Chapter 33
Development of an Affordable MGT-CHP for Domestic Applications

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Abstract The micro gas turbine (MGT) is considered one of the main solutions for the future power generation system to provide secure and stable energy. Thanks to its multi-fuel capability and high values of power-to-weight ratio, it is a suitable candidate for many applications such as Combined Heat and Power (CHP) systems, range extenders, and auxiliary power units. Among these applications, the micro-CHP system benefits from both the electricity and exhaust heat of the MGT for household or industrial process applications. The MGT could be integrated with a heat exchanger to introduce a CHP boiler to the domestic boiler market. To reduce the cost and size of the package and to compete with a traditional boiler the simple Brayton cycle without the recuperator is considered and all of the useful energy in the exhaust gas is transferred to the heat exchanger to provide hot water. To further reduce the cost of the system to compete in the market, off-the-shelf components were adopted in this project. In this article, the development process of this product is presented including conceptual design based on the type and size of the market. It follows with an evaluation of off-the-shelf compressor and turbine modulus from the automotive turbochargers to match the operating conditions. Here, the MGT is designed in a way that can be adapted to the boilers with minimum components change. A high-speed alternator was powered with a tie grid drive/inverter to enable a bi-directional connection of the power unit to the network. A comparison between the product definition and experimental results of a demonstrator prototype is presented which reveals gaps between design and prototype outcomes. Analysis shows that 23% of the power degradation can be recovered by enhancing the cooling. Potential development and improvement scenarios are addressed for future development.

Keywords Micro gas turbine · CHP · Simple cycle · Boiler · Performance · Experiment

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33.1 Introduction

Micro gas turbine technology has been under development for past decades. Gas turbines brought several advantages such as high power-to-weight ratio, low emission, and fuel flexibility in the automotive industry in the late 80s to substitute the internal combustion engine technology. Employing a high-speed generator, MGT was converted to be used in hybrid vehicles in the 1990s. Although the hybrid electric drive was not mature enough in that period [1], the turbomachinery side has advanced in superchargers. Besides, the MGT has been adapted in the hybrid power generation system on the decentralized power generation market to cover the intermittencies of renewable resources [2, 3] and to adjust the frequency of the distributed power generators.

The MGT has already been proved to be utilized satisfactorily in many engineering fields and specialized applications [1], however, the combined heat and power generation system is one of the most widespread general applications.

There are some challenges in transferring the technology from industrial gas turbine to micro-scale. Visser et al. [4] reported the high viscous losses of low Reynolds flow in the turbomachinery passages, high tip clearances to blade height ratio, high heat losses and relatively high auxiliary system losses as the major technical issues besides the cost.

The micro gas turbine, specifically in the lower power rate, provides lower electrical efficiency in comparison to internal combustion engines, however, it could provide higher overall efficiency in CHP mode as well as lower maintenance and operating cost due to lower moving parts and lower oil consumption.

Samad Power Ltd. (SP) was founded in 2011 to develop micro gas turbines for several applications including a small-size CHP system for a domestic application. This paper reviews the development process and the challenges in one of the early generations of SP's products. Based on the market study and thermodynamic cycle analysis, the appropriate size for the domestic CHP, related cycle parameters and the required specifications of each subsystem are designed. The MGT components are mostly sourced from the off-the-shelf automotive turbocharger parts to reduce the production cost, however, the combustion chamber is designed based on cycle parameters to match the system requirements. The overall system is arranged in the format of a domestic boiler. Test results showed some gaps between the prediction values and actual performance output from the experimental prototype which is discussed in this paper.

33.2 Market Study

Approximately, there are 26 million household boilers, in the range of up to 30 kW heat output, exist in the UK. On top of this, a further 1.4 million boilers installation per year is required to keep the demand stable [5]. The figures can be much higher if

Table 33.1 Product requirement definition

Performance		Operating life	
Power output	2.5–3.0 kW	Service intervals	~ 5000 h
Heat output	20–30 kW	Overhaul	~ 20,000 h
Total efficiency	90%	Design life	~ 40,000 h

Europe or global demand be added. Also, for a CHP to be eligible for Feed-in-Tariff (FiT) incentive in the UK market, the output of the appliance was limited to up to 2 kW of electricity [6]. Hence a product in the range of 2 kW electrical output and 30 kW heat output was considered to be appropriate for this application to get the best share of the market. Considering the power electronic losses including generator, rectifier and inverter, 2.5–3 kW shaft power is considered for the MGT. A summary of the required micro-CHP system is presented in Table 33.1.

33.3 Concept Development

Although the clean-sheet design of turbomachinery for new application requirements sounds like the most optimized solution, it is not the optimum method due to the required R&D cost and effort. Therefore, the selection of the off-the-shelf turbomachinery elements of the automotive industry is chosen as a design strategy in this phase to reduce the cost of development. Thermodynamic cycle analysis reveals that the MGT pressure ratio, turbine entry temperature and shaft rotational speed are about 2.0, 1200 K, and 120,000–180,000 RPM, respectively.

33.4 Preliminary and Detailed Design

Turbomachinery

To achieve the design scopes based on the chosen strategy, the matching of several turbomachinery components is investigated. There are various manufacturers in this field, among which, the products of Garrett Motion Inc are considered for component matching analysis. An in-house component matching tool was developed in the course of this study. The matching procedure which is based on mass flow balance and pressure consistency in the components is shown in Fig. 33.1. Based on this procedure, using the steady-state energy equations and the compressor and turbine characteristic map, one can estimate the necessary power requirement during the compression process and extra shaft power.

The output of integration scenarios that resulted from the above-mentioned procedure is plotted in Fig. 33.2. Each turbomachinery combination is indicated in XX-YY-ZZ name format in which XX, YY and ZZ are turbine family, compressor size and

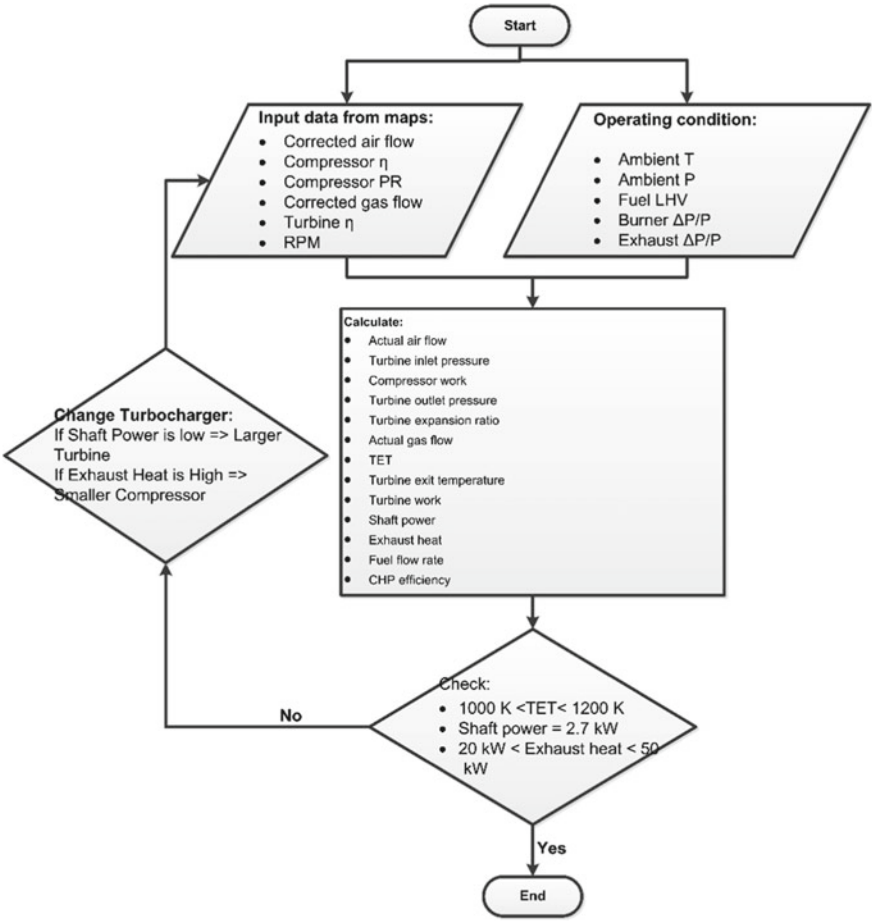

Fig. 33.1 Turbomachinery matching procedure

turbine trim, respectively. Considering the detailed characteristics of the components, the scenario with the turbine family of 20 and compressor size of 44 is selected. In this stage, design point calculation is carried out by GasTurb to indicate the characteristics of the cycle as well as the boundary condition of each component.

Figure 33.3 shows the model of the proposed concept in GasTurb [7] and the cycle parameters at defined stations. This model has been used to provide the required data for the detailed design of the combustion chamber and test analysis.

Combustion Chamber

A can-type combustor to provide a diffusion flame combustion is designed to accommodate the required air mass flow and turbine entry temperature. The reverse flow concept that originated from the aero gas turbine is employed to not only provide

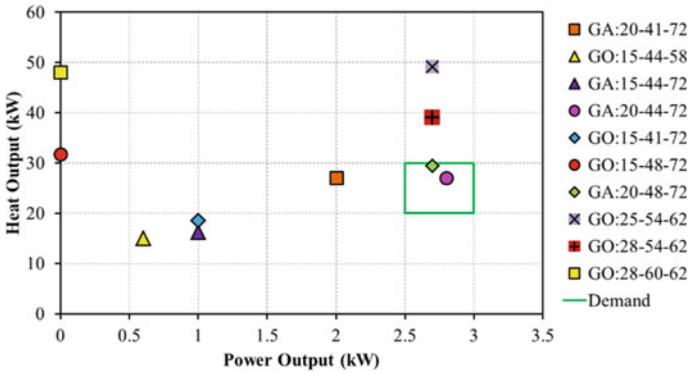

Fig. 33.2 Estimated output opportunity of turbomachinery combination scenarios

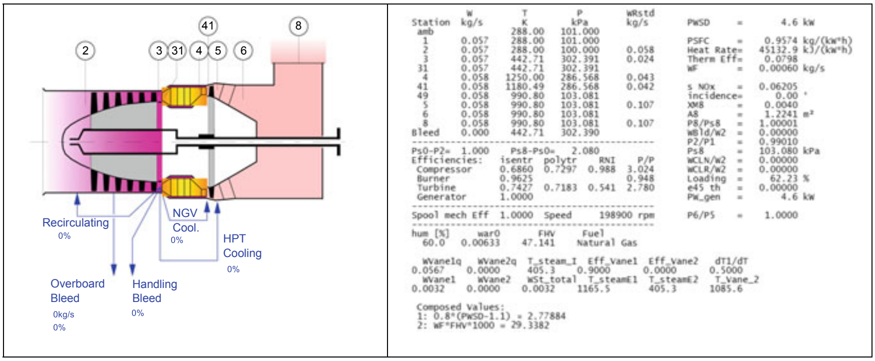

Fig. 33.3 GasTurb simulation model and sample results

sufficient cooling all around the chamber but to reduce the heat radiation to the ambient. The well-known zero-dimensional method of [8] (Sect. 33.4) is utilized the design the overall dimensions of the combustion chamber as well as the number, size and position of cooling holes. Cold flow simulation with specific fuel–air ratios [9] is carried out in ANSYS CFX for the detailed design of swirlers and holes to deliver the desired air/fuel mixing. Figure 33.4 shows the CFD result of cold and hot analysis in the designed combustion chamber.

33.5 Experimental Evaluation

A CHP test rig was developed to measure the performance parameters of the develop micro gas turbine. The test rig is equipped with appropriate sensors and techniques to provide the following measurements of cycle parameters:

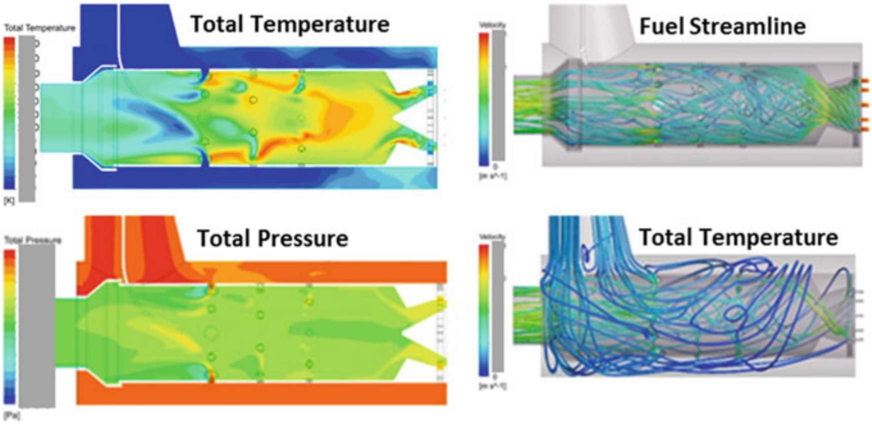

Fig. 33.4 CFD result of the combustion chamber

- Ambient temperature and pressure
- Compressor outlet temperature and pressure
- Turbine inlet temperature and pressure
- Turbine outlet temperature
- Compressor inlet mass flow
- Fuel mass flow
- Shaft output power.

A high-speed alternator was powered with a tie grid drive/inverter to enable a bi-directional connection of CHP to the network. Moreover, the temperature of the oil and cooling water in both inlet and outlet are measured to calculate the heat loss through these two systems. The micro-CHP test rig, equipped with mentioned measurements, is shown in Fig. 33.5.

33.6 Results and Discussion

Several tests were conducted to experimentally investigate the performance of the engine in different scenarios. In Fig. 33.6 three different results are compared. It shows the result of a performance of a fresh engine (test after assembly) at 170 kRPM, the performance of the degraded engine (after 20 h of operation) at 170 kRPM, and the performance of the engine at 200 kRPM. It could be seen that the power output is considerably less than the estimated power of the simulation which could be the result of neglected losses mainly the mechanical loss of the bearing, heat loss of the hot sections and the power loss of the generator. The other issue that can be seen in these results is that the output power of the system degrades after a couple of hours of operation. This power degradation is obvious in comparing the results of the fresh

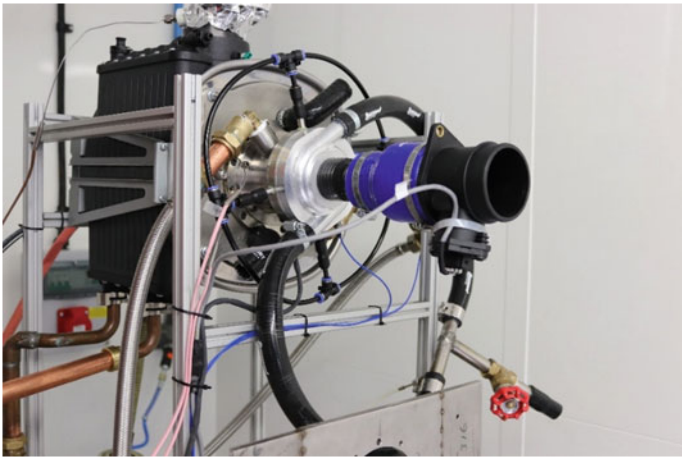

Fig. 33.5 Micro-CHP experimental test rig

engine with the one after 10 h of operation at the rotational speed of 170 kRPM. Moreover, it could be seen that at the rotational speed of 200 kRPM, the power does not increase with higher turbine inlet temperatures.

The effect of several parameters including mass flow rate, oil feed temperature, shaft speed, and oil feed pressure have been investigated to find a possible correlation between these parameters and the observed power reduction. In Fig. 33.7, it could be seen that mechanical losses do not have a meaningful correlation with the first three mentioned parameters but do have a correlation with oil feed pressure.

This mechanical loss has a constant value in pressures higher than 19 PSIG but increases linearly at pressures lower than this value. It was also found that the oil feed pressure can be correlated with the oil feed temperature (Fig. 33.8).

Having these correlations, it is estimated that by providing better cooling for the oil system, it would be possible to keep the oil pressure higher than 20 PSIG. The micro gas turbine power, consequently, would reach 2000 W at 1275 K, 200 kRPM.

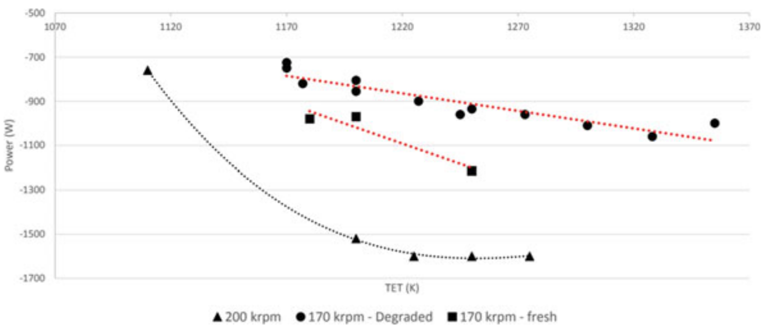

Fig. 33.6 Sample test results in different conditions (negative value for generation)

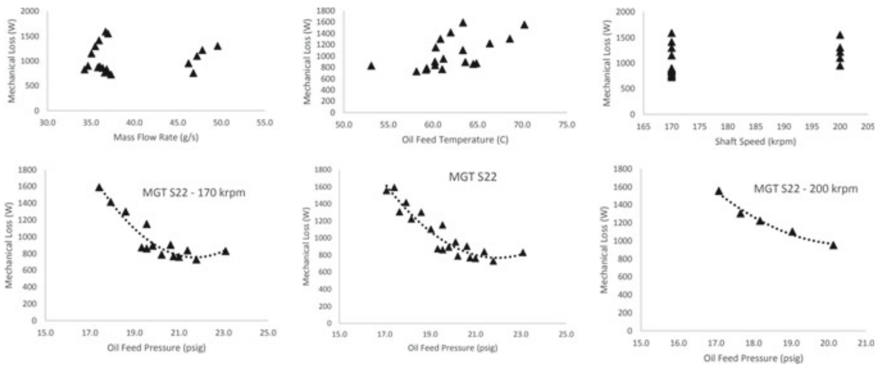

Fig. 33.7 Effect of different parameters on the MGT power loss

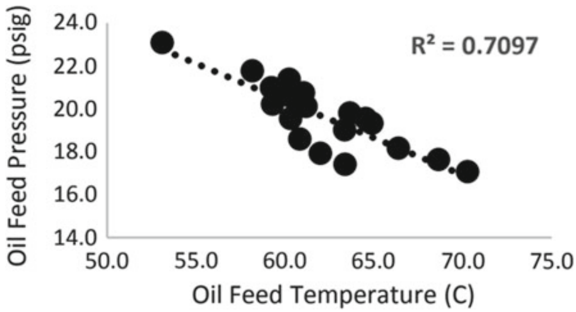

Fig. 33.8 Correlation between oil feed pressure and temperature

The predicted trend is shown in Fig. 33.9 which needs further development and testing to be verified.

33.7 Conclusion

This paper reviewed the development process of the micro gas turbine for a micro-CHP system based on available off-the-shelf turbocharger technology. An in-house code was developed to match the turbomachinery performances to define the product concept regarding the overall power and heat output. The concept was modelled into GasTurb for detailed test analysis and to provide the boundary condition for combustion chamber design. 0D equations and 3D CFD simulation were employed in the conceptual and preliminary design of the combustion system. A prototype was integrated and experimental tests were conducted to validate the design. Experimental results show significant deviation from predicted values. Although the available turbocharger technology shows a great potential to integrate an MGT in small sizes within the proposed procedure, there are technical gaps that need to be addressed to

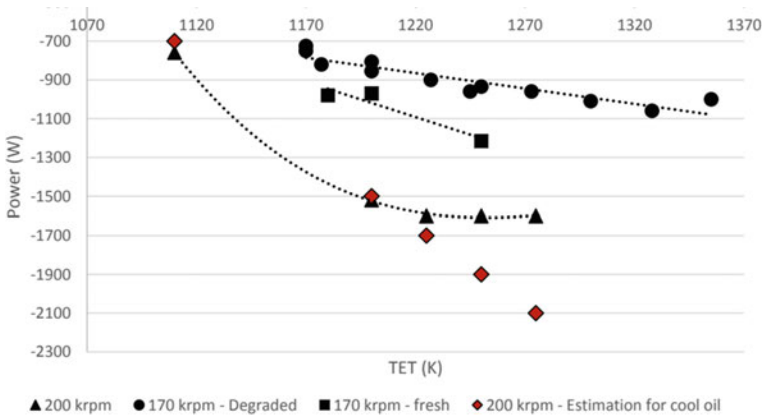

Fig. 33.9 Estimation of the performance with enhanced oil cooling (negative value for generation)

achieve the target power and efficiency targets. The authors believe that this would be established by enhancing the efficiency of components and reducing the consumption of auxiliary systems.

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