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Research paper

Analysis of Maisotsenko open gas turbine bottoming cycle

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HIGHLIGHTS

- Developed an accurate air saturator model.
- Introduced Maisotsenko bottoming cycle (MBC) as a power generation cycle.
- Performed Thermodynamic optimization for MBC and air bottoming cycle (ABC).
- Performed detailed sensitivity analysis for MBC under different operating conditions.
- MBC has higher efficiency and specific net work output as compared to ABC.

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ABSTRACT

Maisotsenko gas turbine cycle (MGTC) is a recently proposed humid air turbine cycle. An air saturator is employed for air heating and humidification purposes in MGTC. In this paper, MGTC is integrated as the bottoming cycle to a topping simple gas turbine as Maisotsenko bottoming cycle (MBC). A thermodynamic optimization is performed to illustrate the advantages and disadvantages of MBC as compared with air bottoming cycle (ABC). Furthermore, detailed sensitivity analysis is reported to present the effect of different operating parameters on the proposed configurations' performance. Efficiency enhancement of 3.7% is reported which results in more than 2600 tonne of natural gas fuel savings per year.

1. Introduction

Electricity has an essential role in our daily life. However, with ever increasing cost of fossil fuels and natural gases, improved power generation with higher efficiency and lower capital cost is of high demand. Conventional combined cycles which include a gas turbine topping cycle and a steam turbine bottoming cycle is the most efficient combined power plant system. Nevertheless, it is not the most economically justified cycle for smaller scale power plants because of the presence of the condenser and the heat recovery steam generator (HRSG) in its bottoming cycle. It is reported that conventional combined power cycles are not the most economical alternative for power plants with 50 MWe or lower capacities [1].

There have been many suggestions for steam bottoming cycle replacement. Organic Rankine cycle is one of the most promising options to be employed as the bottoming cycle because of its low operating temperature [2]. Several studies were carried out to investigate the possibility of integrating an organic bottoming cycle [3–7]. Another recently proposed bottoming cycle is the integration of an air turbine cycle which is referred to as the air bottoming cycle (ABC). There are several ongoing investigations evaluating the ABC power plant configuration [8–20]. In general, ABC has low capital cost and short start up time [21]; nonetheless, its relatively high operating temperature does not suit to be utilized as a bottoming cycle. Due to its high operating temperature, ABC cannot fully recover the waste heat available in the flue gases of the topping cycle. In order to enhance the heat recovery capability of ABC, steam and water injection was proposed by Ghazikhani et al. [22]. Water and steam injection result in specific work and efficiency enhancements [23–25] which indicate humid air turbines with matching capacity would be utilized as the bottoming cycle.

Maisotsenko gas turbine cycle (MGTC) is a recently proposed humid air turbine cycle that is primarily suggested by many investigators [23,26–28]. A research and development firm located in based in Arvada, Colorado developed a new power generation cycle which includes humid gas turbines [29–31]. An air saturator is utilized in MGTC which properly recovers the waste heat of the turbine exhaust gases by air heating and humidifying processes. Air saturators can be used in combined power plants bottoming cycle for heat recovery purposes. Thus, MGTC is an appealing innovative

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Nomenclature

Symbols

E	Air saturator effectiveness [−]
LHV	Fuel lower heating value [kJ/kg]
T	Temperature [K]
P	Pressure [kPa]
$\dot{W}$	Power [MWe]
h	Specific enthalpy [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
$\dot{n}$	Number of mole [−]
w	Specific work [kJ/kg]
x	Mole fraction [−]
η	Efficiency [−]

Abbreviations

ABC	Air bottoming cycle
ASDH	Air saturator degree of humidification
BCPR	Bottoming cycle pressure ratio
CEPCI	Chemical engineering plant cost index
HRSG	Heat recovery steam generator
LMTD	Log mean temperature difference
MBC	Maisotsenko bottoming cycle
MFRR	Mass flow rate ratio
MGTC	Maisotsenko gas turbine cycle
TCPR	Topping cycle pressure ratio
TIT	Turbine inlet temperature

Subscripts

B	Bottoming cycle
T	Topping cycle
a	Air
c	Compressor
da	Dry air
dew	Dew point temperature
f	Fuel
g	Gas
ha	Humid air
i	Mixture property at state i
net	Net
p	Pump
t	Turbine
sat	Saturated
w	Water
wbt	Wet bulb temperature
w_{inL}	Lower air saturator water inlet
w_{inU}	Upper air saturator water inlet
w_{inU_m}	Upper air saturator maximum water inlet

alternative for bottoming cycle implementation because of its ability to humidify the compressed air. In this paper, the integration of a topping gas turbine with a bottoming MGTC is referred as Maisotsenko bottoming cycle (MBC). In principle, humid air has higher heat capacity and mass which makes it to be an appealing alternative working fluid for heat recovery processes. In steam injected ABC configuration proposed by Ghazikhani et al. [22], a Heat Recovery Steam Generator (HRSG) along with a heat exchanger and a humidifier are used to accomplish air heating and humidifying processes in the bottoming cycle. Nonetheless, MBC combines HRSG, heat exchanger and humidifier is integrated into one component called the air saturator. Consequently, the capital investment cost of that option is reduced significantly as compared to HRSG. In addition, level of air humidification can be controlled by the amount of water added to the air saturator. Moreover, MGTC developers claim that the cycle does not suffer at part load because of its ability to constantly add moisture to air [28].

At the time of writing the paper, the number of published studies investigating MGTC is very limited. Energy and exergy analysis of MGTC was performed by Alsharif et al. [27] to investigate the importance of using an air saturator in MGTC. Additionally, the paper studied the effect of integrating a Maisotsenko cooler at compressor inlet for air cooling purposes and reported the significant improvement achieved by its integration. Authors of the last study concluded also that MGTC has a satisfactory flexibility to adopt the variations of ambient conditions. Based on our knowledge, there is no available published research in the literature investigating the implementation of MGTC as the bottoming cycle and this concept is mainly introduced in this paper for the first time.

As a result of the great interest in power plant technologies, this paper introduces a new concept in gas turbine power plants by investigating the employment of MGTC as the bottoming cycle. Furthermore, the effects of bottoming cycle mass flow rate, topping cycle turbine inlet temperature (TIT), topping cycle pressure ratio (TCPR) and bottoming cycle pressure ratio (BCPR) on the overall gas power plant efficiency and specific work output are investigated. Another important factor in assessing the performance of the power plant is the level of the humidification process inside the air saturator which is of important interest to be studied. Finally, a detailed thermodynamic optimization is carried out to compare the performance of MBC with ABC at their respective optimum operating conditions with identical integrated topping cycle.

2. MBC configuration

Maisotsenko bottoming cycle consists of a topping gas turbine and a bottoming MGTC. Fig. 1 illustrates the MBC's schematic layout whereas Fig. 2 presents the T-s diagram of the gas turbine-Maisotsenko bottoming cycle. As indicated in Figs. 1 and 2, the ambient air is drawn into the topping cycle compressor (1) from the surroundings in which it is compressed adiabatically (1–2). After compression, air flows into the combustion chamber in which it mixes with fuel and heat is liberated in an isobaric process (2–3). In the last step of the topping cycle, flue gases leaving the combustion chamber are expanded adiabatically in a gas turbine to produce mechanical work (3–4) which in turn is converted into electricity in the generator. Exhaust gases from the turbine go through the air saturator where they are cooled down to the wet bulb temperature of the bottoming cycle air (4–5).

In the bottoming cycle, ambient air is drawn into the compressor (6) and is then compressed adiabatically (6–7). After the compression, the compressed air enters the air saturator where it is heated and humidified by the exhaust gases from the topping cycle gas turbine (7–11). In principle, air saturator utilizes the waste heat available in the topping cycle gas turbine exhaust gases to increase the air wet bulb temperature. Fig. 3 is presented to better understand the air saturator's principle of operation. In this basic operation, the compressed air is divided into three streams in the lower section of the air saturator. These streams are cooled down sensibly to their dew point temperatures by indirect evaporation of water (7–8). Two of these streams mix together while the third stream is fed backward to the lower section of the air