Energy Conversion and Management 136 (2017) 418–430

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Exergy optimization of cooling tower for HGSHP and HVAC applications

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ARTICLE INFO

Article history:
Received 17 October 2016
Received in revised form 2 January 2017
Accepted 8 January 2017

Keywords:
HVAC
HGSHP
Exergy destruction
Box–Behnken design
Constrained optimization

ABSTRACT

In the present work, a constrained inverse optimization method for building cooling applications is proposed to control the mechanical draft wet cooling tower by minimizing the exergy destruction and satisfying an imposed heat load under varying environmental conditions. The optimization problem is formulated considering the cooling dominated heating, ventilation and air conditioning (HVAC) and hybrid ground source heat pump (HGSHP). As per the requirement, new second degree correlations for the tower outlet parameters (water temperature, air dry and wet-bulb temperatures) with five inlet parameters (dry-bulb temperature, relative humidity, water inlet temperature, water and air mass flow rates) are developed. The Box–Behnken design response surface method is implemented for developing the correlations. Subsequently, the constrained optimization problem is solved using augmented Lagrangian genetic algorithm. This work further developed optimum inlet parameters operating curves for the HGSHP and the HVAC systems under varying environmental conditions aimed at minimizing the exergy destruction along with the fulfillment of the required heat load.

1. Introduction

The mechanical draft cooling towers are widely used in heating, ventilation and air conditioning (HVAC), water-cooled multi-split air-conditioning, hybrid ground source heat pump (HGSHP), chillers and many more applications [1]. Particularly, either in the HVAC or water cooled multi-split air-conditioning systems, the cooling tower rejects the heat equivalent to the capacity of the system (in tons) and the heat input to the compressor (defined by heat rejection factor i.e., 1.25 of the system capacity in tons) [2]. The HGSHP is an improved version of ground source heat pump (GSHP) that uses a supplementary heat sink to reject the additional heat during cooling dominated operations [3]. Therefore, in HGSHP applications, the heat load on the cooling tower may continuously vary depending on the operational and the environmental conditions. In order to ensure the optimum operation of any modern thermal system, the exergy destruction within the system should be as minimum as possible under all inlet and environmental conditions [4]. Specifically, in cooling towers, the exergy performance is governed by parameters such as; heat load, ambient dry-bulb temperature, relative humidity, water inlet temperature along with water and air inlet flow rates. But at the same time, in HVAC and HGSHP, a required heat load imposed on the system must be satisfied by the cooling tower under fluctuating environmental conditions. While meeting the required heat load, it is desirable if the exergy destruction is also minimized corresponding to the operating conditions.

Many optimization studies on the cooling tower assisted building cooling systems were presented earlier in several literature. For instance, Lu et al. [5] presented a HVAC optimization study in which the cooling tower inlet water temperature was assumed constant. Moreover, the effect of ambient dry-bulb temperature was not considered. Fong et al. [6] reported an optimization study of the HVAC system, but, the effects of varying ambient conditions were not correlated. Wang et al. [7] proposed an event based optimization method for the HVAC system using the On/Off sequencing of the cooling tower. They ignored the optimum operation using the variable frequency drive fan and pump. Moreover, like the above discussed literatures, other optimization studies also considered fixed ambient conditions and ignored the effects of inlet as well as environmental parameters on the exergy destruction within the cooling tower [8,9]. Sayyaadi and Nejatolahi [10] presented a multi-objective optimization study to simultaneously optimize the exergy destruction and the total production cost of the system. However, in this study, fixed cooling tower approach, range and water inlet temperature were considered. Furthermore, their effects on the optimum performance were also ignored. Similar issues were found for cooling towers used in HGSHP applications, where literatures were although reported on the On/Off

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http://dx.doi.org/10.1016/j.enconman.2017.01.024
0196-8904/

Nomenclature

a	interfacial area, m^2/m^3
A_{fr}	frontal area, m^2
c_p	specific heat at constant pressure, J/(kg K)
C	constraint
e	error function
E	total exergy, W
F	objective function
h	specific enthalpy, J/kg
I	exergy destruction, W
K	mass transfer coefficient, kg/(m^2 s)
l	total number of constraints
ll	lower limit of bound
Le_f	Lewis factor
m	mass flow rate, kg/s
n	number of inequality constraints
N_p	population size
OP	offspring population
p	coefficient
P	random population
q	heat transfer rate, W
Q	heat load
R	gas constant, J/(kg K)
r	total number of independent/control variables
s	specific entropy, J/(kg K)
S	positive shift
T	temperature, °C
ul	upper limit of bound
U	absolute uncertainty
X	design variable
Y	dependent variable
z	tower height, m

Greek symbols

ϕ	relative humidity, %
ω	specific humidity (kg/kg of dry air)
λ	Lagrange multiplier
ψ	penalty factor
Θ	sub-problem objective function
σ_T	standard deviation of recorded temperatures

Subscripts

0	restricted dead state
00	environment or dead state
a	air
eq	equality
f	saturated liquid
fr	frontal
g	guessed
i	inlet
inv	inverse
j	index for the node along the tower height
k	index for number of constraints
ma	air-vapour mixture
o	outlet
t	index for generation/iteration of NSGA-II
v	vapour
w	water
wb	wet-bulb

Superscripts

$*$	exact or required

cooling tower control [11,12], but the effect of all inlet parameters was not taken into the consideration [13].

From the above discussion regarding the cooling towers either used in HVAC or HGSHP applications, the unavailability of a detailed exergy destruction minimization study meeting a given heat load can be pointed out. Further, the effect of environmental conditions (such as ambient dry-bulb temperature and relative humidity) and other operating parameters (such as heat load and tower inlet water temperature) in the optimization studies are also not completely addressed. Therefore, the present study is motivated towards the exergy destruction minimization within the cooling tower satisfying an imposed heat load on the tower either by HVAC or HGSHP system. For the required heat load attainment, a constraint is formulated using the least squares method. The objective function of the exergy destruction and the constraint are simultaneously minimized using the constrained augmented Lagrangian genetic algorithm (ALGA). The present method optimizes three parameters (such as, inlet water temperature, mass flow rate of water and air) at the tower inlet under the effect of two environment driven air inlet parameters (dry-bulb temperature and relative humidity). As per the demand of the problem, second degree correlations of the essential tower outlet parameters (such as, water temperature, dry and wet-bulb temperatures of air) against all tower inlet parameters (such as, dry-bulb temperature, relative humidity, water inlet temperature, water and air mass flow rates) are formulated using the Box–Behnken design (BBD). However, experimentally it appears challenging to analyze the cooling tower output performance under simultaneous effect of all of the above-mentioned parameters, because it is difficult to control the environmental conditions. Therefore, the present study uses a prediction model aided by non-dominated sorting genetic algorithm (NSGA-II) in conjunction with the BBD to formulate the second-degree polynomial functions for three important cooling tower outlet parameters (such as, water outlet temperature along with dry-bulb temperature and wet-bulb temperature at the air outlet). These predicted outlet parameters are then used to formulate the objective function for exergy destruction and the constraint satisfying the required heat load. The problem formulation is presented in the succeeding section.

2. Problem formulation

The motivation of the present work is to meet the building cooling load imposed on the cooling tower either by a HVAC or HGSHP system minimizing the total exergy destruction. In the first case, when the cooling tower is connected to a building cooling HVAC system, almost a fixed amount of heat needs to be rejected. The amount of heat rejected in the cooling tower is defined by the cooling tower ton that is 1.25 times of the system capacity in refrigeration tons (i.e., 1 ton of cooling tower $= 1.25 \times 12,661 = 15,826$ kJ/m) [2]. The multiplying factor (1.25) in the cooling tower tonnage (i.e., load) calculation is known as the heat rejection factor (HRF) that accounts for the cooling load served by the HVAC system and the heat added to the compressor. In addition to this, by measuring the refrigerant flow rate along with the temperatures at the evaporator inlet and compressor outlet, the heat load to be served by the cooling tower can be easily calculated. However, in HGSHP systems, the heat load on the cooling tower keeps changing depending upon the operating conditions and cooling requirements. Then, the heat load required to be rejected in the cooling