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Experimental investigation and radial basis function network modeling of direct evaporative cooling systems

Kadir Kavaklioglu [a], Mehmet F. Koseoglu [a,*], Oguz Caliskan [b]

[a] *Pamukkale University, Mechanical Engineering Department, Denizli, Turkey*
[b] *Selcuk University, Mechanical Engineering Department, Konya, Turkey*

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ABSTRACT

Radial basis function network method is used for modeling a direct evaporative cooling system. Air dry exit temperature, air pressure drop across the cooler and cooler efficiency are predicted using these models. The inputs are pad thickness, air inlet speed, air dry inlet temperature, relative humidity at the inlet and feed water temperature. The data for the models are taken from the experiments performed specifically for this purpose. Model validation is performed using twofold cross validation method. A grid search is used to determine optimal network parameters, such as, optimum number of radial basis elements and spread parameter. Validated models are tested against ordinary least squares models for the output variables. The results indicate that it is feasible to apply radial basis function networks to model direct evaporative coolers.

1. Introduction

Evaporative cooling process is an efficient way of cooling and humidification of residential and office buildings as well as some industrial spaces [1,2]. It has found applications in various high-power industrial units, too [3,4]. Water, among widely used working fluids, has the highest latent heat of evaporation, has a very low cost, has no personal and environmental side effects, and is readily available everywhere. Therefore, it has almost become the de facto working fluid for evaporative cooling systems (ECS). Evaporative cooling systems can be divided into three main categories: direct evaporative cooling, indirect evaporative cooling, and indirect-direct evaporative cooling [5]. Direct evaporative coolers in which incoming air stream comes directly into contact with the wetted medium are the subject of this study.

When the water comes into contact with incoming air some evaporation occurs and the energy of evaporation is supplied by the air. As a result, the exit air stream temperature drops and humidity increases because of the added water vapor. The amount of sensible heat removed from the air is equal to the latent heat of evaporation of water which evaporates into air. In the process no net heat is added to or extracted from the whole system; so entrance and exit states fall on a constant wet bulb temperature line which almost coincides with constant enthalpy line.

According to the standards, there are certain criteria to be used in assessing the performance of direct evaporative coolers [6,7]. Air outlet temperature, pressure drop, and saturation efficiency are three of the most important of them. Air outlet temperature ($T_{out,db}$) is the dry bulb temperature of the moist air at the cooler outlet and is one of the important parameters especially since it is the parameter that the users of ECSs care the most. Pressure drop across the pads (ΔP) is another important performance parameter as it relates to the fan power required to drive the system. Finally, the direct evaporative cooling efficiency (η) is probably the most important performance parameter as it indicates how close a given ECS is to the maximum possible cooling. This efficiency is defined as the actual temperature drop across the ECS divided by the maximum possible temperature drop.

$$\eta = \frac{T_{in,db} - T_{out,db}}{T_{in,db} - T_{in,wb}} \tag{1}$$

Here, $T_{in,db}$ is the dry bulb temperature of the air at the inlet of the ECS, and $T_{in,wb}$ is the wet bulb temperature at the inlet conditions. As mentioned previously, $T_{out,db}$ is the dry bulb temperature of the air mixture at the ECS outlet. Determining these three parameters is essential in evaluating performance of evaporative coolers.

Evaluating these three parameters requires a few additional sensors around the cooler. For instance, air outlet temperature

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* Corresponding author at: Pamukkale University, Mechanical Engineering Department, 20070 Kinikli, Denizli, Turkey.

E-mail address: mfkoseoglu@pau.edu.tr (M.F. Koseoglu).

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Nomenclature

Symbols

ANN	artificial neural network
$\boldsymbol{c}$	center vector
$\boldsymbol{C}$	centers matrix
e	model error
ECS	evaporative cooling system
MLR	multiple linear regression
n	number of hidden elements
N	number of data samples
OLS	ordinary least squares
r	residual
P	pressure
RBF	radial basis function
RBFN	radial basis function network
RMS	root mean squared
RMSE	root mean squared error
T	temperature
x	input variable
$\boldsymbol{x}$	input vector
$\boldsymbol{X}$	input matrix
y	output variable
$\boldsymbol{y}$	output vector

Greek letters

α	MLR coefficients
β	RBFN weights
ϵ	measurement error
ε	effectiveness
ϕ	radial basis function
$\boldsymbol{\Phi}$	radial basis matrix
η	efficiency
σ	spread parameter

Subscripts

db	dry bulb
h	hidden
i	data index
in	inlet
j	input index
k	hidden index
l	learning
out	outlet
t	test
wb	wet bulb

requires a temperature sensor at the outlet, pressure drop requires two pressure sensors at the inlet and the outlet, and cooler efficiency requires wet bulb temperature of the air at the inlet which cannot even be measured directly. As will be seen later in this paper, the models developed in this research will eliminate the need for the sensors at the cooler outlet. This will lead to design simplifications and cost reduction. Since manufacturing costs are crucial for success in the marketplace, it is believed that the findings in this research will be important for the cooler industry. On the other hand, this research will be important for the academic side of the evaporative cooling society. This is mainly because of the difficulties with the wet bulb temperature evaluation. Thermodynamic wet bulb temperature is an important and unique property of a given moist air sample. Many air conditioning applications require the estimate of wet bulb temperature. It is needed in this paper for the calculation of cooler efficiency. Dry bulb temperature and humidity values can be measured easily, however, the same cannot be said for wet bulb temperatures. Calculation of wet bulb temperature requires a trial-and-error procedure since there is no direct analytical expression. By the models developed in this study, the need for iterative wet bulb temperature calculations is completely eliminated. Cooler efficiency is calculated directly in a one-pass function.

Evaporative coolers have been the subject of many analytical, experimental, and modeling studies. In their numerical study, Tavakoli and Hosseini made a 3D laminar flow modeling for cooling pads of evaporative coolers. They obtained relations for saturation efficiency as a function of number of waves and Reynolds number [8]. Khan et al. developed a numerical formulation and validated with simulations for evaporative cooling problems [9]. Similarly, Camargo et al. [10,11] developed a model for simultaneous heat and mass transfer in direct evaporative coolers and they determined the saturation efficiency from the model and compared with on field measurements. They also made a thermoeconomic analysis of evaporative coolers coupled to an adsorption dehumidifier. In another study, Halasz developed a general mathematical model for all evaporative coolers [12]. Dai and Sumathy made a theoretical study on cross flow direct evaporative coolers and determined the effect of some operational parameters like inlet air temperature, humidity, etc. [13]. In a study, Wu et al. obtained a correlation for cooling efficiency from their simplified heat and mass transfer analysis for drip type direct evaporative cooler [14,15]. They also numerically investigated direct evaporative coolers. In their numerical simulation, evaporated water was treated as the mass source for air flow. As a result, they obtained the influences of several parameters (dry and wet bulb temperature, air velocity, and pad thickness) on cooling efficiency. Artificial neural network modeling to predict various performance parameters of a direct evaporative air cooler has been also used [16,17]. In addition to analytical and modeling studies, many experimental work on performance evaluation of evaporative coolers and cooling pads alone have been performed. Malli et al. experimentally determined the performance of widely used cellulosic pads [18]. Similarly, Barzegar et al. conducted an experimental research on cellulosic pads made out of Kraft and Neutral Sulfite Semi Chemical corrugated papers as evaporative media [19]. They concluded that the cellulosic pad made out of Kraft paper with 2.5 mm flute size had the highest performance in comparison with the other cellulosic pads. A regenerative evaporative cooler with finned channels has been produced by Lee and Lee to determine the performance at different operating conditions [20]. Performances of evaporative coolers are investigated for humid climates too. Xu et al. have conducted an experimental study for the possible application of evaporative coolers in greenhouses. They showed that evaporative cooling can be an efficient alternative for greenhouse cooling [21]. In attempts to improve the performance of evaporative coolers for high relative humidity climates and to be able to reach temperatures below wet bulb temperature many experimental and modeling studies have been conducted. Hasan studied four types of indirect evaporative coolers to conclude that cooling air to temperatures lower than the ambient wet bulb temperature is possible [22]. Later, he used a modified version of the ε-NTU method for indirect evaporative cooling and presented an example for a regenerative air cooler case [23]. Jradi and Riffat developed a detailed numerical model of a cross-flow heat and mass exchanger for buildings air-conditioning applications [24]. In addition, they built a rig for experimental validation. They performed parametric studies to achieve optimum cooling system performance.