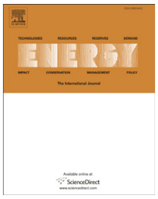
Energy 114 (2016) 995–1006

Contents lists available at ScienceDirect

Energy

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



Operational energy minimisation for forced draft, direct-contact bulk air cooling tower through a combination of forward and first-principle modelling, coupled with an optimisation platform

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A R T I C L E I N F O

Article history:
Received 28 March 2015
Received in revised form
5 July 2016
Accepted 19 August 2016

Keywords:
Cooling tower
Simulation
Cooling system
Bulk air cooling
Modelling
Optimisation

A B S T R A C T

Bulk air coolers (BACs) are extensively used in the deep-level mining industry to cool ambient air for underground use. BACs contribute significantly to the mine's chilled water requirements and it was therefore the purpose of this study to utilise a modelling method to predict the thermal performance of mechanically ventilated direct-contact bulk air cooling towers and perform energy optimisation. The model consisted of a combination of forward and first-principle methods based on underlying energy balance and heat transfer principles. The model allowed for the explicit estimation of the BAC outlet conditions for given inlet conditions, without the need for iterative calculations. This model was validated with operational data obtained from a bulk air cooler of a deep-level gold mine in South Africa. Average prediction errors of between 0.5 °C and 0.7 °C for the outlet water temperature were achieved. Subsequently, the model was coupled with an optimisation platform to optimise the electrical energy consumption of the BAC. Energy savings of 13% were obtained using the optimisation model for a period of high energy demand. This paper showed that such a modelling and optimisation approach could be useful to reduce the operation energy cost of thermal systems in general.

1. Introduction

Direct contact cooling towers are commonly used in a wide variety of applications where heat transfer between water and air is required. These include heating, ventilation, and air conditioning applications in buildings, mine cooling systems and industrial process plants [1]. Bulk air coolers (BACs) are extensively used in the deep level mining industry to cool ambient air for underground use. The mechanical working of BACs is the same as that of a traditional wet cooling tower, except that it has the objective of cooling the ambient air using chilled water instead of cooling the water using ambient air [2]. Mining accounts for around 15% of the total energy consumption in South Africa while mine cooling systems typically consume in the region of 25% of a deep level mine's total energy consumption [3]. BACs contribute significantly to the mine's chilled water requirements, up to 50% of the cooling system's capacity, and are therefore responsible for a significant portion of the energy consumption of deep level mines that require air cooling. Du Plessis et al. [4] suggested average savings of 33.3% by applying energy saving strategies to entire cooling systems which included BAC control, although the contribution due to the BAC on its own was not quantified. From their study it was also determined that older traditional BACs are operated at constant loads with limited or no control other than on-off control. To minimise the energy consumption of BAC's while in operation would require an explicit mathematical model representing the outlet performance of the BAC, as the inlet conditions vary, with acceptable accuracy in order to be coupled with an optimisation algorithm.

The study and performance-modelling of cooling towers (and BACs) are not novel, as various methods with several levels of accuracy and relevance have been proposed. The first formally documented work in this field was done by Merkel in the early 19th century. Kloppers and Kröger [5] indicated that the Merkel, e-NTU and Poppe methods are among the most popular models used for predicting the performance of cooling towers and are extensively

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http://dx.doi.org/10.1016/j.energy.2016.08.069
0360-5442/

Nomenclature

BAC	bulk air cooler
C	pump flow admittance factor [m^{-4}]
C_p	specific heat capacity [J/kg K]
COP	coefficient of performance
h	enthalpy [J/kg]
$\dot{m}$	mass flow rate [kg/s]
MIN	minimum
N	dataset length
P	pressure [Pa]
$\dot{Q}$	cooling [W]
R	correlation coefficient
RH	relative humidity
RMSRE	root mean square of relative error
T	temperature [ºC]
$\dot{W}$	power [W]

Sub- and super-scripts

a	air
BAC	bulk air cooler
calc	calculated
e	evaporator
ex	excess
i	inlet
j,k	index numbers
m	motor
min	minimum error
mine	mine
PCT	pre-cooling tower
p	pump
real	real measured value
rej	rejection
o	outlet
s	saturation
tot	total
w	water
wb	wet bulb

Greek letters

ϕ	saturated enthalpy/water temperature
β	effective heat transfer coefficient [W/K]
Δ	difference
ρ	density [kg/m^3]

used in cooling tower design. Although widely used for cooling tower design, these models are not ideally suitable for optimisation as they require iterative computation.

Khan et al. [6] investigated the effect of fouling in the cooling tower packing material and its effect on the cooling performance of the tower. The study reported a decrease of 6% in effectiveness and an average 0.4 °C increase in the water outlet temperature due to fouling according to their suggested model. Their study highlights the importance of suitable variable selection when modelling cooling towers to ensure a transparent and robust model. They considered a sensitivity analysis and reported that the two most important parameters influencing the performance of counter-flow cooling tower design are the air inlet wet bulb temperature, $T_{a,i,wb}$ and the water outlet temperature, $T_{w,o}$. These models were based on the steady-state energy and mass balance of incremental volume sections with the solution obtained through iterative computation with respect to the air humidity ratio and temperatures. These are also iterative in nature and are not ideal for optimisation purposes.

Part-load cooling tower operation has been considered by various studies. In some studies, the air flow rate was held constant and varying water flow rates were considered, whilst in other studies, the water flow rate was held constant and varying air flow rates were considered. The water-to-air mass flow ratio, $\dot{m}_w/\dot{m}_a$, also known as the liquid-to-gas ratio or L/G ratio, has a significant effect on cooling tower performance. Söylemez [7] performed optimisation in terms of $\dot{m}_w/\dot{m}_a$ and found that the optimum ratio increased as the water inlet temperature increased. He suggested that the water mass flow rate be increased for locations with lower ambient pressures in order for $\dot{m}_w/\dot{m}_a$ to remain within the optimum range. The model used by him was based on the e-NTU method which requires iterative computation. Lemouari et al. [8] confirmed that the cooling water range increases with an increase in the air flow rate while it decreases with an increase in the water flow rate. They also conclude that the best water cooling is achieved with any combination of higher water inlet temperatures and lower water flow rates. Both these models were based on numerical methods which also require iterative computation.

A paper by Pan et al. [9] suggests that several of the existing non-linear cooling tower studies are black box approaches with limited transparency. Their study also considered methods comprising a data-driven approach of modelling the performance of cooling towers during regular operation. This is in contrast to the detailed methods described earlier, which require a large number of geometrical parameters to define the system. These may not always be available. Heidarinejad et al. [10] developed models that incorporate a detailed analysis of the various zones inside the cooling tower: namely the spray, fill and rain zones. Earlier modelling approaches often only considered the fill zone while the consideration of adding the spray and rain zones yielded improvements of approximately 1.25% in the calculation error of determining the effective volume of a cooling tower. The model by Pan et al. [9] is based on a multi model approach method by iterating and adding various local solutions in order to obtain a global solution. Their modelling method is described in detail by Xue and Li [11]. The modelling approach by Heidarinejad et al. [10] is also based on the steady-state energy and mass balance of incremental volume sections similar to Khan et al. [6] and therefore resulting in these models being somewhat unsuitable for operational optimisation.

Chargui et al. [12] studied the effect of incorporating water-loss due to evaporation and suggest that modelling, where the inlet and outlet water flow rate is assumed to remain constant, may incur errors in the range of 1 °C in the water outlet temperature. They also found that between 1% and 4% of the water entering the cooling tower is lost through evaporation. The modelling method used in their study was based on the e-NTU method which, as stated earlier, would not be ideally suited for operational optimisation.

According to Wang et al. [1], the complex models constructed to model the various components of the cooling tower in refined detail are not always practical. Therefore, the research team suggests that the measured actual process data could reflect the actual process parameters and performance with more ease and simplicity. The objective of their study was to develop a model with which the outlet water temperature, $T_{w,o}$, can be calculated in terms of variables that include the water inlet temperature, $T_{w,i}$, the inlet