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An experimental and multi-objective optimization study of a forced draft cooling tower with different fills

Kuljeet Singh, Ranjan Das *

School of Mechanical, Materials and Energy Engineering, Indian Institute of Technology Ropar, Nangal Road, Punjab 140001, India

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ABSTRACT

In the present study, a forced draft mechanical cooling tower has been experimentally investigated using trickle, film and splash fills. Various performance parameters such as range, tower characteristic ratio, effectiveness and water evaporation rate are first analyzed for each fill. Thereafter, based upon the experimental data, pertinent correlations have been developed for performance parameters by considering mass flow rates of water and air as design variables. Each of the performance parameters is considered to be an individual objective function and all objectives are then simultaneously optimized for maximizing the performance of the cooling tower using elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II). The multi-objective optimization algorithm gives a set of possible combinations of design variables, which is referred as the optimal Pareto-front, out of which a unique combination is selected based upon a decision making criterion. The proposed decision making procedure evaluates a Decision Making Score (*DMS*) based on assigned performance priorities for each point of the Pareto-front. Depending on *DMS* a unique combination of design variables is then selected for each type of fill that maximizes the tower's performance. These optimal points and the corresponding objective function are finally compared and based upon the highest *DMS* value, the wire-mesh (trickle) fill is found to be the most efficient fill under the present experimental conditions. The methodology presented in this work has been made more generalized, so that it can be easily implemented in industrial forced draft cooling tower operating under a wide range of temperatures.

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1. Introduction

A forced draft cooling tower is a commonly used device in power plants which extracts heat from water coming out of the condenser and rejects it to atmosphere by means of air flow. It is primarily used to supply cooled water in various oil refineries, chemical processes, thermal power plants and air conditioning systems [1]. The basic principle of cooling tower is based upon evaporative cooling that is facilitated through direct contact of air and water. The stream of air evaporates some water into itself to produce the cooling effect for major portion of the water stream. Based upon their construction, cooling towers are broadly classified into two categories involving natural and mechanical draft. Natural draft cooling towers use the temperature difference between the hot air inside the cooling tower and the ambient air that assists the air flow through the cooling tower. Subsequently, water is sprayed against the air stream by nozzles and the evaporative cooling is finally achieved. As compared to natural draft cooling tower, the mechanical draft cooling tower uses a blower to facilitate air flow through the tower. Depending upon the fan/blower location, mechanical draft cooling towers can be further categorized into forced and induced draft types. In a forced draft cooling tower, fan either at the inlet or at the bottom pushes the air within the tower, whereas, in an induced draft type, a fan is installed either at the tower exit or at the top that allows the air to be drawn through the tower. Furthermore, depending upon flow directions of air and water, cooling towers can be again classified into counter and cross flow types. In mechanical draft cooling towers, fills (packing) play an important role in the rate of heat transfer between water and air by maintaining the contact time [2]. Cooling tower fills are generally of three types such as splash, trickle and film fills. Splash fill increases the heat transfer area between water and air by splashing water into small droplets using successive layers of splash bars. Wooden splash and plastic splash are some examples of splash fills. As compared to splash fills, trickle fills are comparatively finer, which are made up of either plastic or metal grids (e.g. wire mesh fills) and used for spreading the water into droplets. However, a film fill

* Corresponding author at: School of Mechanical, Materials and Energy Engineering, Indian Institute of Technology Ropar, Nangal Road, Rupnagar, Punjab 140001, India

E-mail address: ranjandas81@gmail.com (R. Das).

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Nomenclature

a	interfacial area (m^2/m^3)
C_p	specific heat at constant pressure kJ/(kg K)
DMS	decision making score
e	effectiveness (%)
F	Pareto-front
f	objective function
h	specific enthalpy (kJ/kg)
K	mass transfer coefficient kg/(m^2 s)
M	number of objective functions
Me	tower characteristic ratio or Merkel number
m_{eV}	water evaporation rate (kg/s)
m	mass flow rate (kg/s)
n	number of efficient points
N_p	population size
p	pressure (N/m^2)
P	random population
Q	offspring population
R	range (°C)
T	temperature (K)
U	uncertainty
V	volume of exchange core (m^3)
W	weightage factor
x	design variable

Greek symbols

ω	specific humidity (kg/kg of dry air)

Subscripts

a	air
abs	absolute
fg	fluid–gas mixture
norm	normalized value
sa	saturated air at bulk water temperature
wb	wet bulb
v	vapor
w	water
I	index for Pareto-front
i	inlet
o	outlet
t	index for iteration

forms a thin film of water over the fill surface surrounded by air and accordingly the water is cooled [3]. Corrugated, flat and honeycomb fills fall under this category.

To study the performance of the cooling tower, Merkel [4] proposed a method, popularly known as Merkel method, that is one of the oldest methods which simplifies the solution by making certain assumptions [5]. It is reported that Merkel method is simple to apply which gives correct result for the outlet water temperature if an appropriate value of the evaporation coefficient is used [6]. Making some simplifications in the assumptions of Merkel method, Jaber and Webb [7] proposed *e-NTU* method for cross-flow and counter flow cooling towers. Subsequently, another popular method was demonstrated by Poppe and Rogener [8], which is commonly referred to as Poppe method. The reason behind the popularity of Poppe method is attributed to the fact that it accurately predicts the water content at the air outlet [9] which makes it practically suitable where the experimental data is unavailable.

Many studies on cooling tower performance with different types of fills were reported by various researchers under various operating conditions. For example, Bedekar et al. [2] experimentally studied the performance of a counter flow cooling tower using film type packing and trends of different performance parameters were reported. Goshayshi [10] experimentally estimated the mass transfer and pressure drop characteristics employing corrugated fills installed in different arrangements. Kloppers and Kroger [11] proposed a correlation of the loss coefficient occurring due to the presence of frictional and drag effects for splash, trickle and film fills. Similarly, several studies have been reported which reveal the application of diverse fills (packing) with different orientations [12–16].

The optimization of cooling towers is an emerging area of interest for many researchers in order to either maximize the performance or to minimize the cost of the system. Toward this direction, Söylemez [17] proposed an optimal heat and mass transfer area to minimize the involved cost. Further, Söylemez [18] also theoretically optimized the thermo-hydraulic performance of a counter flow cooling tower and proposed an optimal water to air ratio under different inlet water temperature and ambient pressure. Cortinovis [19] proposed a model of a single objective optimization problem to minimize the operating cost of a mechanical draft cooling tower. Ramakrishnan and Arumugam [20] presented a model to predict and optimize the cold water temperature using the Response Surface Method (RSM) and Artificial Neural Network (ANN). Additionally, several studies have been also reported which optimize various operating parameters in order to minimize the total annual cost of cooling towers using different algorithms such as Mixed-Integer Non Linear Programming (MINLP), Artificial Bee Colony (ABC) and many more [21–24]. Recently, for design and cost optimization purpose, a simple method has been presented to calculate optimum packing height based upon Merkel equation [25]. Al-Bassam and Alasseri presented a comparison of variable frequency drives with dual speed motors in cooling tower application. The study has been further extended to optimization of electricity and water consumption using variable frequency drive fans [26]. Wang et al. proposed and implemented an optimization strategy for a fan operation using Non Negative Garrote (NNG) variable selection procedure [27].

It is revealed from the literature that majority of the optimization studies are aimed at a single objective. For a cooling tower, there are many performance parameters such as range, tower characteristic ratio, effectiveness, evaporation rate and all of them are required to be simultaneously considered for completely optimizing its overall performance. Based on this idea, in the present study a problem is formulated for a forced draft cooling tower involving different fills in which multiple performance parameters are optimized simultaneously. Three different types of fills such as wooden splash, wire mesh and honeycomb have been considered in the present work, where each of them respectively belongs to splash, trickle and film type. At first, for each type of fill (wooden splash, wire mesh and honeycomb), relevant objective functions are formulated for different performance parameters (range, tower characteristic ratio/Merkel number, effectiveness and evaporation rate) using the experimental data. These objective functions (4 for each type of fill) consist of two control variables (unknowns) involving mass flow rates of water and air. Next, for each type of fill, objective functions have been simultaneously optimized (either maximized or minimized) using multi-objective genetic algorithm and different combinations of water and air flow rates are obtained. These possible combinations are referred to as a single Pareto front (set of optimized points) optimizing each of the objective functions. Finally, after generating the Pareto front for each fill, the decision making approach has been proposed to select the most optimum

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