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The effects of internal leakage on the performance of a micro gas turbine

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HIGHLIGHTS

- Degradation characteristics of a micro turbine by internal leakages are analyzed.
- An off-design analysis was carried out after validation using actual operating data.
- Three types of leakages were comparatively analyzed using parameter sensitivities.
- The leakage from combustor inlet to turbine exit showed the largest efficiency loss.
- Performance losses were compared to those by compressor fouling and turbine erosion.

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ABSTRACT

Micro gas turbines are manufactured to have a compact structure and small volume, which makes them more vulnerable to internal leakages compared to heavy-duty gas turbines. Accordingly, precise diagnosis of the performance degradation in a micro gas turbine is important. This study investigates the characteristics of degradation. Performance maps were used for the compressor and turbine, and a multi-segment counter-flow heat exchanger model was used for the recuperator. The component models were refined using actual operation data, resulting in precise simulation of the reference operation without leakage. A performance analysis was carried out, and the results were analyzed for three types of leakage with the following paths: from the compressor outlet to the recuperator's cold-side outlet, from the compressor outlet to the combustor outlet, and from the combustor inlet to the turbine outlet. The third path produced the largest reduction in engine efficiency. The degradations were also compared with those related to compressor fouling and turbine erosion, which are the most common causes of degradation in a gas turbine. Even when qualitatively similar performance changes were observed, the root cause could be determined by analyzing differences in performance parameters such as the fuel flow.

1. Introduction

Micro gas turbines (MGTs) are small gas turbines with power outputs of dozens to hundreds of kilowatts. Generally, large gas turbines are designed based on a simple cycle and are mainly composed of an axial compressor, combustor, and axial turbine. However, the turbine blades of MGTs are difficult to cool because of their small size, so they are designed for a low turbine inlet temperature. Thus, a lower design pressure ratio is used than in large gas turbines. Low turbine inlet temperature and pressure ratio lead to low thermal efficiency. A regenerative cycle is commonly used to overcome this problem, where the air from the compressor outlet is heated using the heat of the turbine's exhaust gas.

Fig. 1 shows a schematic of an MGT, which is composed of a centrifugal compressor, radial turbine, combustor, and recuperator. Large gas turbines generally use a variable inlet guide vane in the compressor to maintain high-temperature exhaust gas, even at partial load. However, a variable rotational speed is applied for the same purpose in MGTs. Because of these differences, the behavior of MGTs is different from that of large gas turbines, and many studies have analyzed their performance. Kim and Hwang examined the operation logic needed to achieve high efficiency in recuperative cycle gas turbines [1]. Other studies have analyzed the dynamic behavior of MGTs by considering the thermal inertia of the recuperator [2–5].

Compared with other power generation equipment, gas turbines are very expensive, and their failure or degradation imposes heavy losses on power generation companies. Thus, many studies have been devoted to ensuring the stable operation of gas turbines. Compressor fouling, turbine erosion, and combustor degradation are key issues [6–8]. The causes of performance degradation have been diagnosed using various

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Nomenclature

A	heat transfer area (m^2)
c_P	constant pressure specific heat (kJ/(kg K))
DPC	digital power controller
h	enthalpy (kJ/kg)
i	heat transfer index
LHV	lower heating value (kJ/kg)
M	semi-dimensionless mass flow rate (ms $K^{0.5}$)
$\dot{m}$	mass flow rate (kg/s)
MGT	micro gas turbine
N	rotation speed (RPM)
n	number of heat exchanger segments
p	pressure (kPa)
PR	pressure ratio
R	sensitivity ratio
S	sensitivity (%)
T	temperature (K)
TET	turbine exit temperature (°C)
$\dot{W}$	power (kW)
Y	performance or operating parameter
α	convective heat transfer coefficient (kJ/(m^2 K))
β	beta line
ζ	heat loss of combustor
η	efficiency
Ω	semi-dimensionless rotation speed (RPM/$K^{0.5}$)

Subscripts

c	cold side
cl	clean
comb	combustor
comp	compressor
d	design
dam	damaged
f	fuel
gen	generator
h	hot side
HX	recuperator metal
in	inlet
l	heat exchanger segment index
max	maximum
me	mechanical
out	outlet
s	isentropic
turb	turbine
w	with degradation
wo	without degradation

techniques, including physical models [9], fuzzy logic [10], and a regression method [11]. Tahan et al. reviewed the diagnostic and prognostic methods for gas turbines along with the overall causes of engine deterioration [12].

In recent years, distributed generation has been investigated intensively because it helps to reduce transmission loss and improve the stability of power grids. MGTs are one of the main types of distributed generation sources. However, they have disadvantages of low efficiency and high initial investment compared to other equipment such as reciprocal engines. Thus, the efficiency and cost have been the main issues in many studies of MGTs. Paepe et al. investigated water injection to improve the performance [13]. Stathopoulos and Paschereit reported on the enhanced economics of using a steam-injected MGT [14]. Basrawi et al. considered an optimal operation strategy for an MGT-based trigeneration system [15]. Montero Carrero et al. compared a humidified MGT and a reciprocating internal combustion engine from an economic perspective [16]. The same research group also analyzed electrical and exergy efficiency of the humidified MGT cycle [17] and introduced advanced humidification cycle concepts [18].

MGTs also have various advantages. They have larger specific power, produce less noise, and emit much less pollutants, especially NOx. Some recent studies have focused on reducing the CO_2 emissions of MGTs. Majoumerd et al. and Giorgetti et al. investigated the improvement of the CO_2 capture performance by recirculating the exhaust gas and applying a humid air cycle to an MGT [19]. Zornek et al. presented a new combustor for using biogas and analyzed the variation in the behavior of an MGT with low calorific fuel [20]. Best et al. analyzed the effects on the capture performance of increased CO_2 concentration in the exhaust gas due to exhaust gas recirculation [21]. Ali et al. examined the possibility of applying post-combustion CO_2 capture to an MGT [22]. Giorgetti et al. compared performance of dry and wet MGT cycles with carbon capture [23].

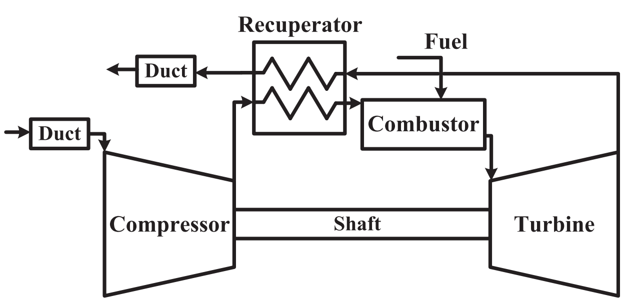

Fig. 1. Configuration of the micro gas turbine.

Thanks to steady efforts in research and development, MGTs have rapidly propagated in the power market in the past decade. The rapid rise in their market penetration has increased the importance of economical operation. Reducing the time and effort consumed for maintenance could contribute substantially to the operational economics of MGTs. Therefore, it is important to analyze the cause and degree of performance degradation based on an accurate diagnosis. Because MGTs have many different characteristics from large gas turbines, it is necessary to develop diagnostic methods that are specific to MGTs. To produce an economical diagnostic system, Davison and Birk tried to diagnose the degradation of components using a minimal amount of information [24]. They also estimated the remaining time to failure of an actual engine [25]. Mahmood et al. developed an MGT model using operation data [26] and diagnosed abnormal behavior through the model [27]. Verstraete and Bowkett investigated the performance variation of an MGT in relation to the heat transfer between components [28].

Because of the compact structure of MGTs, their leakage behavior is also different from that of large gas turbines. Internal leakage occurs when some of the working fluid deviates from the main flow path and flows into other paths or components. Many commercial MGTs are designed to have a small volume and simple shape, and thin plates or seals are used to prevent leakage. However, these components can be damaged by the considerable level of thermal or mechanical stress that occurs during the cyclic operation of an engine. In this situation, the pressure difference between two flow paths separated by damaged or failed components may cause internal leakage. This has a significant effect on the performance, and manufacturers are very interested in this technical issue from the development stage [29]. Leakage is considered to be a cause of degradation in an MGT [27]. Thus, a diagnostic system for stable and economical operation of an MGT needs to consider the performance degradation resulting from internal leakage. However, the effect of internal leakage on the behavior of MGTs has not been