Applied Thermal Engineering 105 (2016) 519–530

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

A feedback model to predict parameters for controlling the performance of a mechanical draft cooling tower ☆

Kuljeet Singh, Ranjan Das *

Department of Mechanical Engineering, Indian Institute of Technology Ropar, Punjab 140001, India

HIGHLIGHTS

- A feedback and control model for the forced draft cooling tower performance.
- Model simulation is presented for three different cases under varying heat load.
- Useful for solar cogeneration, ORC, diesel engine and HVAC applications.
- GA optimized results with feedback control save pump and blower power.
- Performance parameters also improve with feedback.

ARTICLE INFO

Article history:
Received 24 December 2015
Accepted 3 March 2016
Available online 21 March 2016

Keywords:
Forced draft
L/*G* ratio
Inverse optimization
Feedback
Tower control

ABSTRACT

In this work, a feedback model has been proposed in order to control the performance of a mechanical draft cooling tower under varying heat load conditions suiting diverse applications such as solar power generation, HVAC and diesel engine. The model uses specific objective functions to meet the operating conditions related with the process requirement under varying heat load. These objective functions have been formulated using empirical correlations corresponding to different performance parameters developed from experimental data. Thereafter, an inverse method-based feedback model is made to control the cooling tower's performance for different outputs. The simulated model considers different cases closely relating to practical use of the cooling tower. Further, by monitoring the inlet water temperature with time, the controlling variable governed by water to air ratio has been adjusted to optimize the tower operation. It is concluded that for different situations, the proposed inverse feedback model is an optimized tool to control the tower performance.

1. Introduction

Cooling towers are used in several industrial processes involving power generation, petrochemical, refrigeration and air-conditioning and many more [1]. Therefore, the performance of the cooling tower needs to be optimally in line with the process to which it is coupled. Considerable amount of studies addressed the optimization issue of cooling towers. A work estimating the optimum value of heat and mass transfer area has been presented by Söylemez [2] to minimize the cost. Further, the thermo-hydraulic performance has been optimized for counter flow tower [3]. Cortinovis [4] minimized the single objective of operation cost. Similar literatures covering the optimization part of cooling towers for various performance aspects are available [5–7].

The above discussion suggests that the performance control of a cooling tower is an important objective. Although, several studies optimizing the tower performance have been reported, but its control for desired performance in line with connected system also needs to be addressed. For example, if a cooling tower operates under certain ambient conditions, then it is possible that the heat load on the cooling tower imposed by a certain process may be continuously varying. Such systems include low-grade power generation cycles such as solar power generation, Organic Rankine Cycle (ORC) and other low temperature operating cycles in which the heat input may vary depending upon the supply of waste heat [8–11]. Therefore, to control the performance of cooling tower, a feedback model is proposed based on the inverse method that monitors the varying heat load and adjusts the water to air ratio for satisfying the desired output. Firstly, the performance of the

☆ The ISIRD grant received from Indian Institute of Technology Ropar, Punjab for this work is duly acknowledged.
* Corresponding author. Tel.: +91 1881 242245; fax: +91 1881 223395.
E-mail address: ranjandas81@gmail.com (R. Das).

http://dx.doi.org/10.1016/j.applthermaleng.2016.03.030

Nomenclature

A	approach (°C)
a	interfacial area (m^2/m^3)
c_p	specific heat at constant pressure [kJ/(kg °C)]
c	coefficient
e	effectiveness (%)
F	objective function
G	air flow rate (kg/s)
H	head (m)
h	specific enthalpy (kJ/kg)
h'	saturated air enthalpy at bulk water temperature (kJ/kg)
K	mass transfer coefficient [kg/(m^2 s)]
L	water flow rate (kg/s)
Me	tower characteristic ratio
m_{eV}	water evaporation rate (kg/s)
N	number of samples
n	number of independent variables
P	power (kW)
p	pressure (N/m^2)
R	range (°C)
T	temperature (°C)
u	uncertainty
V	volume of exchange core (m^3)
v	independent variable in uncertainty analysis

Greek symbols

ω	specific humidity (kg/kg of dry air)
σ_T	standard deviation

Subscripts

a	air
abs	absolute
cr.	current
ex.	exact/required
fg	fluid–gas mixture
g	guessed value
i	inlet
k	index for iteration
o	outlet
wb	wet bulb
v	vapour

cooling tower has been estimated at different levels of heat loads (inlet water temperature) and water to air ratios. Then, empirical correlations for performance parameters have been developed from experiments. These correlations are then used in relevant objective functions, which have been formulated to get a desired output from the tower under varying heat load conditions. In the next section, the experiment setup and procedure have been discussed.

2. Experimental setup and procedure

A counter flow forced-draft cooling tower with wire mesh packing (Fig. 1) is studied having dimensions $0.30 \times 0.30 \times 1.35$ m with 1.2 m fill height. Warm water from the tank is supplied at top of the tower by a centrifugal pump through a gate valve and rotameter having range 0–11 LPM. Water is distributed over the packing and droplets of water come into contact with air supplied from the bottom by means of a centrifugal blower. Air flow rate is measured using orifice plate alongwith U-tube manometer containing water as working fluid. The cold water is again collected in tank, where water is heated and re-circulated. To maintain a desired temperature in tank, a heater of 2 kW is installed in the tank that is powered through a digital temperature controller. After calibration, six K-type thermocouples are used to measure the temperature at different locations i.e. water inlet, water outlet, DBT and WBT at air inlet and outlet. The data acquisition system (DAQ) of National Instruments is used to record the temperature data from thermocouples. Experimental procedure is described below.

L/G ratio and $T_{L,i}$ are two major factors which strongly govern the cooling tower performance. In this study, five levels of $T_{L,i}$(36.4–45.3 °C) have been maintained, which are in line with different applications such as HVAC, petrochemical industry and other plants [12]. At each $T_{L,i}$, nine levels of L/G ratio (1–5) are used, which are widely used in different processes. First, the water tank heater is lighted through a digital temperature controller having desired setting. After achieving the desired water temperature, pump and air blower are powered. The warm water supplied at top is cooled by air entering from the bottom through sensible and evaporative cooling, which is collected in tank, where it is again heated and re-circulated. Under steady state, temperatures at different points are recorded using DAQ system. Performance parameters are explained next.

3. Performance characteristics and empirical correlation

In this work, the objective is to establish a feedback system based on inverse method to achieve a desired performance from a forced-draft cooling tower. So, first the important performance parameters at different levels of $T_{L,i}$ and L/G ratio are estimated as discussed below.

$$[1]\ \text{Range}:\ R = T_{L,i} - T_{L,o} \tag{1}$$

Depending upon the process, a desired $T_{L,o}$ is needed for different chemical processes [12] For example, in ORC, the condenser should be operated at a particular temperature difference between working fluid and cooling water to ensure optimum performance [13]. Moreover, low water temperature is advisable in applications such as HVAC, but in engines, relatively higher temperatures are required. It is found that low cold water temperature also increases the total cost of the tower [14].

$$[2]\ \text{Approach}:\ A = T_{L,o} - T_{wb,i} \tag{2}$$

The operating cost of the cooling tower is inversely proportional to approach [14]. So, to minimize the cost of the entire system, a balance between range and approach needs to be maintained.

$$[3]\ \text{Effectiveness}:\ e = \frac{Range}{Range + Approach} = \frac{T_{L,i} - T_{L,o}}{T_{L,i} - T_{wb,i}} \tag{3}$$

During heat transfer process within tower, water droplet is surrounded by film of air. The enthalpy difference between film and air provides driving force for cooling. The tower characteristic ratio is expressed as [7,15],

$$[4]\ \text{Tower characteristic ratio}:\ Me = \frac{KaV}{L} = \int_{T_{L,o}}^{T_{L,i}} \frac{c_{p,L}dT}{h' - h_G} \tag{4}$$

Eq. (4) is solved with Chebyshev four point method [16],

$$\frac{KaV}{L} = \int_{T_{L,o}}^{T_{L,i}} \frac{c_{p,L}dT}{h' - h_G} \cong c_{p,L}\frac{T_{L,i} - T_{L,o}}{4}\sum_{j=1}^{4}\frac{1}{\Delta h_j} \tag{5a}$$