



Research Paper

The design of countercurrent evaporative condensers with the hybrid method

M. Fiorentino^a, G. Starace^{b,*}^a Decsa S.r.l., Via Cappelletta, Voghera 27058, Italy^b Department of Engineering for Innovation, University of Salento, via per Monteroni, Lecce 73100, Italy

HIGHLIGHTS

- Limitations to the of evaporative condensers performance evaluation were overcome.
- The hybrid method was applied to the countercurrent evaporative condenser design.
- A wide experimental campaign was carried out on a purposely built up test rig.
- A 50% increase of water flow rate was found leading to a 14% heat transfer increase.

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ABSTRACT

The heat and mass transfer in evaporative condensers are complex to model analytically and numerical simulations, when applied to multi-phase fluid dynamics in complex paths, often involve too high computational costs. Experimental campaigns at full scale of different heat transfer geometries and tube arrangements involve long lead times and high costs as well. The aim of the present work is to overcome the present limitations and to apply a new method to evaluate the overall performance of the countercurrent evaporative condensers, starting from the experimental, numerical or analytical data with a small scale approach. A test bench has been purposely designed and built up in order to reach and keep constant all the parameters determining the evaporative condenser heat transfer performance. In previous experimental contributions available in the literature, the air conditions were not controlled: here, an air handling unit placed before the evaporative condenser inlet allows to set up temperature and relative humidity of air in large ranges. An extended experimental campaign has been carried out to get affordable data to be used to find a relationship correlating the dry bulb temperature and relative humidity of air after its interaction with water and the condenser tubes surfaces, while all the parameters were set up and controlled. The regression function fits well the experimental data as the predicted values of temperature and relative humidity are characterized by a maximum percent deviation lower than 2.5% and 4% respectively. An iterative procedure was then implemented to determine the conditions of air going through the evaporative condenser in order to extend small scale results to full scale performance according to real geometries. The effect of the water flow rate on the cooling capacity was investigated and the results show that an increase of 50% of the sprayed water leads to an increase of 14% of the performance.

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1. Introduction

The evaporative cooling is a well-established technology used to improve the heat rejection, even if the related heat and mass transfer phenomena are not perfectly predictable.

This is why researchers are still making efforts to model the heat transfer in cooling towers, evaporative coolers and condensers.

The contributions in the literature can be classified as approaching the problem with:

- mathematical and numerical models [1–9];
- theoretical and experimental investigations [10–14];
- experimental studies [15–20].

Bykov et al. [1] proposed a method able to compute the water and air temperature variations and air enthalpy change in three different zones: a. the area above the tube bundle b. the tube bundle c. the area between the water basin and the tube bundle.

* Corresponding author.

E-mail address: giuseppe.starace@unisalento.it (G. Starace).

Nomenclature

<i>AHU</i>	air handling unit
<i>PID</i>	proportional integral derivative
<i>RTD</i>	resistance temperature detector
$\dot{G}$	flow rate [$\text{m}^3 \text{h}^{-1}$] for air, [l min^{-1}] for water
$\dot{m}$	mass flow rate [kg s^{-1}]
<i>n</i>	rows number
<i>Q</i>	heat transfer rate [W]
R_{adj}^2	adjusted coefficient of determination
<i>RH</i>	relative humidity [%]
T_{db}	dry bulb temperature [$^{\circ}\text{C}$]
T_{wall}	outer surface temperature of electric heaters [$^{\circ}\text{C}$]
T_{water}	water temperature [$^{\circ}\text{C}$]

x specific humidity [$\text{kg kg}_{\text{dry air}}^{-1}$]

Greek symbols

$(\beta_0 \beta_1 \beta_2 \beta_3 \beta_4 \beta_5 \beta_6 \beta_7 \beta_8 \beta_9 \beta_{10} \beta_{11} \beta_{12} \beta_{13} \beta_{14})$ regression coefficients
 ε convergence tolerance

Subscripts

evap evaporated
in inlet section
out outlet section
setpoint set conditions at the outlet of the air handling unit

Webb [2] developed a unified theoretical treatment based on the Merkel hypothesis for cooling towers, evaporative coolers and condensers, since the air side heat and mass transfer phenomena are governed by the same process.

Qureshi and Zubair [3,4] evaluated the effect of fouling on the cooling capacity of evaporative coolers and condensers with a mathematical model. Then Qureshi and Zubair [5] carried out a sensitivity analysis and detected the condensing temperature and inlet relative humidity as the main parameters affecting the evaporative condenser performance.

Acunha Jr and Schneider [6] simulated the air and water flows in evaporative condenser by commercial available CFD codes (Ansys Fluent), but without modeling the heat and mass transfer.

Jahangeer et al. [7] presented a numerical model for a single straight tube of an evaporative condenser, with water and air in crossflow configuration. They assumed a constant wall temperature, solved the equations using the finite difference technique and computed the heat transfer coefficients as well.

Fiorentino and Starace [8] carried out two-dimensional numerical analyses on the heat transfer core of an evaporative condenser, consisting in the portion of fluid between two staggered tubes.

They simulated the condensing refrigerant by assuming a constant wall temperature hypothesis. They studied the influence of air conditions and wall temperature on the heat transfer coefficient. Then Fiorentino and Starace [9] continued their analysis on the established water flow modes, by varying the water-to-air ratio and the tubes arrangement.

Leidenfrost and Korenic [10] implemented a mathematical model that simulated the evaporative condenser during steady state operation. Then Leidenfrost and Korenic [11] analyzed the system behavior at different air, water and refrigerant flow rates and under different ambient conditions. They carried out an experimental campaign in order to validate the results with experimental data.

Nasr and Hassan [12] designed an innovative evaporative condenser for small size refrigeration system application and studied its performance through experimental tests. They implemented a simplified theoretical model, validated with experimental results, for the heat and mass transfer phenomena.

Tissot et al. [13] studied the improvement effect of evaporative cooling on the COP (about 22%) by spraying water on the heat transfer surface of a dry condensing unit. Then they proposed a numerical model whose results were in good agreement with experimental data.

Islam et al. [14] carried out an experimental campaign on an air conditioning system operating with an evaporative condenser. A theoretical model for a small segment of the condenser tube was described in detail and a good agreement with experimental data was observed.

Etouney et al. [15] experimentally investigated the evaporative condensers performance: they noticed that the efficiency increased with the water to air flow ratio and obtained empirical relationships for the heat transfer coefficients.

Hajidavalloo and Eghtedari [16] compared the performance of an air conditioning system using dry and evaporative condensing units. The experimental tests showed that the power consumption can be decreased down to 20% and the coefficient of performance can be improved around 50%.

Liu et al. [17] studied the cooling performance, the heat transfer coefficient and the COP of an air conditioning system using an evaporative condenser at different compressor frequencies, dry bulb temperatures, air velocities and water flow rates.

Junior and Smith-Schneider [18] performed experimental analyses on a small scale evaporative condenser. They collected 40 samples and obtained an empirical relationship to predict the heat rejection as a function of the refrigerant and water temperatures, the dry and wet bulb temperatures and the water to air flow ratio. This analysis was carried out without any control on air conditions.

Fiorentino and Starace [19–22] designed and built up a test rig capable to measure and control all the parameters affecting the cooling capacity of evaporative condensers. An AHU placed before the heat and mass transfer test section allows setting up a wide range of air conditions. Experimental tests at small scale were performed that allowed to make a sensitivity analysis depending on the inlet dry bulb temperature and relative humidity, the sprayed water flow rate and the temperature.

In the present work, a hybrid method adapted to the evaporative condensers design and optimization [23] used to extend the experimental tests (at small scale) to the overall system is described. The whole heat transfer domain is divided in micro-volumes and regression function is determined to describe their performance depending on working parameters.

The regression technique is based on data (either experimental, or numerical, or theoretical), referred to micro-volumes to be used to obtain predictor functions for each previously identified response variable depending on all the explanatory variables. An iterative procedure, taking into account the real geometry, allows then to evaluate the overall heat exchanger performance as an integration of different local contributions.

2. The experimental campaign

2.1. The setup

A scheme of the experimental setup with all components and measuring devices is illustrated in Fig. 1.

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