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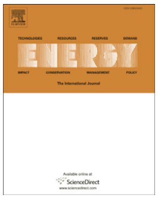

A comparison of micro gas turbine operation modes for optimal efficiency based on a nonlinear model

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ABSTRACT

The novel contribution of this paper is that Micro gas turbine (MGT) operation modes for optimal efficiency are compared based on a nonlinear model, and the variable-speed control is proposed for optimal efficiency. The nonlinear mathematical MGT model is established based on thermodynamic analysis, which can completely reflect the MGT operational characteristics. When the air flow rate is fixed, the rotational speed of the rotor greatly influences the MGT efficiency. At a certain value of speed, the system efficiency reaches its maximum. On this basis, the efficiency of four MGT operation modes are studied: 1. constant speed of a simple cycle, 2. variable speed of a simple cycle, 3. constant speed of a regenerative cycle, and 4. variable speed of a regenerative cycle. In this paper, the relationship between optimal efficiency and the corresponding rotational speed of different output powers formulated using a numerical calculation method is studied. The optimal efficiency formula can be used to generate the given speed of the MGT speed controller for optimally efficient operation. The results show that the variable-speed operation mode of the regenerative cycle exhibited the highest system efficiency and has an evident efficiency optimization effect under a small load.

1. Introduction

Micro gas turbines (MGTs) using simple cycles and multiaxis structures first appeared in the 1940s. Because of their lack of regenerators and heavy gear box, their efficiency is lower than that of internal combustion engines. These disadvantages have limited the development of MGTs. With the development of high-efficiency compact heat exchangers, high-speed pneumatic bearings, high-speed permanent magnet generators, and power electronic technology, the modern advanced MGT has developed rapidly since the 1990s [1]. Compared with the internal combustion engine, the modern advanced MGT has the advantages of a greater ratio of power to volume [2], operation with diverse forms of fuel, lower noise, less pollution, and suitability for combined cooling, heating, and power (CCHP) system [3]. The MGT generation system is an important distributed generation system [4,5], and many scholars have done a lot of research work in turbomachinery performance analysis [6,7], MGT performance analysis [8,9] and so on.

Because of the MGTs high response and high combined cycle efficiency, the MGT has drawn great attention in both research and application fields. However, in some special applications, the MGT is limited, largely because its performance is not perfect.

Efficiency is an important indicator of performance in MGTs. Improving the operating efficiency of MGTs can reduce costs, which is conducive to increasing their popularity. There are many factors that affect efficiency (e.g., humidity, ambient temperature, fuel type, and cooling technology). Existing research results show that a relative humidity in the range of 30%–45% has less of an impact on efficiency. When the ambient temperature is in the range of 26.7°C–37.8 °C, the efficiency increases by 1% for every 5.6 °C rise in temperature. Compared with combustion of diesel oil and heavy oil, the efficiency of burning natural gas is the highest [10]. Some researchers have studied the efficiency from the viewpoint of MGT design, demonstrating that the higher the design temperature ratio, the lower the fuel consumption and the higher the part load efficiency. The design value of the pressure ratio has little effect on efficiency [11]. The MGT design is related to the complex internal structure and field operation, which are not the focus of this paper. In this paper, we perform the theoretical research work to improve MGT efficiency from the control perspective.

To study MGT efficiency from the viewpoint of theoretical

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Nomenclature

α	comprehensive heat transfer coefficient
α_a	heat transfer coefficient between air and metal wall
α_g	heat transfer coefficient between gas and metal wall
$\bar{G}_c$	similarity mass flow of compressor
$\bar{G}_t$	similarity mass flow of turbine
$\bar{n}_c$	similarity speed of compressor
$\bar{n}_t$	similarity speed of turbine
$\dot{\eta}_c$	reduced efficiency of compressor
$\dot{\eta}_t$	reduced efficiency of turbine
$\dot{\pi}_c$	reduced pressure ratio of compressor
$\dot{G}_c$	reduced mass flow of compressor
$\dot{G}_t$	reduced mass flow of turbine
$\dot{n}_c$	reduced speed of compressor
$\dot{n}_t$	reduced speed of turbine
η_B	combustion efficiency
η_c	efficiency of compressor
η_{MGT}	efficiency of MGT
η_t	efficiency of turbine
κ_a	isentropic exponent of air
κ_g	isentropic exponent of gas
π_c	pressure ratio of compressor
π_t	expansion ratio of turbine
σ	regenerator effectiveness
τ_F	time constant of Flow regulating valve
τ_T	integral ratio of temperature controller
A	comprehensive heat transfer area
a	coefficient of valve positioner
a_1	inlet total pressure recovery coefficient of compressor
A_a	heat transfer area between air and metal wall
A_g	heat transfer area between gas and metal wall
b	coefficient of valve positioner
c	coefficient of valve positioner
c_1	relative coefficient of compressor
c_2	relative coefficient of compressor
c_3	relative coefficient of compressor
c_{pa}	average specific heat at constant pressure of air
c_{pg}	average specific heat at constant pressure of gas
$G_{ASC}(s)$	transmission function of anti radiation cover
G_c	mass flow of compressor
G_f	mass flow of fuel
G_t	mass flow of turbine
$G_{VP}(s)$	transmission function of valve positioner
J	rotor moment of inertia
K_{eoni}	integral gain of speed closed-loop PI controller
K_{eonp}	proportional gain of speed closed-loop PI controller
K_F	feedback coefficient of Flow regulating valve
n	speed
p_1	Inlet total pressure of compressor
p_2	outlet total pressure of compressor
p_3	input pressure of turbine
p_4	outlet total pressure of turbine
P_a	atmospheric pressure of environment
P_c	consumption power of compressor
P_f	power of fuel
P_{ML}	load power
P_m	output power of MGT
P_t	output power of turbine
Q_u	low heat value of fuel
t	time
T_1	inlet temperature of compressor
t_1	relative coefficient of turbine
T_2	output temperature of compressor
T_2'	temperature of cold outlet end
T_3	input temperature of turbine
T_4	output temperature of turbine
T_4'	temperature of hot outlet end
T_m	metal wall average temperature of recuperator
T_R	temperature setpoint
Z	constant
*	refers to the stagnation parameter
ref	reference value of the corresponding variable

derivation and numerical simulation, it is necessary to set up a mathematical model of the MGT. Widely used in the existing literature are the Rowen model [12–15], the IEEE model [16–19] and component-based models that are widely used for performance simulation of turbomachinery [20]. In these two models, each link of the gas turbine is simplified as a linear or a delay link in the near-design condition, and gas flow, compressor pressure ratio, turbine expansion ratio, efficiency, and other process variables are not included. In addition, the models do not include the regenerator; therefore, the accuracy for off-design operation is poor. Other models, such as the aero-derivative model [21], GAST model [22], WECC model [23–25], CIGRE model [26], frequency-dependent model [27], and fluid network model [28–30], are too simple to accurately describe the efficiency and output power characteristics of the MGT under the off-design condition. Furthermore, the measured curve is difficult to describe mathematically. The efficiency of the compressor and turbine under the off-design condition has been presented in the published literature and can be expressed as an analytic formula relating speed and gas flow [31–34]. At the same time, a mathematical model of the regenerator has been considered [35], so a nonlinear mathematical model of the MGT has been established.

Compared with the existing nonlinear mathematical model, the model used in this paper has the following characteristics: 1) It uses a static average model of the heat exchanger, and 2) the analytical formula for the efficiency of the compressor and turbine under the off-design condition is adopted [36]. The nonlinear mathematical model of the MGT used in this paper is that proposed by the authors of [36]. On this basis, under different load conditions the relationship between speed and efficiency is studied. The curve of efficiency and control variables can be drawn using these mathematical relations. The operating point of the optimal efficiency can be clearly demonstrated from the variation of the curve.

The major work of this paper is to analyze the difference in the optimal efficiency operation law for two different MGT structures of simple and regenerative cycles. There are two operation modes for each structure common operation and optimal efficiency operation so there are four different operations to study. In this paper, the efficiency of the four operation modes is calculated quantitatively to identify the best operation mode in the whole operational condition range, and the degree of efficiency improvement is given. We obtain the relationship between the load and the variable speed for optimal efficiency, which is applied in the control system.

The article is organized as follows: Section 2 presents the nonlinear mathematical MGT model. In Section 3, we analyze the optimal efficiency operation. Sections 4 and 5 present the optimal