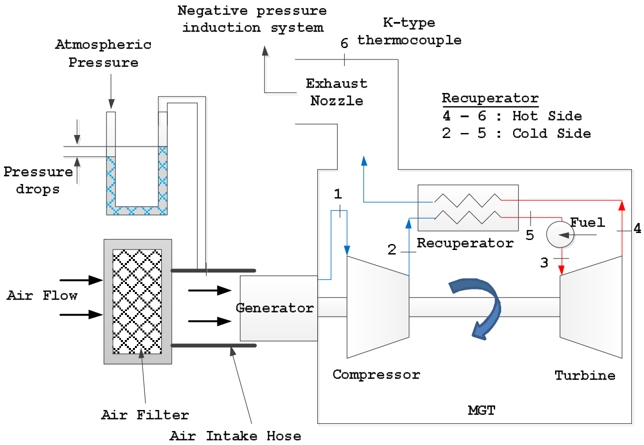

Figure 4: Test Rig Instrumentation for the 28 kW MGT fitted with two automotive air filtration systems

Given the whole unit design, the packaging of the power electronics is potentially not an ideal location as the heat generated by the MGT can be transferred to the inverter and cause the controller to limit the electrical power output if the inverter heat sink temperature exceeds 85 °C. Therefore, the concern will be closely monitored during the test. The inverter is connected to a 250 kW battery cycler via 14 V 45 Ah batteries to smooth the voltage output in order to provide a constant source of energy.

Filter Media	0 MHN 690
Dust holding capacity at air flow rate of 236 g/s	248 g
Fractional efficiency at 4 µm particle size at 0.11 m/s	90%

Table 2: Air filter specifications for automotive applications based on ISO 5011

Two air filters are mounted to the MGT induction system (generator). The design of the air filter is based on side flow entry with a plenum size of 0.01428 m^2. The specifications of the air filter are shown in Table 2. The intake runner length is 100 mm and the diameter is 120 mm, which is the same as the generator outer diameter. The air filter element is designed for 190 g/sec. A calibrated Diesel fuel (Carcal RF-06-08 B5) is used and supplied through a fuel meter at 0.02 bar (gravity feed equivalent). K-type thermocouples are used to measure the temperature of the exhaust nozzle (point 6) as shown in Figure 4. A water gauge is used to measure the pressure different before and after the air filtration system. A weather station is used to measure the ambient condition of the room, i.e. pressure, temperature and relative humidity. For point 1 to point 5, all parameters are measured using the control interface of the MGT,

The MGT test rig was set up inside the state-of- the-art University of Warwick's powertrain research facilities with a room size of 192.5 m^3 and protected by fire safety and CO monitoring systems. The room size is important to ensure that the MGT has a sufficient supply of air into the intake system and to control the room temperature. The test rig was mounted on an under floor bed-plate to prevent excessive vibration during the tests.

4 Experimental Results

A step input to the MGT control system is used to demand the power from the MGT. When the turbine reaches its idle speed (45,000 rpm), the power demand is held at 0 kW until the air fuel ratio (AFR) is stabilised at approximately 180:1 (see Figure 5). This is mainly due to the characteristics of the MGT during the cold-start regime. The power demand is then increased by 5 kW intervals until it reaches the maximum power at 28 kW.

A total of six experiments have been conducted using the same test parameters set-up. Three tests were with the air filter (*"with filter"*) and the other three were without the air filter (*"no filter"*). The ambient temperatures of the room have been varied between 21°C and 27°C in order to observe the effect of the ambient temperature to the performance of the MGT in relation to the air filtration system. This is also to mimic the temperature rise in the engine compartment of a vehicle, which can vary up to a maximum of 100°C depending on the operating state (from idle to uphill driving) [22].

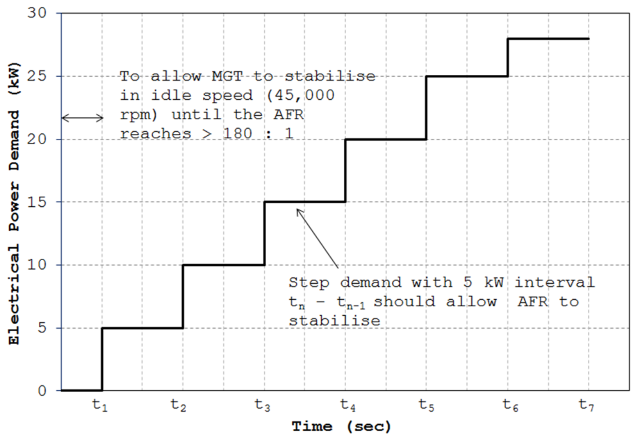

Figure 5: Step input power demand with 5 kW intervals

4.1 Electrical power demand vs. power output

Figure 6 shows the test results with the automotive air filtration system at 22°C ambient temperature. It can be observed that the AFR fluctuates significantly during cold-start and gradually starts to stabilise when the MGT operates within its optimal efficient parameters such as pressure ratio, recuperator temperature, etc. [23]. The MGT is seen to deliver the same electrical power outputs as the electrical power demand between 0 kW and 20 kW. However, the MGT can only hold the demand at 25 kW for couple of seconds before gradually reducing to 23 kW electrical power output. At 28 kW electrical power demand, the electrical power output is seen to maintain at 23 kW electrical power output. Both electrical power outputs are running at maximum turbine speed at 96,000 rpm and the AFR at 118:1. The compressor inlet temperature is noticed to rise together with the inverter heat sink temperature, which can potentially be the source of the electrical power output reduction.

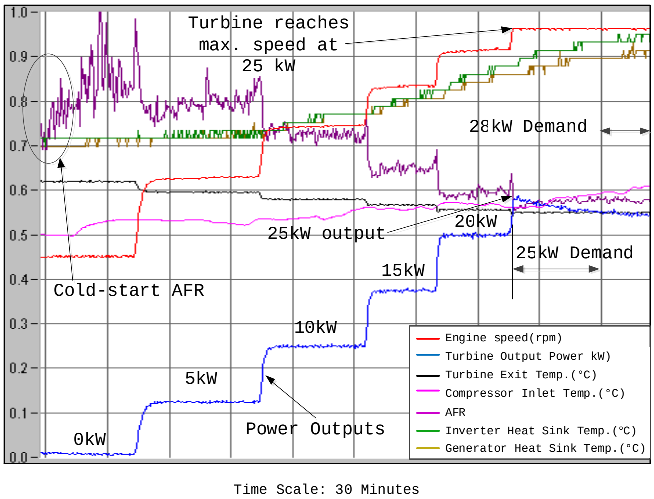

Figure 6: MGT's test result with 5 kW interval step input demand at 22°C ambient temperature (with filter test 3)

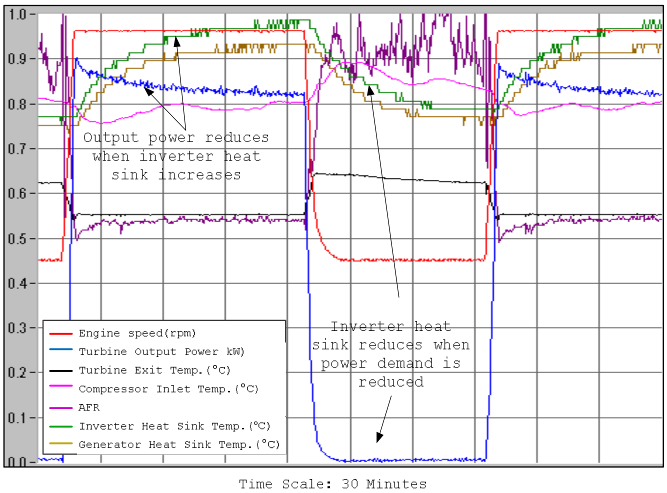

Figure 7: MGT test result with 100% step input demand at 22°C ambient temperature (with filter)

Another set of tests has been carried to investigate the effect of the inverter heat sink temperature on the electrical power output and to segregate the influential factors of the air filtration system as shown in Figure 7. Two step inputs have been used to excite the electrical power output from 0% demand to 100% demand. It can be noticed that the electrical power outputs are reduced in relation with the increase of the inverter heat sink temperature.

4.2 MGT characteristics (air filter vs. no air filter)

Small deviations of the electrical power output have been seen between the "*with filter*" tests and "*no filter*" tests as shown in Figure 8 predominantly at the maximum electrical power demand. Since the ambient temperature exceeds the ISO 2314 test standard at 18°C [24], the maximum electrical power outputs are plotted against the manufacturer data in order to correlate the electrical power outputs with the ambient temperature. It can be noticed that the results are deviated between 3% - 9% (see Figure 9). This is mainly due to the influence of the inverter heat sink temperature to the MGT power control strategy.

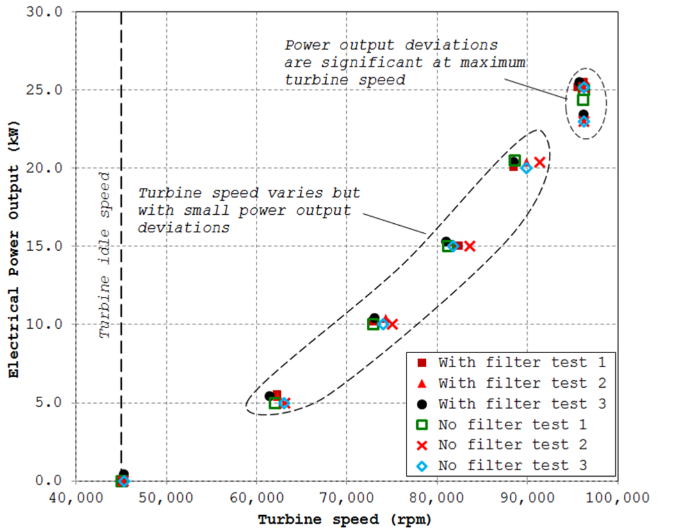

Figure 8: MGT electrical power output vs. turbine speed at 5kW electrical power demand intervals, ambient temperature between 21°C - 27°C (with filter vs. no filter systems)

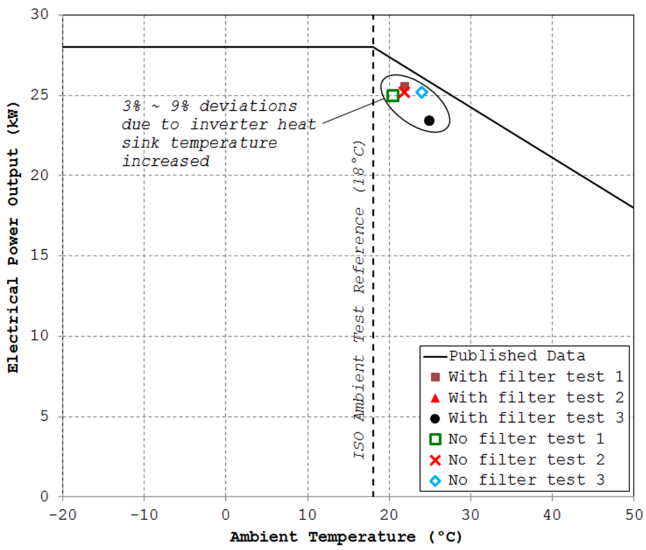

Figure 9: Correlation with manufacture electrical power output vs. ambient temperature at 5kW electrical power demand intervals (with filter vs. no filter systems)

However, the results in Figure 9 show that the electrical power output of the "*with filter*" system is better than the "*no filter*" system. This could be due to the improvement of the air intake quality and the air density. In addition, the electrical power outputs of the "*with filter*" system are closer to the manufacturer performance curve at different ambient temperature with small deviations compared to the "*no filter*" system, with minimum electrical power output of 23 kW at

24°C ambient temperature. In term of the energy balance requirement, all of the electrical power outputs for both test parameters are still within the threshold as shown in Figure 2.

In terms of the air pressure drop across the air filtration system (see Figure 10), it is noticed to commensurate with the engine speed. The air filtration system increases the pressure by 500 Pa at the maximum electrical power output or 5% of the atmospheric pressure. However, the maximum pressure drop is still within the acceptable limit of the system and will not cause any pressure surge on the compressor.

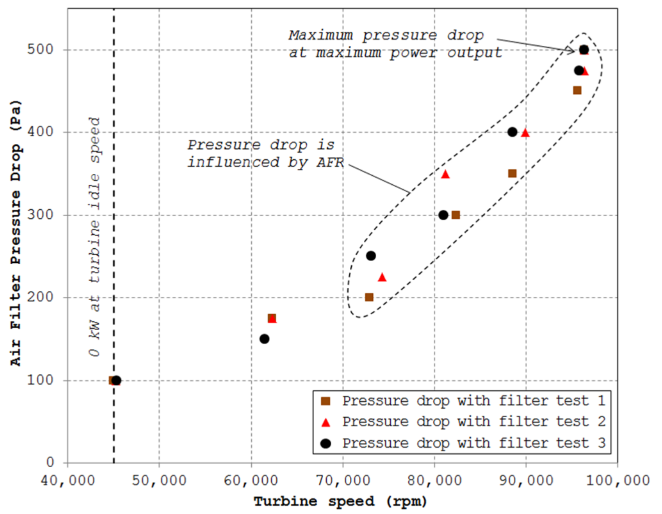

Figure 10: Air filter pressure drop vs. turbine speed at 5kW electrical power demand intervals, ambient temperature between 21°C - 27°C (with filter vs. no filter systems)

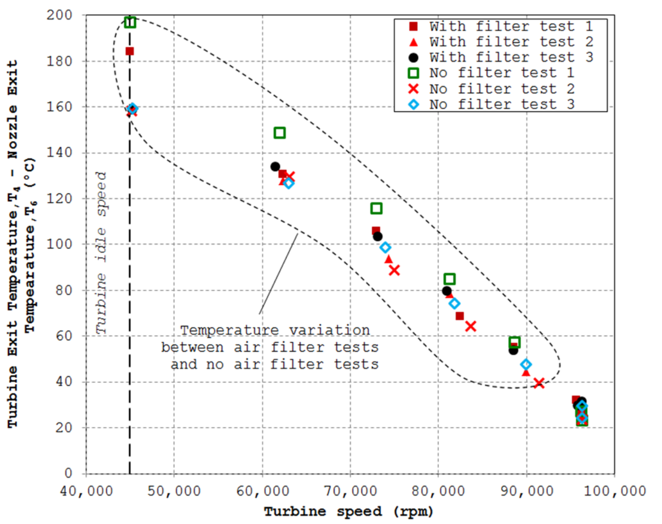

Figure 11: Recuperator heat transfer vs. turbine speed at 5kW electrical power demand intervals, ambient temperature between 21°C - 27°C (with filter vs. no filter)

Figure 11 shows the heat transfer of the exhaust gas into the recuperator system, which is also shown in Figure 4. At idle speed, the maximum heat transfer of the *"with filter"* system is 182 kJ/kg, which is 8% less efficient than the *"no filter"* system at 198 kJ/kg. These values are then reduced gradually as the air mass flow rate is increased and push the hot air inside the recuperator at higher velocity. At the maximum electrical power output, both of the systems generate the same amount of heat transfer into the recuperator system.

It can be seen that the pressure drop and the recuperator heat transfer is controlled by the AFR as shown in

Figure 12. For the speed below than 85,000 rpm, the *"no filter"* system has a higher fuel rate and lower electrical power output. This can potentially increases the HC and CO emissions. On the other hand, the *"with filter"* system improves the MGT efficiency at this operating range where it produces a higher electrical power output with a lower fuel rate.

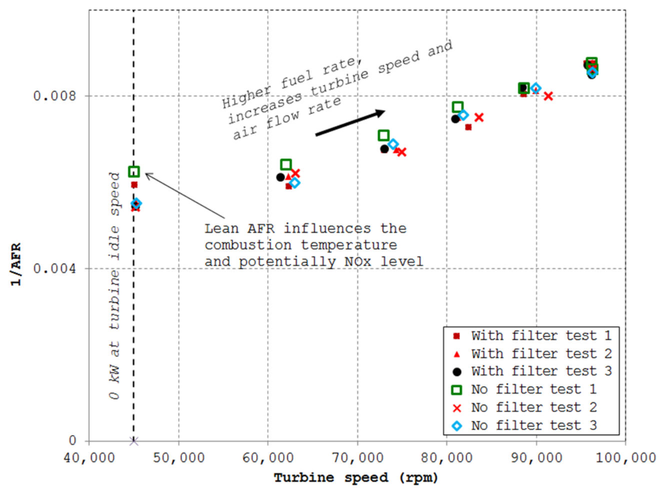

Figure 12: AFR vs. turbine speed at 5kW electrical power demand intervals, ambient temperature between 21°C - 27°C (with filter vs. no filter systems)

5 Conclusions

The experimental results have shown that the used of the automotive air filtration system is feasible in the MGT application without a loss of performance. The method to investigate the air intake system of the MGT has successfully defined the characteristics of the automotive air filtration system. The pressure drops are relatively small and caused no compressor surge. Furthermore, the air filtration system improved the electrical power output efficiency and potentially could reduce the HC and CO emissions. The other possibility for the performance improvement at maximum electrical power output is the efficiency of the air bearing, where it reduced the frictional loss due to the cleaner air quality.

The reduction in the MGT performance was observed to be dominated by the inverter heat sink temperature and the ambient temperature, which is inter-related. For instance, a combination of the high temperature in the engine compartment can reduce the electrical power output quite significantly. However, the concern associated with the inverter heat sink temperature could be resolved with the packaging optimisation of the power electronics within the vehicle system.

Future Work

A series of tests are planned to investigate the characteristics of the MGT as a range extender at different operating points. Some of the test procedures will cover the emissions and performance of the MGT at cold and hot starts; and at transient power demand. The results can then be used for the control strategy development in the vehicle energy requirements. The same test procedures will also be repeated to see the effect of the performance with different blocked air filtration systems until it reaches the compressor surge line to mimic a severe operating condition of a vehicle i.e. sand storm.

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