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ORIGINAL ARTICLE

Performance characterization of different configurations of gas turbine engines

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Abstract This paper investigates the performance of different configurations of gas turbine engines. A full numerical model for the engine is built. This model takes into account the variations in specific heat and the effects of turbine cooling flow. Also, the model considers the efficiencies of all component, effectiveness of heat exchangers and the pressure drop in relevant components. The model is employed to compare the engine performances in cases of employing intercooler, recuperation and reheat on a single spool gas turbine engine. A comparison is made between single-spool engine and two-spool engine with free power turbine. Also, the performance of the engine with inter-stage turbine burner is investigated and compared with engine employing the nominal reheat concept. The engine employing inter-stage turbine burners produces superior improvements in both net work and efficiency over all other configurations. The effects of ignoring the variations on specific heat of gases and turbine cooling flow on engine performance are estimated. Ignoring the variation in specific heat can cause up to 30% difference in net specific work. The optimum locations of the intercooler and the reheat combustor are determined using the numerical model of the engine. The maximum net specific work is obtained if the reheat combustor is placed at 40% of the expansion section. On the other hand, to get maximum efficiency the reheat combustor has to be placed at nearly 10%-20% of the expansion section. The optimum location of the intercooler is almost at 50% of the compression section for both maximum net specific work and efficiency.

1. Introduction

The gas turbine engine is compact, has a light weight and can operate using multiple fuels. This makes gas turbine engines suitable for many aerospace and industrial applications. The

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Nomenclature

A_0, A_1, A_2,…	coefficients of polynomial
C_P	specific heat at constant pressure (unit: J/(kg · K))
f_1	fuel-to-air ratio in the first burner
f_2	fuel-to-air ratio in the second burner
m_C	ratio of turbine cooling flow to total air flow
N	number
P	pressure (unit: Pa)
Q_r	heating value of the fuel (unit: J/(kg · K))
R	gas constant (unit: J/(kg · K))
SFC	specific fuel consumption (unit: kg/J)
T	temperature (unit: K)
T_{5C}, T_{7C}, T_{9C}	corrected temperature
W	specific work (unit: J/kg)

Greek symbols

ε	effectiveness
η	efficiency
γ	specific heat ratio
τ	temperature ratio
π	pressure ratio

Subscripts

1, 2,…	station numbers defined in Figure 2
b	burner
C	compressor
HPC	high pressure compressor
HPT	high pressure turbine
IC	inter cooler
LPC	low pressure compressor
LPT	low pressure turbine
$mech$	mechanical
$prod$	products of combustion
reg	regenerator
t	turbine

economics of power generation using gas turbine engines depends on the fuel cost, running efficiency, maintenance cost, and first cost, in that order [1]. For the fuel cost to be minimized, the efficiency of the engine has to be maximized. Actually, a small improvement in efficiency can be seen as a big amount of money if fuel cost is integrated over the life time of the engine.

On the other hand, the maintenance cost and first cost per unit power ($/kW) can be reduced if the net specific work is increased. Increasing net specific work means that a plant of a smaller size can generate the same power. The size of the plant can be considered as a measure for the maintenance and first costs. Thus, maximum efficiency and maximum net specific work are targeted in the optimization process of the plant.

Also, designing the engine at low turbine inlet temperature (TIT) and small compressor pressure ratio decreases both maintenance and first costs. However, this may decrease both efficiency and net specific work. Thus, a criterion for the total cost may be required to estimate the global optimum of the engine. However, as the fuel cost may be up to 75% of the life cycle cost [1], the increase in efficiency and net specific work will be preferred over a reduction in turbine inlet temperature and compressor pressure ratio [2]. It should be noted that a limit in TIT is imposed by the metallurgical constraints. Also, a practical limit is set by turbo machinery considerations on the compressor pressure ratio for fixed rotating speed.

Many modifications on the simple gas turbine engine have been proposed in order to improve its performance within the allowable range of TIT and compressor pressure ratio. One example is the gas turbine engine employing intercooling, recuperation, and reheating [3,4]. The engine can be made of two spools with free power turbine installed on the low-pressure spool. This free power turbine can be installed in parallel or in series configurations [5]. The percentage changes in performance parameters of the modified cycle over the simple cycle were evaluated, and it was found that to a large extent, the modified engine cycles with unconventional components exhibit better performances in terms of thermal efficiency and specific fuel consumption than the traditional simple cycle [6].

A regenerative gas turbine engine, with isothermal heat addition, working under the frame of Brayton cycle has been analyzed [7]. The temperature during the heat addition is kept constant using a converging duct, thus, it results in an increase in Mach number due to energy conservation. The results show that this engine when designed according to the maximum power density condition gives the best performance and exhibits highest cycle efficiencies. However, the limit on the exit Mach number from the isothermal combustor is a big challenge and restricts the improvement in performance.

It was proposed that combustion to be continued purposely inside the turbine to increase the efficiency and specific power of the engine [8,9]. Ground-based gas-turbine engines for power generation have been analyzed, with the results showing even better performance gains compared with conventional engines. The challenges arising for such modification was reviewed to assess them against the gains [10].

The mathematical model of the plant should be as accurate as possible to select the optimum design point. Some modeling errors could direct towards a design that results in more total cost. This is particularly important for complicated configurations that are proposed to enhance the performance of the plant. In such complicated engines, there is significant change in specific heat from component to component and sometimes from inlet to outlet of the same component. The effect of the variations in specific heat should be considered at each state as function of temperature and fuel-to-air ratio especially when a parametric study is conducted to determine the optimum design point of the plant.

A constant value of specific heat has been used for pure air (all components before the combustion chamber) and a higher