



# Exergetic comparison of two different cooling technologies for the power cycle of a thermal power plant

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## ABSTRACT

Exergetic analysis is without any doubt a powerful tool for developing, evaluating and improving an energy conversion system. In the present paper, two different cooling technologies for the power cycle of a 50 MWe solar thermal power plant are compared from the exergetic viewpoint. The Rankine cycle design is a conventional, single reheat design with five closed and one open extraction feedwater heaters. The software package GateCycle is used for the thermodynamic simulation of the Rankine cycle model. The first design configuration uses a cooling tower while the second configuration uses an air cooled condenser. With this exergy analysis we identify the location, magnitude and the sources or thermodynamic inefficiencies in this thermal system. This information is very useful for improving the overall efficiency of the power system and for comparing the performance of both technologies.

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## 1. Introduction

As interest for clean renewable electric power technologies grows, a number of parabolic trough power plants of various configurations are being considered for deployment around the globe. The first parabolic trough power plant in Europe, Andasol-1, in southern Spain, went into operation in November 2008 and Andasol-2 and Andasol-3 are currently under construction.

Each Andasol power plant consists of a solar field, a thermal storage tank and a conventional power plant section. The power cycle used in the Andasol plants is a traditional Rankine cycle. Induced draft cooling towers are used as condenser cooling technology. The principal heat transfer process in a wet cooling tower is evaporation. As a result, approximately 1 kg of water must be evaporated for each kilogram of steam condensed. Therefore water consumption can be significant. For example: an 80 MWe parabolic trough solar plant, operating with a capacity factor of 27%, will consume about 725 tons of water per year [1]. For sites which have a limited supply of water, water consumption adversely impacts the operating costs of the plant.

There are alternative means for condensing steam that do not require makeup water. An A-frame air cooled condenser, for example, condenses steam through several finned tubes with forced air convection on the outer surfaces of the tubes. The primary advantage of air cooled condensing is the elimination of water consumption for cooling water makeup. Another advantage is the elimination of the cooling tower plume. Elimination of the cooling tower plume presents a unique benefit at solar thermal power plants, as condensation from the cooling tower plume can reduce the optical efficiency of the solar collector mirrors closest to the cooling tower. The primary disadvantage of air cooled condensing is that heat transfer by forced air convection is a less effective heat transfer process than evaporative heat transfer. Therefore larger heat exchanger areas and greater fan power will be required to achieve heat rejection from the cycle comparable to the design state.

The thermodynamic inefficiencies associated with an energy conversion system are assessed with the aid of an exergy analysis conducted at the component level [2,3]. The exergy analysis reveals two things: the destruction of exergy within a system component, and the exergetic efficiency, which in turn shows how effectively the exergetic resources supplied to a component have been used.

Several previous exergy studies have evaluated the performance of thermal power plants. Sengupta et al. [4] conducted an exergy analysis of a 210 thermal power plant. Habib and Zubair [5] performed a second law analysis of regenerative Rankine power plants

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Nomenclature		L	loss
$\dot{E}$	exergy flow rate [kW]	0	environment
$\dot{m}$	mass flow rate [kg/s]	<i>Superscripts</i>	
$p$	pressure [bar]	CH	chemical
$T$	temperature [°C]	PH	physical
$\dot{W}$	electric power [MW]	TOT	total
$y$	exergy destruction ratio [%]	<i>Abbreviations</i>	
<i>Greek letters</i>		ACC	air cooled condenser
$\varepsilon$	exergetic efficiency	CND	condenser
$\eta$	energetic efficiency [%]	CT	cooling tower
<i>Subscripts</i>		DA	deaerator
D	destruction	ECON	preheater
F	fuel	EVAP	steam generator
$j$	$j$ th stream	FWHT	feedwater heater
$k$	$k$ th component	HTF	heat transfer fluid
P	product	SPHT	superheater
		ST	steam turbine

with reheating. Dincer and Muslim [6] conducted a thermodynamic analysis of reheat cycle power plants. Tsatsaronis and Winhold [7] presented a formulation on exergoeconomic analysis and evaluation of energy conversion plants applied to a Coal-Fired Steam Power Plant. In Ref. [8] exergetic and thermoeconomic analyses for a 500-MW combined cycle plant were performed. More recently, Aljundi [9] presented an energy and exergy analysis of a steam power plant in Jordan. Related to solar thermal power plants, Singh et al [10] presented a second law analysis based on an exergy concept for a solar thermal power system. Singh et al evaluated the respective losses as well as exergetic efficiency for typical solar thermal power systems under given operating conditions. They found that the main energy loss takes place in the condenser of the heat engine, and their exergy analysis shows that the collector–receiver assembly is the part where the losses are maximum. Gupta and Kaushik [11] carried out the energy and exergy analysis for the different components of a proposed conceptual direct steam generation solar thermal power plant. In Ref. [12], a 35 MW solar thermal power plant was analyzed with the aid of exergoeconomics.

This paper deals with the comparison of wet and dry cooling technologies for the power cycle of Andasol-1 by means of exergy analysis. The solar field is not considered in the study. Through an exergy analysis, the real thermodynamic inefficiencies (exergy destruction and exergy loss) of the power cycle are identified. This information, which cannot be provided by other means (e.g. an energy analysis), is very useful for improving the overall efficiency of the power system or for comparing the performance of both cooling technologies. The results obtained here are expected to provide information that will assist in decision-making regarding alternative cooling technologies.

## 2. Description of the plant

The power plant has a net power capacity of 50 MWe. The cycle is a conventional, single reheat design with five closed and one open extraction feedwater heaters. The GateCycle flow diagram is shown in Fig. 1.

In direct operation mode, a heat transfer fluid (HTF, Therminol-VP1) is circulated through the solar field to the steam generation system, where steam is produced at a temperature of 373 °C and at a pressure of 100 bar. The HTF fluid acts as the heat transfer medium between the solar field and the power block; it is heated up in the solar collectors and cooled down while producing steam

in the steam generator. The steam generation system consists of two parallel heat exchanger trains (preheater (ECON1)/steam generator (EVAP1)/superheater (SPHT1)) and two reheaters (SPHT2), again connected in parallel. The superheated steam travels first through the high pressure turbine (ST1), where it expands and propels the turbine blades. One extraction is taken from the high pressure turbine to preheat feedwater in one closed feedwater heater (FWH5). On exiting the high pressure turbine, the steam is directed through a reheater, where it is superheated to approximately the same temperature reached at the outlet of the superheater (373 °C) and at a pressure of about 16.5 bar. The superheated steam then passes through the low pressure steam (ST2–3), where again the steam expands and propels the turbine blades. Five steam extractions are taken from the low pressure turbine: one is directed to the deaerator (DA1) and the remaining four are fed to feedwater heaters (FWH1–4). The steam leaving the low pressure turbine, at 0.063 bar, is condensed in a surface condenser by heat exchange with circulating water. The condenser water is cooled using an induced draft cooling tower. The condensed steam (feedwater) is pumped to a sufficiently high pressure (8.38 bar) to allow it to pass through the three low pressure feedwater heaters and into the deaerator. The feedwater is pumped again at the outlet of the deaerator to a pressure slightly higher than the boiling pressure in the steam generator (103 bar). Feedwater passes through the two high pressure feedwater heaters before returning to the preheater to complete the cycle.

## 3. Thermodynamic evaluation

### 3.1. Simulation and modelling

The software package GateCycle 5.61 [13] was used for the thermodynamic simulation of the Rankine Cycle. Table 1 gives an overview on the main parameters and assumptions used in the thermodynamic simulation. Main plant operation data (detailed in Section 2) were fed to the software as input variables. The results of the simulation were compared and validated using simultaneously plant operation data and EES Thermodynamic software [14].

The thermodynamic properties were calculated based on: IAPWS IF97 Steam Tables [15] for water, JANAF Tables [16] for ambient air and NIST Tables [17] for Therminol-VP1 streams.

The power cycle is modelled assuming that all components are adiabatic, except the steam generator system, and operating at

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