Applied Energy 89 (2012) 315–321

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Thermodynamic studies of a HAT cycle and its components

Björn Nyberg *, Marcus Thern

Division of Thermal Power Engineering, Department of Energy Sciences, Lund University, Lund, Sweden

ARTICLE INFO

Article history:
Received 6 April 2011
Received in revised form 8 July 2011
Accepted 20 July 2011
Available online 8 September 2011

Keywords:
Humid Air Turbine
EvGT
Intercooler
Turbine cooling
Makeup water
Cycle analyzis
Cycle performance

ABSTRACT

The electric power grid contains more and more renewable power production such as wind and solar power. The use of renewable power sources increases the fluctuations in the power grid which increase the demand for highly efficient, fast-starting power-producing units that can cope with sudden production losses. One of the more innovative power plant cycles, that have the potential of competing with conventional combined power plants in efficiency but has a higher availability and faster start up time, is the Evaporative Gas Turbine (EvGT) or Humid Air Turbine (HAT). A thermodynamic evaluation of different HAT cycle layouts has been done in this paper. Each layout is evaluated separately which makes it possible to study different components individual contribution to the efficiency and specific power. The thermodynamic evaluation also shows that it is important to look at different cool-flow extracting positions. The effect of water temperature entering the cycle, called make-up water, and where it is introduced into the cycle has been evaluated. The make-up water temperature also affects the optimal pressure level for intercooling and it is shown that an optimal position can be decided considering design parameters of the compressor and the water circuit.

1. Introduction

Advanced gas turbine cycles receive increasing attention due to their high potential, flexibility, low investment costs and low emissions. The Humid Air Turbine, HAT or Evaporative Gas Turbine (EvGT), is an advanced gas turbine cycle that uses water to increase the performance.

The HAT thermodynamic cycle has been investigated by numerous researchers and experimentally investigated by Lindquist et al. [1] and Thern [2] in Lund and also by Hatamiya et al. [3], Araki et al. [4], Higuchi et al. [5], and Araki et al. [6]. Jonsson and Yan [7] present a detailed literature review of humidified cycles and show the potential of this cycle. Gallo [8], Kavanagh et al. [9] and Lindquist [10] presents performance of the complete HAT cycle, consisting of an intercooler, aftercooler, recuperator and economizer, where they vary the pressure ratio and turbine inlet temperatures.

The layout of the HAT cycle makes it possible to extract cooling flows at different locations. Gallo et al. [11] shows that the cooling flows for the turbine should come from a location after the humidification tower, where the air is humidified. Jordal et al. [12] agrees with these findings although Jordal does not investigate an extraction point just after the aftercooler. Cleeton et al. [13] disagrees with Jordal and Gallo and points out that the original position at the end of the compressor is the best position to extract cooling flows due to lower compression work.

The HAT cycle requires make-up water to maintain the mass balance of the system. This water is often colder than the rest of the system and it is therefore important to investigate, where to inject the make-up water. Rao Ashok Domalpalli [14] suggests, in his patent from 1989, that make-up water should be injected directly to the intercooler. This is how Traverso and Massardo [15], Parente et al. [16], Yan et al. [17] and Rosen et al. [18] do. Lindquist [10], Gallo [8] and Kavanagh [19,13] inject makeup water to both the intercooler and the aftercooler, whereas Lazzaretto [20,21] inject solely to the aftercooler. Although different injection points are used no investigation of the effect is presented.

The literature study shows that there are differences between the conclusions drawn by different researchers. The objective of this study is therefore to perform a comparative study, where the performance of different heat exchanger configurations, of the HAT cycle, is evaluated. To get comparative results the theoretical model of the HAT cycle use the same prerequisites, which has been validated with measurements from the Evaporative Gas Turbine (EvGT) pilot plant in Lund.

This paper also shows how the cooling-flow extraction-point affect the demand of cooling air and relate these results to the results obtained by, Jordal, Gallo and Kavanagh. The work discusses the location of makeup water injection point and how it, together with

Abbreviations: LHV, low heating value; COT, combustor outlet temperature; HAT, Humid Air Turbine; ECO, economizer; AC, aftercooler; IC, intercooler.

* Corresponding author. Tel.: +46 46 222 48 62.
E-mail addresses: bjorn.nyberg@energy.lth.se (B. Nyberg), marcus.thern@energy.lth.se (M. Thern).

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doi:10.1016/j.apenergy.2011.07.036

Nomenclature

T	temperature	*pol*	polytropic
P	pressure	*m*	mechanical
Δp	pressure drop	*comb*	combustor
η	efficiency	*cool*	cooling
β	pressure ratio	*air*	air
$\dot{m}$	mass flow	*gas*	exhaust gases
pp	pinch point	*water*	water
δt	minimum temperature difference	*evap*	evaporation
ω	humidification tower performance as water mass fraction in dry air	*min*	minimum
ΔT	temperature difference	*max*	maximum
κ	isentropic coefficient	*el*	electrical

Subscripts

amb	ambient
inlet	from ambient to compressor inlet

the intercooler, changes the performance of the HAT cycle. This result also suggests another intercooler pressure level than the one presented by Lindquist [10] and Kavanagh [19].

2. Method

The calculations in this paper has been performed in the program IPSEpro. IPSEpro is a simulating software developed by SimTech Technology. The program is constructed as a matrix solver connected to a graphical user interface. The governing equations representing models in IPSEpro is fully editable. This makes it possible to have full access to the equations describing the process and it thus prevents any black box scenarios during simulation. IPSEpro uses JANAF thermochemical tables [22] for calculating ideal gas properties and IAPWS IF97 [23] for calculating water and steam properties. The components used in the models for this paper are constructed by the authors and faculty members at the department [24] and has been validated through experiments [10,2].

Assumptions and limitation in this paper to keep in mind when reading the results should be mentioned. The gases that are used in this paper are considered to be ideal. Due to the low pressures used this is a good assumption. The humidification tower component, used in the models assumes that the outlet air stream is completely saturated with water, as showed in previous works [2,25,4]. There are no consideration to material behavior with temperature. This should be thought of when using cold air for cooling the turbine blades and at the high temperature recuperator hot gas inlet. The technical challenge of extracting cooling flows from a position other than the compressor is not evaluated or considered. The size of the heat exchangers are not calculated neither the economical costs and the make-up water has no limitation according to mass flow.

2.1. Modeling

The purpose of the modeling is to create performance maps of the HAT cycle at different configurations. This is done to understand the contribution from each of the components that defines a HAT cycle. The performance map shows the design point performance at varying conditions, e.g. firing temperature and compression ratio. To create such map the model components are described with design parameters and not geometries.

The complete HAT cycle in this work consists of four heat exchangers. Three of which are counter current gas to water exchangers and one is a counter current gas to gas exchanger. The water exchangers are modeled with a fixed pinch-point between the inlet cold water and the outlet hot gas. There is also a minimum difference between the water outlet temperature and the inlet gas temperature. To prevent evaporation of water in the heat exchangers a maximum water temperature is fixed relative to the present pressure. Pressure drop due to fluid friction for the through-flowing fluids are considered.

For the gas to gas exchanger, also referred to as the recuperator, a difference between the hot inlet temperature and the cold outlet temperature is fixed. There is also a pressure drop due to fluid friction for both gases.

A humidification tower is used to humidify the air in the HAT cycle. The humidification tower component in this work is modeled assuming that the air stream is fully saturated at the outlet, and that the gradient of the saturation curve equals the slope of the humidification tower working line at the narrowest section between the two, see Fig. 6. Note that this is not true if the pinch-point occurs at the bottom of the tower.

The water that flows through the tower experience a pressure drop as it is sprayed through a nozzle in the top. This pressure drop

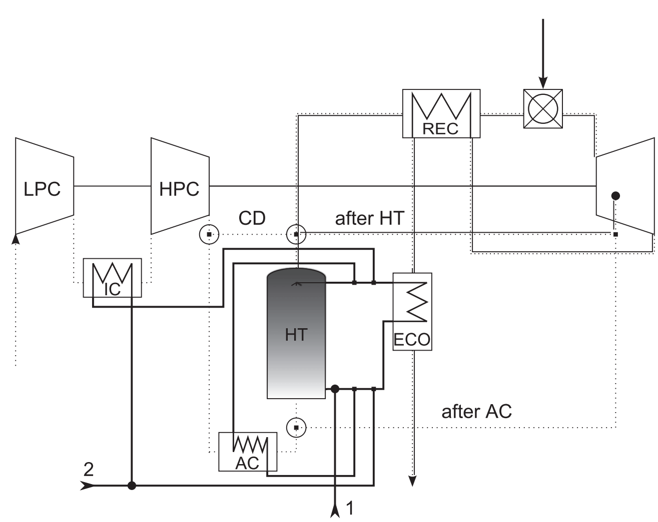

Fig. 1. Layout of a complete humid air turbine cycle. The dotted lines represents air, the solid lines water, fuel or shafts and the both dotted and solid represents humid air. The three cool flow points that has been simulated in this paper are marked. The two makeup water injection points used in the simulations are also shown as 1 and 2.