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Research Paper

Techno-economic analysis of a reheated humid air turbine

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HIGHLIGHTS

- Economiser and recuperator dictate the economic metrics of a reheated humid air turbine system.
- Fuel and equipment purchase cost drive the average cost of the power produced by the system.
- Humid air turbine shows 14% higher thermal efficiency than a typical combined gas-steam plant.
- Humid air turbine show roughly 62% lower total purchasing cost than a combined gas-steam plant.

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ABSTRACT

The purpose of this paper is to identify the economic potential of a reheated humid air turbine system for power generation applications. A parametric analysis is performed to correlate the technology level of the system with the required cost of the electricity for economic viability. The effect of fluctuations of the main cost drivers is evaluated via an uncertainty analysis. The performance of the studied reheated humid air turbine is compared against previously studied humid configurations and well established gas-steam combined cycles. The fuel cost is found to be driving the cost of electricity. The uncertainty analysis also shows the dependency of the optimum cycle design parameters upon the market prices. The analysis reveals the capability of the reheated humid air turbine to be an economically viable option for the power generation sector featuring an estimated cost of electricity 2.2% lower than simpler humid cycles, and 28% lower than established combined cycles currently in service. The outcome of the work constitutes a step forward in the understanding of the economic performance of advanced complex cycles and proves the potential of such systems for applications where high efficiency and economic performance is jointly required.

1. Introduction

Over the past decades, thermal efficiency enhancements in gas turbine systems have been a key driver in the development of advanced power plant configurations. Advanced gas turbine configurations previously studied include steam injection, triple-pressure combined cycles, and humid air turbines [1–5]. Although combined gas-steam cycles are currently an established option in terms of thermal efficiency, several studies have postulated that humid air systems could also be attractive in the small to medium-size power generation market [5–10].

Humid Air Turbines (HAT) or Evaporative Gas Turbines (EvGT) were initially introduced by Rao in the late 80's [11]. Jonsson and Yan [9] performed a techno-economic comparison between HATs and combined cycles. This study proved the capability of the HATs to achieve a similar cost of electricity with a lower specific investment cost. Subsequent cost studies performed by Traverso and Massardo [12], and Kavanagh and Parks [10] showed that HATs are capable to achieve a lower cost of electricity that Combined Cycle Gas Turbines (CCGT), demonstrating the techno-economic potential of this advance cycle for the power generation market. The ability of the HAT systems to recuperate a notable part of the waste heat back into the cycle without the need of a bottoming cycle is the main driver of the observed competence against the CCGTs.

Pedemonte et al. [13,14] experimentally analysed the off-design performance of the air saturator. Wang et al. [15] and Kim et al. [7] studied the effect of the ambient conditions on the performance of the HAT. In both works, it was proved that as the ambient temperature increases the performance of the HAT is less penalised than the 'dry' gas turbines or the CCGTs. During warm days, the humid cycle is capable to evaporate a larger amount of water compensating the negative effect of a poorer compressor performance. In addition, Takashi et al. [16] concluded that humid air turbines show a better efficiency than CCGTs during part-load performance across a similar range of operation. In terms of emissions, Yagi et al. [17] reported that HAT NO_x emissions

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Nomenclature

Symbols

C_x	[J/K] Heat capacity
C^*	[-] heat capacity ratio
c_p	[J/kg K] specific heat capacity
COE	[$/kW h] cost of electricity
$\overline{COE}$	[$/kW h] average cost of electricity
H^+	[J/kg] enthalpy invariant
h	[J/kg] specific enthalpy
h_{fg}	[J/K] specific enthalpy of evaporation
M^+	[-] mass invariant
$\dot{m}$	[kg/s] mass flow
n	[years] years of life of the power plant
p	[Pa] pressure
p_{sat}	[Pa] saturation pressure
PEC	[$] purchase equipment cost
$\dot{Q}$	[W] heat rate
R_x	[J/kg K] specific gas constant
$SPEC$	[$/kW] specific purchase equipment cost
ΔT_{sp}	[K] saturator pinch point temperature difference
T	[K] temperature
t	[hours/year] hours of operation per year
T_{dew}	[K] wet bulb temperature
T_{sat}	[K] saturation temperature
$\dot{W}$	[W] plant power output

Abbreviations

AC	aftercooler
AE	annual expenses
CEPCI	chemical engineering plant cost index
DC	direct costs
EC	economiser
EvGT	evaporative gas turbine
FCI	fixed capital investment
HAT	humid air turbine
IC	intercooler
Int	interests
LNG	liquid natural gas
O&M	operation and maintenance
PFI	plant fixed investment
RC	recuperator
RHAT	reheated humid air turbine
SAT	saturator
TCI	Total Cost of Investment

Subscripts

a	dry air
$comb$	combustor
$comp$	compressor
fin	financing
g	humid air
gen	generator
HX	heat exchangers
i	operational year
in	inlet
ini	initial
max	maximum
min	minimum
out	outlet
v	vapour
w	water

Greek Symbols

η_{th}	thermal efficiency
ε	effectiveness
Ξ	[$] cost
ϕ	relative humidity
ω	water to air ratio

can be as low as roughly 10 ppm due to the high content of water within in the combustion chamber. Moreover, HAT systems are more compact power-units compared with 'dry' gas turbine packages and CCGT and present faster start-up times.

Although previous studies have focused on the performance capabilities of HAT systems, little effort has been invested to understand the full techno-economic potential of this cycle. Chiesa et al. [18] suggested that the addition of a reheater in the gas turbine would augment the thermal efficiency and specific work of the power plant. A reheated HAT system was previously studied by Brighenti et al. [19]. This work confirmed the potential of the reheated HAT configuration to achieve thermal efficiencies beyond the threshold of 60%. Nevertheless, no economic study of the reheated HAT system has been presented so far to identify the economic viability of such a system.

This paper presents a techno-economic analysis of a 40 MW class reheated humid air turbine power plant for power generation. A parametric design space exploration is performed to demonstrate the impact of the heat exchanger technology level on the economic metrics. An uncertainty analysis showing the impact of the main cost driver fluctuations on the cost of the electricity is also included. Finally, the economic performance of the investigated cycle is benchmarked against the performance achieved by high efficiency humid and combined cycle systems previously presented.

2. Methodology

2.1. Cycle configuration and modelling approach

The Reheated Humid Air Turbine (RHAT) analysed in this study, shown in Fig. 1, is based on the configuration previously presented by Brighenti et al. [19]. The cycle layout includes an aftercooler to augment the saturator performance as proposed by Thern et al. [20], an

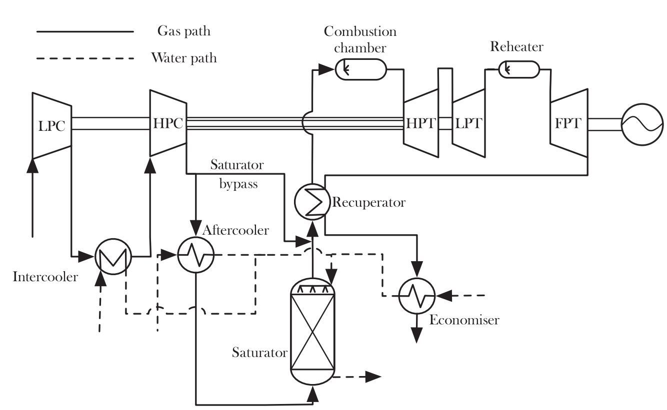

Fig. 1. Reheated humid air turbine system cycle layout.