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1D MODELLING OF A MICRO GAS TURBINE FOR MULTI-GENERATION

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ABSTRACT

1D modelling for micro gas turbines (MGTs) is a major area of interest in the field of distributed multi-generation. In this paper a 1D simulation model for a commercialised MGT has been developed and validated against the manufacturer data using Simcenter Amesim. The developed model is a primarily tool to address the operational challenges of MGT, investigate future fuelling and investigate its integration with other energy storage / conversion systems. At this stage of research, the agility of the developed model is demonstrated by carrying out a parametric study to investigate the effect of varying the compressor inlet temperature on the overall system performance. It was revealed that the air mass flow rate was very sensitive to compressor inlet temperature change. Varying the compressor inlet temperature from 278K to 308K showed an increase of system efficiency by 1.2%.

Keywords: Micro gas turbine, multi-generation, 1D modelling

NOMENCLATURE

Abbreviations	
APD	Absolute Percentage Difference
CH_4	Methane
GTE	Gas Turbine Engine
HEX	Heat Exchanger
HHV	Higher Heating Value
IFP	Institut français du pétrole (French Institute of Petroleum)
LHV	Lower Heating Value
MGT	Micro Gas Turbine
PID	Proportional Integral Derivative
Symbols	
$\dot{m}$	Mass flow rate
P	Pressure
$\dot{Q}$	Heat flow rate
r	Pressure ratio
T	Temperature
η	Efficiency or Effectiveness
ρ	Density
Subscripts	
c	Compressor
f	Fuel
s	System
t	Turbine

1. INTRODUCTION

In the last few decades, decentralised and multi-generation systems have gained increasing attention to meet the increasing demand for energy and fulfil the ever-tight emissions standards [1]. MGTs are the recommended primary engines in small-scale multi-generation systems because of their high agility, low thermal inertia, high power to weight ratio, small physical footprint, small number of moving parts, low noise level, minimal possible vibration and multi-fuel capability. The versatility of MGTs to utilise a wide range of fuel increases the potential of utilising biofuels and other future renewable fuels [2].

The role of system modelling in engineering is indispensable; it is a cost-efficient approach that reduces the need to produce expensive prototypes. 1D modelling is a computationally affordable approach, which performs analysis on the component and system levels with respect to time and one spatial dimension [3].

1D modelling can investigate the capability and limitations of MGTs in multi-generation and their integration with various heat distribution and storage subsystems. It has the capacity to examine complex combustion mechanisms such as the combustion of renewable surrogate fuels and investigate their impact at system level [4].

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The main objective of this paper is to imitate the operation of a commercialised MGT using a 1D modelling approach and examine its validity at a predefined design operating point. A parametric study to assess the effect of varying the compressor inlet temperature on the overall performance of MGT was carried out as a tool to control the combustion temperature in hot environments. This enables the control of associated emissions and service life of the turbine blades.

2. MODELLING METHOD

2.1 System description

A commercialised MGT Capstone C30 of 30.9kW nominal net power output was simulated, which has been previously investigated in numerous research articles and widely implemented in many real-life applications [5-7]. Figure 1 shows a simplified Capstone C30 that operates a recuperated Brayton cycle and consists of a compressor (C), a combustor (CC), a turbine (T), a recuperator (R) and an electric generator (G).

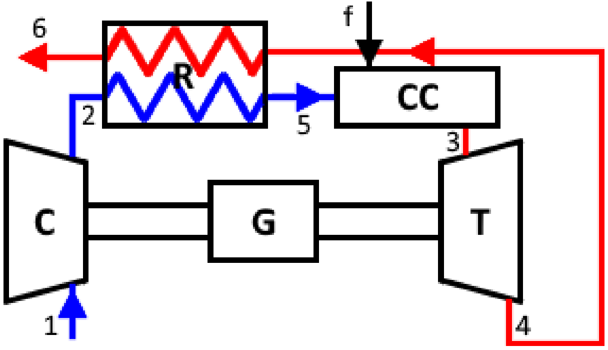

Fig 1 *Simplified schematic of a Capstone C30*

The compressor increases the pressure and temperature of the ambient air from 1 to 2 with a further increase in temperature from the recuperator from 2 to 5. The air is subsequently mixed with the fuel and burned to a peak temperature at point 3. The combustion gases then expand in the turbine stage from 3 to 4 to produce enough power to operate the compressor stage and power generator. The energy of post-turbine gas flow is recovered in the recuperator to pre-heat post-compressor air flow from 4 to 6.

The recuperator is used to improve the thermal efficiency of a Brayton cycle by increasing the post-compressor temperature, which reduces the fuel mass flow rate required to retain the same combustion temperature.

2.2 Model development

The simulation model was developed using Simcenter Amesim™. It is a multi-domain simulation platform featuring several domain libraries. Two main libraries were considered during the modelling stage, are: the IFP Engine library and Gas Turbine Engine (GTE) library. The IFP Engine library provides the turbocharger module that features detailed component map processing as well as heat transfer and mechanical characteristics of the bearing assembly. The turbocharger module imitated the turbine / compressor assembly of the MGT. The GTE library was numerically integrated to provide the detailed fuel combustion modelling.

2.2.1 Combustion modelling

Capstone C30 is designed to utilise natural gas. In a real-life application the purity of pipeline natural gas varies and depends on the molar percentage of methane (CH_4); nevertheless, the minimum permissible molar percentage of CH_4 is 75% [8]. In this investigation, a simplified pure CH_4 composition was utilised. Equation 1 shows the chemical reaction of the complete combustion mechanism for the pure CH_4, which was simulated with the GTE library.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \ (1)$$

2.2.2 Turbomachinery modelling

The turbocharger module in the IFP library was used to model the compressor stage, turbine stage and bearing assembly. These components were interconnected mechanically and thermodynamically. The maps for the centrifugal compressor and radial flow turbine were produced by scaling predefined built-in map processing tool in Amesim to match the system operating point. These maps were then used in conjunction with their respective reference temperatures and pressures. The heat transfer within the turbomachinery components was implemented by employing basic geometric and lubrication properties of the MGT.

2.2.3 MGT system modelling and control

MGT components were integrated as shown in Figure 2. The generator was modelled as an ideal rotating load. In this model the turbine and fuel mass flow rates were adjusted by Proportional Integral Derivative (PID) controllers to achieve the desired power output and operating speed. The starter motor was used to deliver

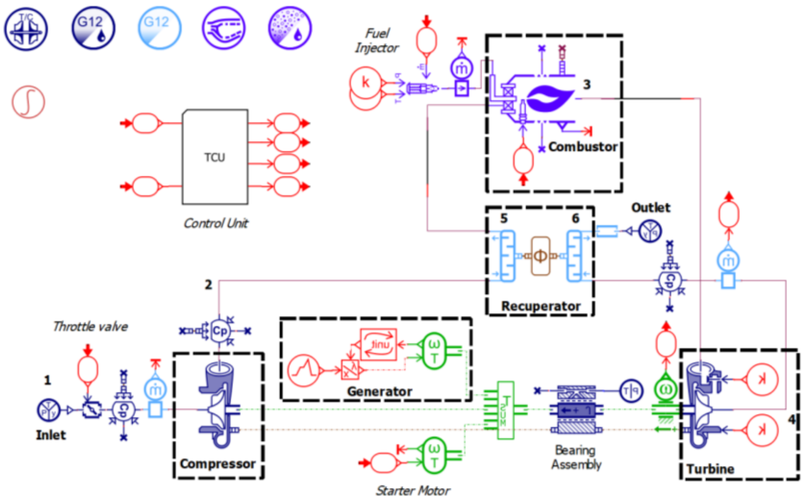

Fig 2 Amesim block diagram of Capstone C30

the necessary starting acceleration to reach the steady-state speed. The ambient conditions were maintained constant at 20°C and 1.013bar.

3. RESULTS AND DISCUSSION

3.1 Model validation

Table 1 shows the results of the developed model results were compared to their analogues experimental data provided by the manufacturer at the design operating condition [9]. Accordingly, the fuel mass flow rate was determined using equation 2.

$$\dot{m}_f = \frac{\rho_f \cdot \dot{Q}_{f,HHV}}{HHV_f} \quad (2)$$

Where HHV_f is the higher heating value of the fuel (39.1MJ/m^3 average), $\dot{Q}_{f,HHV}$ is the heat demanded to deliver the desired shaft power at the design operation (7.62MJ/s) and ρ_f is the fuel density (0.777kg/m^3) [9].The determined $\dot{m}_f$ was 2.523g/s, which has an absolute percentage deviation (APD) of 4.7% compared to the experimental value, showing good agreement between the predicted and the experimental data.

***Table 1** Deviation analysis of the developed model*

Parameter (Unit)	Ref. data	Model Pred.	APD (%)
r_c	3.64	3.97	9.1
T_5 (K)	807.59	782.42	0.59
T_3 (K)	1097.59	1117.84	1.8
T_4 (K)	866.48	830.22	1.4
r_t	3.64	3.69	1.4
T_6 (K)	536.48	535.86	0.12
$\dot{m}$ (kg/s)	0.313	0.301	3.8
$\eta_{s,LHV}$	0.271	0.257	5.1
T_2 (K)	466.42	477.16	2.3
$\dot{m}_f$ (g/s)	2.523	2.404	4.7

3.2 Parametric analysis

In order to demonstrate the capability of the developed model, this section presents a parametric study that assess the effect of changing the compressor inlet temperature on the overall performance of the simulated MGT. This includes the turbine gas and fuel mass flow rates, the combustion temperature and the overall system efficiency and the compressor and turbine efficiencies as shown in Fig. 3.

The decrease in turbine mass flow rate with increasing temperature is primarily due to the decrease in compressor air density. The fuel mass flow rate partially contributes towards this decrease and can be explained by analysing the turbomachinery efficiencies.

At low temperatures the compressor and turbine efficiencies are low, leading to a larger fuel demand. As these two efficiencies increase fuel mass flow rate steeply drops to a point where it is at a minimum corresponding to the maximum system efficiency. Past this point, decreasing turbine efficiency increases the fuel demand with a lower gradient due to the contradicting increasing compressor efficiency.
The combustion temperature increases with increasing the compressor inlet temperature due to the reduction of the air-to-fuel ratio; however, if this was controlled to avoid excessively high temperatures then fuel mass flow rate would decrease leading to insufficient power for the generator with respect to the operating speed. In real life, an optimised operation strategy and MGT configuration is desired to constantly operate MGT at peak efficiency.

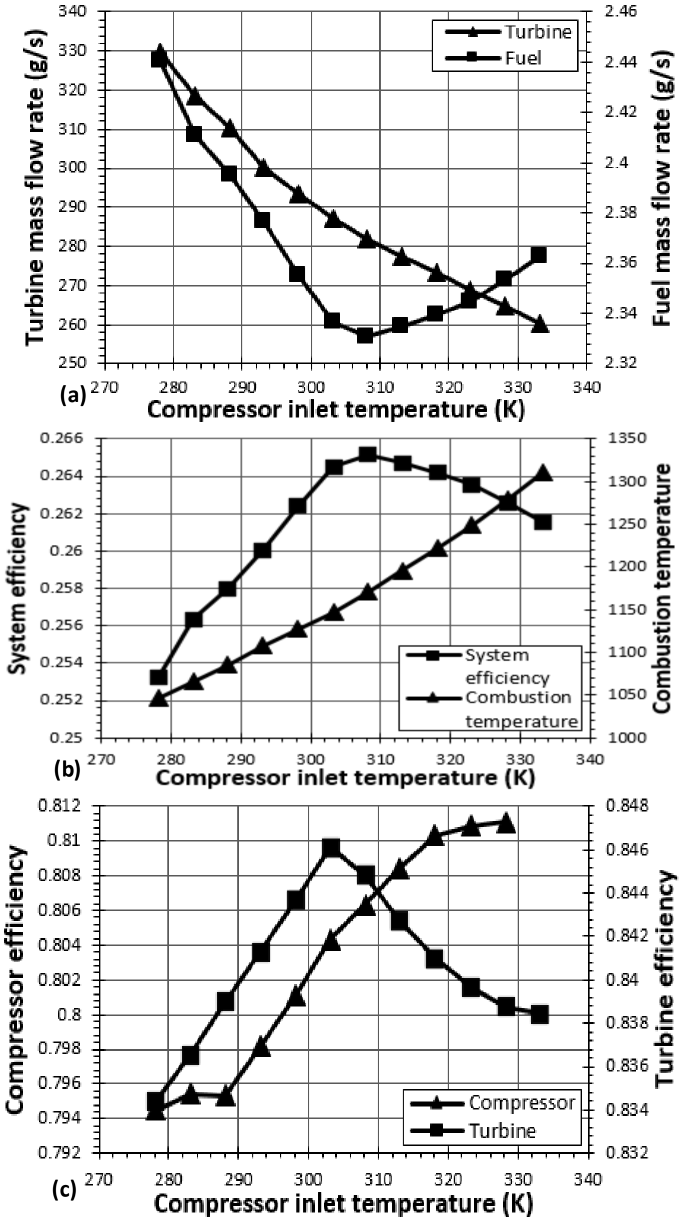

Fig 3 *Effect of compressor inlet temperature on MGT performance*

4. CONCLUSION

The open literature identified the increasing interest in MGTs for multi and decentralised power generation. Given the importance of system modelling to investigate and optimise the operation of MGTs, this work presented the development of a 1D simulation model for a commercially available MGT using Simcenter Amesim.

The simulation results showed a good agreement between the predicted values and the experimental data provided by the manufacturer's data sheet. A parametric study was carried out to demonstrate the capability of the developed model. The parametric study investigated the influence of the compressor inlet temperature on the overall performance of the simulated MGT. Results showed that turbine mass flow rate decreased with compressor inlet temperature and system efficiency peaked at 308.15K, though combustion temperature was allowed to exceed the design operating point's combustion temperature.

The conclusion that can be drawn from this study is that the developed 1D MGT model can be used as a tool to address operational challenges including the investigation of future fuelling combustion in MGTs as well as investigating its integration with other energy storage and conversion systems. Furthermore, the model can be employed in conjunction with 3D computational fluid dynamics to develop and optimise the design of a specific component of the system in more detail whilst maintaining reasonable fidelity and computation cost in the rest of the system [10].

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