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Direct evaporative passive cooling of building. A comparison amid simplified simulation models based on experimental data

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ABSTRACT

Different simplified simulation models of a Passive Downdraught Evaporative Cooling tower (PDEC) were compared by using experimental data. Among these, a series of tests on a Passive Downdraught Evaporative Cooling tower (PDEC) were carried out at the SyTIn (Systems for Technology Innovation) Laboratory of the Department of Architecture and Design, Politecnico di Torino. In addition, other monitored databases were taken from literature and used as input data for the simplified models. The collected inlet airflow data were used for calculating predicted outlet airflow values by using four equations and a software from literature.

The comparison of those outlet airflow data allowed for assessing the effectiveness and the accuracy of the analysed simplified methods, which are also used for simulating the PDEC tower in several dynamic simulation software such as DesignBuilder coupled with *EnergyPlus*. The presented results could help designers in choosing amid different calculation models.

1. Introduction

1.1. General context

Electrical consumption for air conditioning has been increasing constantly in the last decades [1–3]. This trend is directly interrelated to the rising cost of electricity peak [1,2], the risk of blackouts and the growing amount of CO_{2eq} emissions. Indeed, electricity shows a very high GHG emission factor especially in oil-dependent countries like Italy [4]. Air conditioning consumption has to be reduced by 2020 in accordance to the European EPBD 2010/31 Directive setting a goal of Nearly-Zero Energy Building (NZEB) for new constructions. To reach this objective, it is essential to apply passive and/or hybrid cooling systems able to reduce energy consumption while maintaining indoor comfort conditions [5,6,54].

One of these systems is based on evaporative cooling. This solution is particularly effective in mitigating the increasing of indoor temperature due to summer solar and internal gains in hot and temperate dry climate zones [5–11,50,51,56]. There are several evaporative cooling strategies. In particular, this paper focuses on the Passive Downdraught Evaporative Cooling (PDEC) technique used for cooling directly inlet air. Its applicability was already mapped in several studies [12–16]. Moreover, an exergy analysis of the applicability of DEC and IEC technologies in different climates is reported in Ref. [11]. These studies conducted for Southern European countries report that PDEC systems can contribute to reduce the total cooling loads for cooling by 25–85% depending on local climate [12]. Furthermore, scientists demonstrate that a PDEC system could be integrated to more than 70% of the European building stocks [12,17].

All these reasons underlines the importance of studying passive evaporative cooling techniques and developing simplified methods for helping designers to integrate these technologies since the early design phases.

1.2. PDEC systems

PDEC systems can be divided in the following types [12]: cool towers (wetted pad); shower towers (nozzle based); porous media [57]; misting towers (nebulizer) and hybrid systems. This paper particularly focuses on shower tower and misting tower technologies.

The effectiveness of PDEC towers is influenced by several factors

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[18–20] both physical and morpho-technological. Among the former: wind pressure at the inlet air vent; air specific weight, which increases during the cooling process; and motion transfer from the non-evaporated water drops to the airflow. Among the latter: geometry of the tower; aerodynamic design of the system, and, in particular, of the air inlet captors; type of nozzles and their distribution; water flow and its distribution; and height of the tower [12,18,21–25].

The performance of a PDEC system can be determined using various methods, often not taking into account all different variables characterising the evaporative cooling process [10,26]. Among these methods, calculation modules for the energy simulation programmes ESP-r [26,27], TRNSYS [28], DOE2 [29], and EnergyPlus [30,31], and dedicated software were developed [12,32–34,55,60]. To analyse in detail the thermal aerodynamic patterns within a PDEC system, CFD simulations can be carried out [24,26,27,35–37,58]. Since all these methods, particularly the CFD-related ones, require advanced skills and are time consuming, scientists have developed simplified and semi-empirical approaches for estimating the effectiveness of a PDEC tower based on outlet air temperature [12,38,39]. Some of these models are also used for simulating PDEC tower performance in dynamic energy software such as DesignBuilder with EnergyPlus [30,31].

While calculation and simulation methods are abundant, only a few complete monitoring datasets on PDEC systems can be found in literature, among which it is worthwhile to mention the dataset collected by Cunnigham & Thompson in 1986 at Tucson, Arizona [38], and the one on an experimental building in Catania [12]. Other datasets are reported in Refs. [6,24,40–46,59], even if only a few of them show the entire monitored set of data.

This paper described a new original testing dataset, which, together with several experimental data taken from literature, is used as a basis for comparing different semi-empirical methods assessing the performance of a PDEC tower. This comparison aims at enhancing the knowledge base of the problem as well as at helping designers to choose the correct approach in configuring and sizing a PDEC system since the early design phases.

2. The lab PDEC testing

In this paragraph, the description and results analysis of a series of tests carried out on a PDEC tower in the SyTIn (Systems for Technology Innovation) Lab of the Department of Architecture and Design, Polytechnic University of Turin, are presented. This series of data is named “series A”.

2.1. Tests description

The test PDEC tower is built out of a PVC sewage pipe with a length of 3 m and a diameter of 630 mm. It lies on a metal tripod of 1 m height in order to simplify the measuring procedures and to allow for positioning a basin to collect non-evaporated water (Fig. 1). A motor pump to recycle water collected in the basin is used at an average pressure of 7 bars and connected to a water sprayer system composed of a PNR hollow cone nozzle 686 R01A B1SG, spray angle 45°, flow rate at 20 bar 1.2 l/min.

Data are recorded in on–off cycles after 30–45 min of water spraying in order to allow for air temperature sensors stabilizing. After each measure, a discharge time of two hours was considered.

The following variables were measured: inlet Dry Bulb Temperature (DBT), inlet Relative Humidity (RH), water flow rate, water pressure, outlet DBT and outlet RH. A TESTO 452 system was used for measuring DBT (precision ± 1 °C; res. 0.1), RH (precision ±2%; res. 0.1) and air velocity (precision ±0.2 m/s; res. 0.01). The water pressure was measured on a pressure gauge, while the water flow rate is calculated by weighing the water sprayed on a fixed unit of time using a precision balance for laboratories.

2.2. Analysis of results

Inlet and outlet air temperature measured values are shown in Fig. 2 against the calculated minimum theoretical air temperature that can be reached by evaporative cooling. This theoretical limit is represented by the inlet Wet Bulb Temperature (WBT) calculated as a function of the inlet DBT, the inlet RH and the atmospheric pressure (p), using the following equation firstly introduced in Ref. [47]:

$$\begin{aligned} WBT = {} & DBT\ atan\left(0.151\,977(RH\% + 8.313\,659)^{1/2}\right) \\ & + atan(DBT + RH\%) - atan(RH\% - 1.676\,331) \\ & + 0.003\,918\,38(RH\%)^{3/2} atan(0.023\,101\,RH\%) \\ & - 4.686\,035 \quad [°C] \end{aligned} \tag{1}$$

The WBT could be used to calculate the Wet Bulb Depression (WBD), which is the difference between DBT and WBT and is calculated introducing inlet DBT and RH measured values in eq. (1).

As Fig. 2 shows, outlet air temperature measured data reach the calculated WBD values in almost all measuring points. The effectiveness of a PDEC system in reaching the WBT can be calculated through the following equation adapted from Givoni [38,49]:

$$\varepsilon_{WBD,\ covering} = \frac{(T_{in,DBT} - T_{out,DBT})}{(T_{in,DBT} - T_{in,WBT})} \tag{2}$$

ε was calculated for the measured data and a cumulative statistical analysis of the relevant results is represented in Fig. 3, which shows that an effectiveness higher than 90% in the majority of measurements.

3. Comparison between monitored and calculated data

3.1. Models for calculating outlet air temperature

The above analysed measured data were used to compare different simplified methods for predicting PDEC outlet air temperature knowing inlet air values. The chosen methods are four empirical equations, described by Givoni [38,39], and one programme-solving algorithm (PHDC airflow) [12]. These methods can be classified into two main categories. On one hand, equations dependent on measured data including coefficients that are at least partially regressed from these data; on the other hand, expressions independent by outlet-measured data.

3.1.1. Equations based on regression

Givoni presented four simplified equations for calculating the outlet air temperature of a PDEC tower knowing inlet DBT and WBT. Two of these expressions are regression equations. In particular, a first equation is deduced from Ref. [38], and also implemented in DesignBuilder [31]:

$$T_{out,DBT} = T_{in,DBT} - slope\ (T_{in,DBT} - T_{in,WBT}) \quad [°C] \tag{3}$$

Eq. (3) is based on a regression slope coefficient value. This slope coefficient corresponds to the coefficient of the linear regression line of data as shown in the graph of Fig. 4, representing the difference in DBT between inlet and outlet values as a function of WBD of measured data. It is assumed that this regression passes by the