Energy and Buildings 81 (2014) 268–280

Contents lists available at ScienceDirect

Energy and Buildings

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

Prediction of water evaporation rate for indoor swimming hall using neural networks

Tao Lu*, Xiaoshu Lü, Martti Viljanen

Department of Civil and Structural Engineering, School of Engineering, Aalto University, Rakentajanaukio 4 A, 02150 Espoo, Finland

ARTICLE INFO

Article history:
Received 11 December 2013
Received in revised form 9 June 2014
Accepted 18 June 2014
Available online 24 June 2014

Keywords:
Water evaporation rate
Indoor swimming pool
Neural networks
Serial–parallel structure

ABSTRACT

The forecast of water evaporation rate is important in building and energy sectors. However, due to its stochastic nature and complexity, its forecast is rare in the literature. This paper presents a novel neural network approach to predicting water evaporation rate without occupant information for an indoor swimming hall containing five pools in Finland. Input sensitivity is analyzed and two step ahead predictions are compared. The neural networks using water evaporation rate and a binary representation form of time as inputs outperform other models. Experimental data show rapid fluctuations in water evaporation rate during operating hours although relatively stable during non-operating hours. The developed neural network model, however, is able to adapt to fluctuations and reaches good and acceptable accuracies for one- and two-step ahead predictions even for operating hours. The binary form of time simplifies learning process of neural networks. This paper demonstrates the capability of water evaporation rate forecasting without occupant information by neural networks, which might not be possible with traditional empirical models, and their positive impacts on promoting energy efficiency in various applications in general. Finally, the developed method is sufficiently general and can be extended to other systems for forecasting water evaporation rate as well.

1. Introduction

Water evaporation is a natural process in the global energy cycle and the water evaporation rate is a critical energy parameter in system design and control in a broad range of applications and end uses. In building and energy sectors, researches on evaporation of water from swimming pools have attracted much attention. In order to avoid condensation on cold surfaces in a swimming pool, water vapor from the evaporating surface has to be removed by a mechanical means, which requires large amounts of energy on the one hand. On the other hand, the pool water needs to be heated in order to compensate for the heat lost by evaporation. According to statistics, evaporation accounts for 70% of energy loss in both outdoor and indoor swimming pools [1]. Therefore, most researches focus on energy issues and topics about how to efficiently remove water vapor and how to recover latent heat from water evaporation to heat pool water are particularly popular [2–5].

Water evaporation rate is one of the key design and operational variables in the study of various energy performance systems. In spite of this importance, its stochastic nature and complex makes it nearly impossible to predict for indoor swimming pools. Its forecast is rare in the literature even though such issue has been tackled in a variety of contexts, such as many equations were developed for calculating water evaporation rate for both occupied and unoccupied pools aiming at sizing the air conditioning equipment as well as for energy consumption calculations [6–12]. Some improvements were done, for instant, Shah [13] extended his empirical formula for unoccupied pools to include conditions where the density of air in contact with water surface is higher than that of room air, and thus natural convection ceases and essentially all evaporation will be due to ventilating air currents. Related modelings can also be seen in the literature. Santos et al. [14,15] developed a hybrid model to simulate the thermodynamic behavior of outdoor pools. Energy loss due to water evaporation was estimated using an empirical equation. A neural network model was employed to predict monthly average information on ambient relative humidity, ambient temperature and dew point using geographic location information as inputs. Garay et al. [16] proposed a methodology for integrating different modeling and simulation tools with a focus on an indoor swimming pool environment, including the heating, ventilation and air conditioning (HVAC) system and zone environment. Simulation results were used to train a neural network to determine the optimal end of set back of the HVAC system. Water evaporation from the pool was estimated

* Corresponding author. Tel.: +358 40 7268558; fax: +358 9 47023826.
E-mail address: tao.lu@aalto.fi (T. Lu).

http://dx.doi.org/10.1016/j.enbuild.2014.06.027
0378-7788/

Nomenclature

A	area of pool surface (m^2)
b, B	bias
e	error
E	evaporation rate (kg/s; kg/h)
f, F	function
$\hat{f}$	approximated nonlinear function
I	water latent heat of evaporation (kJ/kg)
k	sample number
lw	weight from the hidden layer to the output layer
$\dot{m}$	moisture generation rate (g/s)
P	saturation pressure (kPa)
t	time (s; min)
T	temperature (°C)
u	input
V	air velocity (m/s)
V	volumetric airflow rate (m^3/s)
Vol	volume
w	weight from the input layer to the hidden layer
W	moisture content (g/m^3)
y	output
$\hat{y}$	predicted output

Superscripts

nn	neural networks
sys	system

Subscripts

a	air
enve	envelops
exf	exflitration
exh	exhaust
hall	swimming hall
hidden	hidden layer
i	indoor
input	inputs
ret	return
sou	sources
sup	supply
w	water

Greek letters

Δ	interval
ϕ	relative humidity (%)

by the ASHRAE equation. Ruiz et al. [17] used TRNSYS to model the entire system of an open-air swimming pool, including the solar heating system. Different empirical formulas were used to evaluate energy loss due to evaporation and the best agreement was reached by multiplying the ASHRAE equation by an activity factor of 0.5. The water evaporation rate has typically not been addressed from a forecast perspective in these works [6–17]. The developed and employed equations are mostly empirical and result from regression analysis after a large number of experiments. Therefore, they are valid only for particular conditions where experiments were conducted, and strongly depend on the specific experiments. These empirical formulas cannot be easily adjusted and applied to an occupied swimming pool, where occupants can cause waves, ripples, mist, wet deck, sprays of water droplets by activity and increase additional contact area between water and air because of wet bodies. All these enhance evaporation and give rise to difficulties in using empirical formulas for the purpose of forecasting as some parameters, such as wet deck, contact areas between water and air by wet body, are impossible to estimate accurately.

Currently many indoor swimming pools are still using outdoor air to carry away the evaporated water from pool areas. A smart control strategy for such system is to modulate ventilation based on water evaporation rate so that the system is acting like a demand-controlled ventilation (DCV), which is best known for controlling indoor carbon dioxide (CO_2) (CO_2-DCV). As such, an accurate prediction of water evaporation rate is desired. Since many factors involved in water evaporation (particularly for occupied pools) and some are unpredictable, Artificial Neural Networks (ANNs) are probably the best way to handle such complexity. ANNs provide a "black box" approach to complex modeling systems and they are particularly powerful in modeling high level of non-linearity and managing tasks involving incomplete information, and high complexities and ill-defined problems [18]. With this feature, ANNs have been growing significantly over years in many energy building research areas, such as indoor climate forecast, predictive control, energy consumption prediction and off-line optimization of plant operation [19–23]. ANN was also successfully used in modeling evaporation from natural body of water. Kim et al. [24] applied the generalized regression neural network model (GRNNM) to estimate and calculate the pan evaporation (PE) and the alfalfa reference evapotranspiration in major meteorological stations. The structures of ANN were optimized by the genetic algorithm (GA). Nourani et al. [25] examined different types of ANN for estimating daily evaporation rate of two cities using measured hydro-meteorological data. A sensitivity analysis was performed to investigate the effect of each input parameter on the output of ANN. Kisi [26] proposed the application evolutionary neural networks (ENN) for modeling monthly pan evaporations. Moghaddamnia et al. [27] used ANN and adaptive neuro-fuzzy inference system (ANFIS) techniques to estimate evaporation in a hot and dry climate. However, to date, research on the forecasting of water evaporation rate for indoor swimming pools by ANNs is virtually non-existent. Previous ANN works focus mostly on the prediction of evaporation from nature water resources (e.g. rivers, lakes, plants, land), determined by several climate elements: temperature, humidity, rain fall, drought dispersion, solar radiation, and wind [24–27]. Human factor was ignored in these models, which, however, is a very important contributor to evaporation from occupied swimming pools. This study aims at addressing these important questions.

The objectives are:

- To examine the potential of neural networks (i.e. ANNs) in predicting water evaporation rate for indoor swimming pools. The main aim is to show its suitability in forecasting water evaporation rate for both occupied and unoccupied swimming pools without occupant information, that are impossible with traditional empirical formulas, which require an input of occupant information (e.g. the area of wet deck). Occupant information is often practically impossible to acquire. However, neural networks can use only historical outputs as inputs to predict future outputs. In this study, we will validate this ability.
- To investigate the effect of different features of inputs for neural networks and determine the optimal input pattern. Using merely historical data of water evaporation rate as inputs for neural networks may not generate satisfactory results. It is important to determine the effective form of potential input variables and parameters which have great impacts on evaporation rate and are easy to measure and calculate. Performance comparisons of neural networks for predictions at different input variables and parameters will be made. The results, hopefully, will serve as reference model for selecting optimal input pattern for neural networks in ventilation control application. In addition, major