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Cooling limitations in power plants: Optimal multiperiod design of natural draft cooling towers

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ABSTRACT

In this work we evaluate the effect of weather and cooling towers location on its size and monthly operation by developing a multiperiod optimization formulation aiming at minimum water consumption. Coal based and CSP plants are considered. While the operation of both depends on the weather, CSP plants operation is also characterized by non steady production of energy that also depends on weather conditions. Furthermore, a CHEMCAD simulation is also put together to evaluate the limits in power production as a result of the cooling capabilities in different climates. The mathematical formulation shows that the driving force is limited in winter and that the extreme temperatures of summer reduce the production capacity of the plant due to limitations in the heat transfer capacity. Colder climates require larger towers but show lower water consumption. Hotter climates need additional heat transfer area. It comes a point when the efficiency of the Rankine cycle and, as a result, the power production must decrease by increasing the exhaust pressure of the low pressure turbine so as to be able to refrigerate the system.

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1. Introduction

Thermal plants, either the ones using fossil fuels, or those using renewable resources such as biomass, geothermal energy or Concentrated Solar Power (CSP) [1], require cooling units to reject heat. The use of atmospheric air results in the fact that the operation becomes complex due to the variability of the air conditions over time, temperature and humidity. On top of the variability of the features of the cooling agent, the operation of CSP plants is even more challenging, because when operating along a year, there is a wide range in the power produced. Reference [2] evaluated the operation of such plants for wet cooling systems and ref. [3] extended the study to dry systems. However, neither complete Cooling Tower (CT) sizing nor a full multiperiod optimization was carried out, the system was optimized on an independent monthly basis. The work focused on the optimization of the energy produced from the Sun evaluating the water consumption or the power consumed by the fans at the cooling system using unit operation based designs. Other works in the literature have evaluated the performance of cooling systems, focusing on the operation of the worst case scenario and comparing both dry and wet cooling devices in the case of solar plants with different designs [4,5], for thermal power plants [6], including the development of commercial software for the operation of dry and wet systems [7], the use of different metrics to compare both kind of systems carrying out exergetic [8] or exergoeconomic [9] studies of wet and dry cooling systems and, recently, extending the work to evaluate how different technologies operate for waste to energy plants [10], real CSP plants [11] and in integrated solar facilities with desalinization systems [12]. In general, wet cooling systems allow high efficiency and lower production costs, due to the low energy consumption compared to the need to use approximately 5–10% of the energy produced when dry A-frame type of cooling systems are used. Even from the Greenhouse Gas emissions point of view, considering the CO_2 saved due to the energy produced and the CO_2 consumed per cubic meter of water used, wet systems looked promising [3]. However, careful consideration must be taken to reduce water consumption for a more sustainable operation. The water – energy nexus is a trending topic nowadays due to the raising concern on water availability worldwide. Cooling towers are at the centre of that link because they are the units that represent the water consumption in the production of power [13,14].

Studies on CT's design have been around for the last 30 years. Typically, two separate approaches have been presented. Civil

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engineering approach for the design of the structure [15] and size of the actual unit [16,17], and the unit operations kind of approach, where the performance based on mass and energy balances is considered [18,19]. Lately, unit optimization using mathematical programming techniques has also been included into the list, focusing on mechanical draft kind of towers for steady state operation [20]. Some recent work also compares different types of CT's under various annual conditions evaluating the performance of natural draft cooling tower in different seasons [21]. Natural Draft towers are the most affected by atmospheric conditions and consume the largest amount of water [22]. However, fossil based thermal power plants typically use natural draft wet cooling towers. Furthermore, CSP plants have become mature reaching sizes of 400 MW, with the particular feature that they are allocated in regions where high temperatures are common. The advantage may be the low humidity of the air. However, the availability of water in these regions is limited. Thus, the design of efficient cooling systems within a range of operating conditions becomes of high importance. To compute the operation of the plant limited by the cooling capabilities, a simulation of the thermodynamic cycle of the power plant is required. In the literature, the analysis of power plants typically focuses on its efficiency in steady state or their dynamic operation. There are some examples using process simulators such as ASPEN. But, in most cases [12,23], the power block is rather simplified. Comparatively, fewer are the studies that evaluate the numerous extractions from each section of the turbine [24–27], using specific software like Cycle Tempo [28], GateCycle [8] or Ecosimpro and their Power Plant Transient simulator [29]. Cooling limitations and maximum capacity production due to weather limitations have only been considered lately [30,31], but the models for the cooling tower and the power plant are simplified and did not consider geometric and unit operation details.

In this work we evaluate the effect of the weather and location on tower size and operation for natural draft cooling towers. The cooling tower must be designed so that it operates efficiently under variable weather conditions, because this unit typically limits the efficiency of power plants and determines the water footprint of the facility, not only conventional ones but also solar thermal facilities. We have developed a mathematical formulation for the multiperiod optimization of the geometric design and performance of natural draft cooling towers. The formulation corresponds to a large NLP problem that must be solved to optimality. In this way we go a step further versus previous works [2] where no actual sizing was performed and the CT was considered to operate independently as if a different tower was available each month. The paper is organized as follows. Section 2 presents the problem formulation. Section 3 shows the details of the modelling including mass and energy transfer, rules of thumb and geometric constraints. In section 4, we present the cases of study and the operating conditions for CSP and coal/biomass based plants are presented as well as the optimization procedure. Note that in case of CSP plants, there is not only seasonal variability of the air conditions, but also in the heat load to be rejected. In section 5 we present the results of the operation of the tower and the geometric properties as well as the operation capacity limitations due to cooling capabilities by modelling a Power plant using CHEMCAD. Finally, section 6 draws some conclusions.

2. Problem formulation

The design of cooling towers can follow two approaches:

1. The tower is designed for the multiperiod operation. This design is robust. The challenge is the problem formulation to systematically consider the optimal design under variable operating conditions.
2. The tower is designed for certain conditions, either larger heat rejection or minimum driving force and evaluated on a monthly basis to decide on the design variables. A geometry capable of dealing with the variation of the operating conditions is selected via overdesign so that the unit can operate in scenarios with different limitations. This procedure typically requires trial and error and can lead to infeasible operation apart from the fact that any overdesign is always a burden for the economics

Therefore, the optimization of the design of natural draft cooling towers is formulated as a multi period NLP problem for the optimal operation of the cooling tower with minimum water consumption, where the actual design of the tower, in terms of mass transfer packing and tower dimensions, remains constant so that it is feasible to operate it at any time.

$$\begin{aligned} &\min CT = C(d) + \sum_{t=1}^{\Gamma} f_t(d, x_t) \\ &st. g_t(d, x_t) \leq 0 \quad \mathrm{t} = 1, \ldots, \Gamma \\ &\quad h_t(d, x_t) = 0 \quad \mathrm{t} = 1, \ldots, \Gamma \end{aligned} \tag{1}$$

where d are the design variables, fixed time period after time period, and x_t are the operating variables. The constrains g and h in eq. (1) refer to the mass and energy balances, phase equilibrium, geometric constrains, etc., as it will be described in section 3.

In order to weight the contribution of the area and diameter of the column within the objective function, we look for weights, α and δ, so that all the contributions are in the same order of magnitude such as water loss, heat exchanger area and column diameter. The idea is to account for the material of construction prioritizing smaller towers. Furthermore, typically no more than 90% saturation of the exiting air is reached. Thus, a penalty is imposed over the air final relative moisture, φ, if more than 90% is required for the column to operate. Again, the weight for this term, β, is taken so that all the contributions of the objective function are within the same order of magnitude. Thus, the objective function becomes

$$CT = \alpha Area_{HX} + \delta diameter + \frac{1}{12}\left(\sum_{p=1}^{12} f_{wa}(p) + \beta \sum_{p} (\phi(p) - 0.9)\right) \tag{2}$$

Subject to the constraints described in section 3, eqs. (11), (15)–(39). The problem is written in GAMS® with around 1550 eqs. and constraints and similar number of variables and solved using a multi start optimization procedure with CONOPT as preferred solver.

Finally, weather limitations may result in the need to alter operating pressures and temperatures of the exhaust steam to be able to cooldown the rejected heat. To evaluate for the losses in efficiency of the Rankine cycle as a function of the exhaust pressure of the steam, a CHEMCAD simulation of the power island has also been developed. CHEMCAD is a modular rigorous process simulator that allows considering the proper thermodynamics of the species involved. We used it to build the process flowsheet corresponding to the Rankine cycle of a power facility including all the 7 extractions used to reheat up the condensed steam before feeding it to the boiler again.

3. Process model

We divide this section into the evaluation of the packing design

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