Applied Thermal Engineering 117 (2017) 584–590

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

# Experimental investigation of packed-bed cross-flow humidifier

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## HIGHLIGHTS

- The performance of a cross-flow packed-bed humidifier is presented.
- Capacity, saturation efficiency, and specific energy consumption are calculated.
- The specific energy consumption is almost constant for the same packing material.
- Effectiveness-NTU model is adopted to estimate the effectiveness of the humidifier.

## ARTICLE INFO

*Article history:*
Received 5 August 2016
Revised 11 February 2017
Accepted 14 February 2017
Available online 16 February 2017

*Keywords:*
Humidifier
Cross-flow
Packed-bed
Experimental
Modelling
Effectiveness
Humidification capacity
Saturation efficiency

## ABSTRACT

This paper presents the experimental performance of a cross-flow packed-bed humidifier. In this humidifier, hot water is sprayed over packing material where air flows though it in a cross flow arrangement. The air is heated and humidified while flowing through the humidifier duct. The humidification capacity, saturation efficiency, and specific energy consumption are calculated using the experimental data of the inlet and outlet conditions for both air and water streams. The variation of these performance indicators with the mass flow rate ratio of water-to-air, the water inlet temperature, and the packing volume; is investigated. It was found that the specific energy consumption is almost constant with variation of the mass flow rate ratio, packing thickness, and water inlet temperature within the investigated range of these parameters. An effectiveness model originally developed for cross-flow packed-bed cooling tower is adopted to estimate the effectiveness of the humidifier. In addition, the effectiveness and the number of transfer units of the humidifier are determined using the experimental data. The model was found to be in a good agreement with the experimental measurement at high capacity ratio with a deviation of 6%. However, the model underestimates the effectiveness at lower capacity ratio with a maximum deviation of 30%.



## 1. Introduction

Humidifiers are devices which increase the moisture content of air or a carrier gas. They are widely used in heating, ventilation, and air conditioning (HVAC) systems to ensure a comfortable and healthy environment for workers and residents [1]. Industrial humidifiers are used to adjust the humidity level to prevent static electricity buildup in industries such as packaging, plastics, textiles, electronics, semiconductors, automotive manufacturing, pharmaceuticals, electrostatic painting, and powder coating. Humidifiers are used also to preserve material properties such as in paper industry to prevent shrinkage and paper curl and in food industry to maintain the freshness of food against the dryness caused by cold temperatures in cold storage rooms. In addition, humidifiers are used in medical ventilators and hospital operating rooms. Recently, humidifiers are used in small-scale water desalination systems such as the humidification dehumidification desalination (HDH) process [2] as well as in proton exchange membrane (PEM) fuel cells [3].

There are different types of humidifiers however, they can be classified as steam or heating element humidifiers, atomizing or spray humidifiers, wetted element or packed bed humidifiers [4,5], and bubble columns or spargers [6]. Steam humidifiers inject steam directly into air or add heat to evaporate supplied water to the conditioned space. Steam and heating element humidifiers consume large energy generated from gas, fossil fuel, or electricity to evaporate the liquid water in a steam generator [4]. Atomizing or spray humidifiers spray fine water droplets into air stream which are evaporated and added to the air. There are different

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http://dx.doi.org/10.1016/j.applthermaleng.2017.02.061
1359-4311/

**Nomenclature**

| | |
|---|---|
| $A_c$ | cross sectional area ($m^2$) |
| $A_s$ | total surface area ($m^2$) |
| $C_R$ | capacity ratio (–) |
| $c_w$ | specific heat of water (kJ $kg^{-1}$ $K^{-1}$) |
| $f$ | slope of the saturated air enthalpy versus temperature (kJ $kg^{-1}$ $K^{-1}$) |
| $h$ | specific enthalpy (kJ $kg^{-1}$) |
| $K_m$ | mass transfer coefficient (kg $m^{-2}$ $s^{-1}$) |
| $\dot{m}$ | mass flow rate (kg $s^{-1}$) |
| $P$ | pressure (kPa) |
| $T$ | temperature (°C) |
| $v$ | velocity (m $s^{-1}$) |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | effectiveness (–) |
| $\eta$ | efficiency (–) |
| $\rho$ | density (kg $m^{-3}$) |
| $\sigma$ | correction factor defined by Eq. (5) (kJ $kg^{-1}$) |
| $\omega$ | humidity ratio ($kg_v$ $kg_a^{-1}$) |

*Subscripts*

| | |
|---|---|
| *a* | dry air |
| *av* | average |
| *c* | corrected |
| *in* | inlet |
| min | minimum |
| max | maximum |
| *out* | outlet |
| sat | saturated air condition |
| *th* | theoretical |
| *v* | vapor |
| *w* | water |

*Abbreviations*

| | |
|---|---|
| MR | mass flow rate ratio |
| NTU | number of transfer units |
| SEC | specific energy consumption (kW h $kg^{-1}$) |

mechanisms of atomizing such as ultrasonic, centrifugal atomizing, pneumatic atomizing, and air washers. Wetted element humidifiers force air to flow over a water film so that water diffuses into the air stream as vapor. Packed bed humidifier is a wetted element humidifier where the elements are made of random or structured packing material which has high surface area-to-volume ratio that increases the diffusion surface area.

The principle of operation for all of these devices is same. When water is brought into contact with air that is not saturated with water vapor, water diffuses into air and raises the humidity. If the water temperature is higher than the air temperature, the air will be heated and humidified. If the water temperature is lower than the dew point temperature of the air (i.e. chilled water is used), the air will be cooled and dehumidified. If the water is circulated adiabatically (i.e. without being heated or cooled), it will approach the wet bulb temperature and the air will be cooled and humidified which is known as the air washer or evaporative cooling process. Packing material is typically used in wetted element humidifiers to increase the dispersion of water droplets, the contact area, and the contact time. Devices that contain packing material are known as packed bed towers with water sprayed at the top and air flows in counter or cross flow arrangement. Special types of packed bed towers that are used to cool water are called cooling towers.

The performance of humidifiers is usually measured by its humidification capacity which is the rate of water vapor added to the air [4]. This capacity is limited when the air becomes saturated. Therefore, the saturation efficiency is also used as a performance index for humidifiers which is defined as the increase in the humidity ratio to the maximum increase in the humidity when the air is fully saturated at its exit temperature. The energy effectiveness (or simply effectiveness) of the humidifier is an important performance indicator which is defined as the ratio of the total energy transferred to the air (both latent and sensible) to the energy that will be consumed if the exit air is fully saturated at the water inlet temperature [7].

There are few analytical models that could be used to design or evaluate the performance of humidifiers. These models were originally derived for counter-flow wet cooling towers such as Merkel's model [8], Poppe and Rogener [9] (known as Poppe's model), Braun's effectiveness model [10], and the ε-NTU (effectiveness – number of transfer units) model by Jabber and Webb [11]. Critical assumptions were made in some of these models in order to obtain an analytical solution. These assumptions are such as neglecting the water loss due to evaporation, a Lewis number of unity, and a linear relationship for saturation air enthalpy with respect to water temperature. Klopper and Kröger [12,13] gave a detailed review and comparisons of these models and found that Poppe's model is more accurate than the Merkel and ε-NTU ones for both counter and cross-flow cooling tower. However, Poppe's model equations must be solved numerically and iteratively and it is relatively complex. On the other hand, ε-NTU model by Jabber and Webb [11] can be employed under normal ambient conditions if only the water outlet temperature is an important consideration in the design of a cooling tower.

In this paper, cross-flow humidifier is investigated experimentally to evaluate its performance. The inlet air is heated and humidified using hot water which is sprayed at the top of structure packing material. The effect of the mass flow rate ratio of the water and air as well as the water inlet temperature and packing volume on the humidification capacity, saturation efficiency, and specific energy consumption is presented. Finally, the ε-NTU model of Jabber and Webb [11] originally developed for counter- and cross-flow cooling tower is adopted to predict the humidifier effectiveness which is compared with the measured one. The reason for choosing this model to validate its accuracy for the cross-flow humidifier, is that it is has an analytical expression for the effectiveness and does not need complex numerical and iterative procedures.

## 2. Experimental details

A schematic of the packed-bed cross-flow humidifier used in this study is shown in Fig. 1. The humidifier consists of a duct with cross sectional dimensions of 30 cm × 30 cm and a length of 90 cm. Three structured packings (Brentwood XF125 cross-fluted film fill) of 10 cm thickness are installed inside the duct and separated by a distance of 20 cm. The purpose of using three packings in-series is to study the effect of increasing the packing volume (or thickness) which consequently increases the total surface area and the number of transfer units. An axial flow fan is installed at the humidifier entrance so that the air at room temperature is blown through the humidifier and passes through the packing material. Hot water is sprayed over the packing material and flows downward to a small