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Parametric and optimization studies of reheat and regenerative Braysson cycle

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ABSTRACT

A detailed parametric and optimization studies of reheat and regenerative Braysson cycle has been carried out. The effect of compressor and turbine inlet temperatures, temperature rise in a stage of multi-stage compression, individual component efficiencies and exit pressure of reheat turbine on the performance has been studied. The effect of perfect cooling after regeneration leads to a gain of 7.4% in maximum exergy efficiency and 20% in maximum power output. A computer programme has been developed to evaluate the optimum pressure ratio for minimum specific fuel consumption and maximum power output. It is interesting to note that the optimum pressure ratio for maximum power output and minimum specific fuel consumption are different and they vary by a wide margin. It has been further seen that this optimum pressure ratio is a function of turbine inlet temperature. A thermodynamic system will have degeneracy in operational effectiveness with the decrease in component efficiencies due to aging. Hence the variations of optimum pressure ratio with component efficiencies are also studied and reported in this work. To make the system economically viable, it has been recommended to design the system for the operating condition of minimum specific fuel consumption rather than for maximum power output.

1. Introduction

The gas turbine technology has undergone a lot of development in recent years to merit its use in a wide spectrum of applications ranging from aircraft propulsion, marine propulsion and power plants. This range of applications is due to some explicit advantages associated with the gas turbines. Lot of research has been done to enhance the performance of gas turbines and this has fructified with the inclusion of waste heat recovery through regeneration, turbine reheating, compressor intercooling and introducing steam into the gas turbine combustor. A power generation cycle has the highest efficiency, when it runs on a reversible cycle with isothermal heat addition and low temperature isothermal heat rejection. The temperature of heat rejection can be decreased by implementing a combined cycle power plant in which the heat rejected from Brayton cycle is used to drive the steam turbine cycle. Such cycles are being used the world over due to their higher energy and exergy efficiencies.

Frost et al. [1] proposed an alternative to the combined cycles and termed it as Braysson cycle. The Braysson cycle is inherently an air driven cycle, and therefore the complexities involved in installing and running the heat recovery steam generator, condenser and other auxiliaries of a combined cycle plant are totally eliminated in this cycle. Braysson cycle is a hybrid of the high temperature heat addition Brayton cycle and the low temperature heat rejection Ericsson cycle. The Braysson cycle was subjected to further studies based on both the first and the second law analysis by many researchers. Zheng et al. [2] carried out an exergy analysis for an irreversible Braysson cycle and analyzed the influence of various parameters on its performance. It has been shown that both the power output and the efficiency of the cycle are greater than those of Brayton cycle. Zheng et al. [3] also derived the analytical formula for power output, efficiency, maximum power output and the corresponding efficiency of an endo-reversible Braysson cycle with the heat resistance losses in the hot and cold-side heat exchangers using finite time thermodynamics. He also analyzed the influence of the design parameters on the performance of the cycle. Zheng et al. [4] carried out the optimization of the above parameters of endo-reversible Braysson cycle. Furthermore the effects of

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Nomenclature

Upper case

CIT	Compressor inlet temperature (K)
H	Total enthalpy (kJ)
N	Number of stages of multi-stage intercooled compressor
NDPO	Non-Dimensional Power Output
P	Pressure (N/m^2)
SFC	Specific Fuel Consumption
T	Temperature (K)
T_0	Dead state temperature (K)
TIT	Turbine inlet temperature (K)

Lower case

c_p	Specific heat at constant pressure of both air and gases (kJ/kg K)
e_f	Specific exergy of fuel (kJ/kg)
h	Specific enthalpy (kJ/kg)
l.c.v	Lower calorific value of fuel (kJ/kg)
m_f	mass flow rate of fuel in the combustion chamber (kg/s)
m_{f1}	mass flow rate of fuel in the reheater (kg/s)
m_g	mass flow rate of gases through the main gas turbine (kg/s)
m_{g6}	mass flow rate of gases through the reheat gas turbine (kg/s)
r_p	pressure ratio across the main compressor
r_{p1}	pressure ratio across the main turbine
r_{p2}	pressure ratio across the reheat turbine
r_{po}	overall pressure ratio across the multi-stage intercooled compressor
s	Specific entropy (kJ/kg K)
t_r	Temperature ratio

Symbols

η_c	Isentropic efficiency of the main compressor
η_{cs}	Isentropic efficiency of a stage of multi-stage intercooled compressor
η_T	Isentropic efficiency of the turbine
η_{ex}	Exergy efficiency
η_{reg}	First law efficiency of regenerator
γ	Ratio of specific heats
K	$(\gamma-1)/\gamma$
ΔT	Temperature rise in a stage of multistage compression process (K)

various design parameters on those optimum values were studied. Yasin et al. [5] performed the analysis of endo-reversible Braysson cycle based on ecological criteria. The ecological objective function was defined and its maximization was achieved for various design parameters. Sreenivas et al. [6] performed the second law analysis of an irreversible Braysson cycle. The overall second law efficiency and the component-wise second law efficiencies were derived. The thermodynamic losses occurring in each component were obtained. Zhang et al. [7] presented a novel model of the solar-driven thermodynamic cycle system consisting of a solar collector and a Braysson heat engine. The performance characteristics of the system were optimized on the basis of the linear heat-loss model of a solar collector and the irreversible cycle model of a Braysson heat engine.

The main drawback of Braysson cycle is the difficulty in achieving isothermal compression in multistage intercooled compressor. However, a few proposals were made by some researchers. Georgiou and Xenos [8] incorporated a regulated water injection, which was coordinated with the compression process, so that the evaporation of water droplets may maintain a near constant temperature of the fluid. The study provided an analysis for the water injection rate and showed that the additional work needed to drive the process was not affected significantly by the injection. Georgiou et al. [9] also proposed a multistep intercooled compression process on a solar-driven Braysson heat engine as a feasible solution for implementing isothermal compression in Braysson cycle. The results indicated that such a plant may reach efficiency levels of above 30%, i.e. exceeding the efficiencies of the conventional Photovoltaic plants by a wide margin.

However, Chandramouli et al. [10] have recently proposed reheat and regenerative Braysson cycle with the inclusion of cooler and showed that it reaches the efficiency of the conventional Braysson cycle at a very lower pressure ratio. The study also included the influence of number of stages of multistage intercooled compressor on exergy efficiency and came to the conclusion that it can work with fewer stages (N = 10) and attain higher efficiency than the conventional Braysson cycle with isothermal compression (which is an ideal proposition). Thus one need not go for isothermal compression. Hence a parametric analysis of this reheat and regenerative Braysson cycle is required to study the effect of different parameters on the cycle performance for its practical implementation.

Parametric analysis and optimization of thermodynamic cycles have been investigated by several authors in the last few years due to their practical importance. Within this framework, Heat engines [11–13], Stirling engine [14–20], Ericsson [21,22] Refrigeration [23–28], Brayton [29–34], Organic rankine [35–42] as well as Braysson [43–45] cycles have been investigated. These are mostly theoretical in nature and have been analyzed through thermodynamic analysis.

The current study focuses on parametric analysis of reheat and regenerative Braysson cycle and optimization of working pressure ratio for dual operating conditions (maximum NDPO (Non-dimensional power output) and minimum SFC). The parametric analysis is related to the study of the effect of free variables like temperature rise in a stage of multistage intercooled compressor, TIT (turbine inlet temperatures), CIT (compressor inlet temperatures), pressure at the exit of reheat turbine and individual component efficiencies on exergy efficiency, taking into account the mass of fuel added in the combustion chamber and reheater.

2. Description of flow diagram

The Fig. 1 shows the flow diagram of Braysson cycle with regeneration and reheating with important components. It consists of a main turbine and a large extra bottoming reheat gas turbine for expanding the gases to vacuum pressure. The gases from the main turbine are reheated to the maximum temperature of the cycle before letting into the reheat turbine. The gases at the outlet of reheat turbine are let into a regenerator and are further cooled in a cooler and passed into the multi-stage intercooled compressor. The