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Thermoeconomic investigation of basic and intercooled gas turbine based power utilities incorporating air-film blade cooling

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A R T I C L E I N F O

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A B S T R A C T

In present work thermoeconomic features of two different gas turbine power utility configurations, namely basic gas turbine cycle (BGT) and intercooled gas turbine cycle (IcGT) are presented and compared thermoeconomically. A computer code has been developed using various models comprises governing equations, in order to obtain the results for particular power utility and operating parameters. The analytical model also contains blade cooling phenomenon, which is described schematically in this paper. Among numerous thermoeconomic methodologies, the average cost theory approach has been adopted for the present investigation. The current work focuses on thermoeconomic comparison of power utilities based on above mentioned cycles. Also, the behavior of cycle performance parameters, with cycle operating parameters (compressor pressure ratio and turbine inlet temperature) of proposed cycle has been reported. Results obtained showed that IcGT based power utility requires 47.34% higher fuel during operation and delivers near about 40% higher plant specific work. The total cost rate of IcGT cycle is slightly higher in the base case parameters (compressor pressure ratio = 36, turbine inlet temperature = 1500 K, isentropic efficiency of compressor = 88% and isentropic efficiency of turbine = 90%) compared to BGT and at the same time it delivers lower electricity cost (2.872 cents/kWh), which is 28% less due to higher plant specific work.

1. Introduction

The increased gap between energy demand and supply has increased the focus on improving thermodynamic efficiency of energy systems at lowest possible cost as well as enhanced environmental performance (Kumari and Sanjay, 2015). The power utility energy systems are subjected to availability of fuel for electricity generation. In recent past, in comparison to coal based power plants, natural gas fired gas turbine based power plants have been the focus of attention for power utility developers due to availability and reduced price of natural gas. Nowadays, during analysis of energy systems, the cost involved and its environmental impacts are as important as its efficiency. The present paper is an attempt to investigate the cost involved in setting up power utilities based on proposed cycles in terms of total cost rate (fuel cost rate + total investment cost rate). In this paper, gas turbine based energy conversion system is considered, as they offer higher thermodynamic performance with low emission compared to coal based power plants. Aydin (Hakan, 2013) has analyzed LM6000 gas turbine power plant on thermodynamic performance basis and reported that exergetic sustainability index is obtained as 0.651 and 0.978 for two investigated cases in the particular article. O. K. Singh and S.C. Kaushik (Singh and Kaushik, 2013) have analyzed the hybrid cycle (Brayton-Rankine and Kalina) and reported that energy efficiency, exergy efficiency, and net power output increased by 0.54%, 0.51% and 1.27% respectively. Pouria Ahmadi et al (Pour et al., 2012). reported the effect of operating parameters on investigated trigeneration cycle and also reported that carbon dioxide emissions for the trigeneration system are less than for the typical combined heat and power systems or gas turbine cycles. Emission model proposed by N.K. Rizk and Mongia is used in the work (Rizk and Mongia, 1993), which reports the effect of mixing and spray evaporation in gas turbine combustor. The work also provides an insight into the regions within the combustor that could be responsible for the excessive formation of NOx, CO (carbon-monoxide) and UHC (unburnt-hydrocarbon). In the present study basic and complex gas turbine is taken into consideration for thermoeconomic investigation. In the power utility eco-system, LMS100 PA

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Nomenclature

A	Air
A_{sg}	Surface area for gas heat transfer
c	Cost per unit of exergy ($/MJ)
$\dot{C}$	Exergetic cost flow rate ($/h)
c_p	Specific heat at constant pressure (kJ/kg K)
$\dot{C}_D$	Cost rate of exergy destruction ($/h)
$\dot{C}_L$	Cost rate of exergy loss ($/h)
$\dot{C}_T$	Total cost flow rate ($/h)
$\dot{C}_F$	Cost rate of fuel exergy ($/h)
$\dot{C}_P$	Cost rate of product exergy ($/h)
$\dot{C}_f$	Cost rate of fuel supply ($/h)
c_f	Cost of fuel supply ($/MJ)
$c_{p,cool}$	Specific heat of coolant stream
E	Exergy per unit mass of gas (kJ/kg)
$\dot{E}$	Exergy flow rate (MW)
$\dot{E}_D$	Exergy destruction rate (MW)
F_{sa}	Correction factor to account actual blade surface
G	Constant in cost equations
h	Specific enthalpy of the stream (kJ/kg)
$\bar{h}$	Convective heat transfer coefficient (W/m^2 K)
LHV	Lower heating value of fuel (MJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
N	Number of hours of plant operation per year
p	Pressure (bar)
p_0	Reference or ambient pressure (bar)
$\dot{Q}$	Heat transfer rate (kW)
r_{pc}	Pressure ratio
R	Gas constant (kJ/kg K)
s	Specific entropy (kJ/kg K)
$S_{g,bl}$	Blade perimeter (m)
St	Average Stanton number
t	Pitch of blade (m)
T_b	Blade material temperature
T_g	Gas temperature
T_0	Reference or ambient temperature (K)
T	Temperature (K)
V	Molar air/fuel ratio
w	Plant specific work (kJ/kg)
x_0	Percentage of excess air
y_D	Exergy destruction ratio (%)
y_L	Exergy loss ratio (%)
Z	Purchase cost associated with the component ($)
$\dot{Z}$	Investment cost flow rate ($/h)
ε_{cool}	Coolant effectiveness
$\eta_{iso,air}$	Isothermal effectiveness of film air cooling method

Greek symbols

γ	Specific heat ratio
θ	Thermodynamic property function
η_{AC}	Compressor isentropic efficiency (%)
η_{CC}	Efficiency of the combustion chamber (%)
η_{GT}	Gas turbine isentropic efficiency (%)
φ	Maintenance factor
f	Exergoeconomic factor
ε	Exergetic efficiency (%)
ζ	Ratio of mass of coolant to mass of gas flow (kg/kg of gas)

Subscripts

0	Reference environment
a	Air
C	Compressor
B	Blade
cool	Coolant
CC	Combustion chamber
D	Destruction
e	Exit
f	Fuel
g	Gas
i	Inlet, stream
j	Coolant stream
k	Component number
L	Loss
mech	Mechanical
net	Net work
Tot	Total
q	Heat
w	Work

Acronyms

BGT	Basic gas turbine
C	Compressor
AFC	Air film cooling
CC	Combustion chamber
CRF	Capital recovery factor
GT	Gas turbine
HPC	Higher pressure compressor
IcGT	Intercooled gas turbine
LPC	Lower pressure compressor
TIT	Turbine inlet temperature

and GT-29 are two such complex gas turbine based utilities manufactured by GE Power and Alstom respectively. LMS100 by GE Power is an intercooled gas turbine based power plant.

The thermoeconomic investigation is based on exergy related cost of each stream, in which the cycle and all its streams are analyzed thermodynamically to obtain the quantum of exergy related to each stream. In the field of thermodynamic analysis of gas turbine, various researchers have reported key findings related to the performance of energy conversion systems. Goktun (Goktun and Yavuz, 1999) have studied the thermal efficiency of regenerative Brayton cycle featuring isothermal heat addition and reported that the application of an isothermal heat addition process in regenerative gas turbine engines may result in significant efficiency improvements of over 10% compared with conventional engines. Sanjay et al (Sanjay et al., 2007). have reported energy and exergy analysis of gas-steam combined cycle and also have concluded that reheat pressure is an important design parameter and its optimum value gives maximum plant efficiency while C.F McDonald and D.G. Wilson (McDonald and Wilson, 1996) have studied the complex gas turbine cycles (recuperated and regenerated gas turbine cycle) and reported the benefits of recuperation and regeneration, also stated that, these engines will be in the mainstream of the 21st century gas-turbine industry. R. Bhargava et al (Bhargava and Peretto, 2002). have reported the thermoeconomic optimization technique for complex gas turbine cycles and analyzed the gas turbine performance on thermodynamic basis. R. Bhargava et al (Bhargava