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Part-load performance modelling of a reheated humid air turbine power cycle

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HIGHLIGHTS

- A novel method for the part-load performance simulation of a reheated HAT system is described.
- Predicted performance is shown across a range of turbine inlet temperatures settings.
- The impact of sea water and ambient air temperature on the performance of the cycle is evaluated.

ARTICLE INFO

Keywords:
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ABSTRACT

Humid air turbines have previously demonstrated the potential to deliver high efficiency and power output combined with low emissions. This paper investigates the part-load performance of a 40 MW class advanced humid air turbine for power generation applications across a range of operating conditions. The paper investigates the impact of the main burner and reheater burner on the system's part-load power output and thermal efficiency and provides insights into the behavior of the key modules across the power spectrum of operation including the saturator tower which was never reported previously. The impact of the ambient air and sea water temperature on the cycle's performance are also investigated. The outcome of the research shows that the thermal efficiency if the system is less than 0.26% penalized when operating down to 50% of the design power output. Sea water temperature was found to have a more notable impact than ambient air temperature on both power output and thermal efficiency Overall, this work constitutes a step ahead in understanding the potential benefits of an advanced humid air turbine system for power generation applications across a range of operating conditions which is not previously shown.

1. Introduction

Humid air turbine (HAT) systems are among the most efficient gas turbine based thermal cycles as highlighted by Jonsson and Yan in [1]. Previous studies (Rao et al. [2], Chiesa et al. [3], Jonsson and Yan [4]) have demonstrated effective utilization of low-quality waste heat within these cycles and the high thermal efficiency these systems can achieve. Chiesa et al. [3] performed a comparison between a number of humid cycles whereby HAT was identified as the most efficient, with a maximum thermal efficiency of 54%. Jonsson and Yan [5] and Traverso et al. [6] presented detailed techno-economic studies that showed that HAT cycles can offer lower investment cost and higher thermal efficiencies than combined gas turbine cycles (CCGT). Ågren and Westermark [7,8] introduced the concept of saturator by-pass while Jonsson and Yan [5] proved that this would not only increase the efficiency of the cycles for high pressure ratios but also reduce the specific investment cost of the whole system. Among others, Kavanagh and Parks ([9,10]), Moller et al. [11] and Nyberg et al. [12] studied the impact of each heat exchanger on the efficiency of the cycle. The influence of the ambient temperature on the off-design performance of the cycle was studied by Wang et al. [13] and Kim et al. [14] concluding that the cycle is less sensitive to ambient temperature variations than simple gas turbine cycles. Both works investigated the impact of the ambient temperature but since a closed water loop was assumed the impact of the water temperature was never considered. Wei et al. [15] conducted an experimental investigation on the off-design performance of a small-sized HAT cycle to conclude that the thermal efficiency increased by 3.1% compared to a simple cycle configuration. Takahashi [16] investigated the part-load performance of an advanced humid air turbine (AHAT) and the impact of ambient temperature. The off-design performance of the saturator tower was previously studied experimentally by Pedemonte et al. [17,18], whereas a methodology for the

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Nomenclature

Symbols

C	heat capacity (kJ/K)
C^*	heat capacity ratio (-)
kxA	overall heat transfer coefficient x heat transfer area (Inverse of total resistance) (kW/K)
M	mass flow rate (kg/s)
P	pressure (MPa)
$\hat{P}$	power output (MW)
Q	heat transfer (MW)
R_a	specific gas constant of dry air (J/(kg K))
R_v	specific gas constant of dry vapor (J/(kg K))
T	temperature (K)

Abbreviations

AC	aftercooler
CC	combustion chamber
CCGTs	combined cycle gas turbines
CHAT	cascade humidified advanced turbine
EC	economizer
EvGT	evaporative gas turbine
HAT	humid air turbine
HPC	high-pressure compressor
HPT	high-pressure turbine
IC	intercooler
LPC	low-pressure compressor
LPT	low-pressure turbine
OPR	overall pressure ratio
pp	percentage point
PR	pressure ratio
PT	power turbine
REC	recuperator
RH	reheater
relPR	relative pressure ratio
SAT	saturator
TIT	turbine inlet temperature
vIGV	variable inlet guide vanes

Subscripts

a	dry air
g	gas
in	inlet
2	top section of the saturator
sat	saturation
w	water

Greek Symbols

β	saturator by-pass
ε	effectiveness
ω	absolute humidity
Φ	relative humidity

simulation of the saturator tower was developed by Aramayo-Prudencio et al. [19]. Brighenti et al. [20] studied the design point performance of a reheated humid air turbine cycle and the impact of the technology of selected components on the preliminary acquisition cost of the heat exchanger units. As Chiesa et al. [3] highlighted, such a cycle features notably better performance relatively to a single burner system that may promote the exploitation of humid cycle power plants in applications where high thermal efficiency and high power-to-plant size rations are of importance.

A potential application for a reheated HAT system may be within the power generation or the marine propulsion markets. The high thermal efficiency and low NO_x and SO_x emissions [22] could potentially make such power plants attractive in view of future marine emission regulation [23]. Nevertheless, the part-load performance of open water loop HAT systems remains still unexplored. This paper presents a methodology for the modelling and simulation of the steady state part-load performance of a 40 MW reheated HAT cycle across a range of operating conditions. The impact of the outlet temperature of both combustion chambers on the power output and thermal efficiency of the cycle is examined. The impact of ambient air and water temperature on the cycle performance is also presented.

2. Methodology

2.1. Cycle description

Fig. 1 shows the reheated HAT cycle layout analyzed herein comprising a dual-shaft, and free power turbine gas-turbine arrangement. The cycle features a reheater combustion chamber upstream of the power turbine. A detailed description of the power system is presented by Brighenti et al. in [20]. In this study, an open water loop is used to supply the heat exchangers. The evaporation process in the saturator and an efficient droplet eliminator at the gas outlet of the saturator acts as a water-treatment device, enabling the use of direct sea water [24]. The cycle design is a result of the optimization of the design parameters for maximum thermal efficiency as shown by Brighenti et al. [20]. No mechanical or heat losses are considered. The cycle design parameters is reported in Table 1.

To capture future trends in recuperator and air/water heat exchanger design and exploit the full thermal efficiency potential of the RHAT cycle, 90% recuperator effectiveness was assumed for this study while an effectiveness of 95% was assumed for all air/water heat exchangers. The assumed effectiveness level for the recuperator and the air/water heat exchangers is slightly higher than the current standards and as such larger units in size will be required with knock-on effects in the overall system's volume, weight and cost. The impact of the effectiveness (defined as $\varepsilon = Q/Q_{max}$) of the recuperator and air/water heat exchangers on the acquisition cost, weight and performance of the cycle layout at design point has been previously analyzed by Brighenti et al. in [20]. For the current study, the assumed heat exchanger effectiveness levels are considered to be representative of near future trends and are educated by the effectiveness levels of the WR21 heat exchangers previously reported by Crisalli and Parker in [21].

Marine diesel fuel proprieties were used for combustion calculations [25]. Turbine cooling flows are calculated using the methodology proposed by Young and Wilcock [26]. Typical values for maximum metal temperature ($T_{m,max}$ = 1300 K), film cooling effectiveness

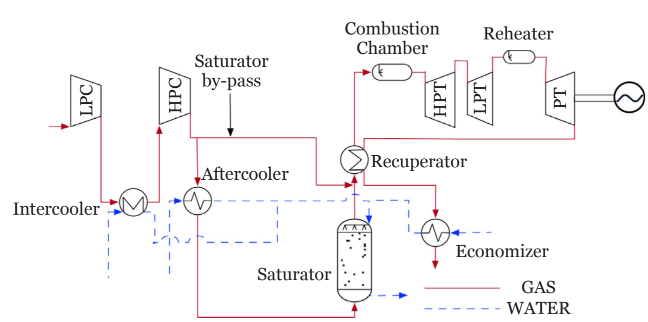

Fig. 1. Reheated HAT system layout.