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Research Paper

Development of mass transfer coefficient correlation for a ceramic foam packing humidifier at elevated pressure

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HIGHLIGHTS

- A mass transfer coefficient correlation is developed for ceramic foam packing.
- The correlation is evaluated by experimental data.
- The effects of pressure and inlet conditions on heat and mass transfer are analyzed.

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ABSTRACT

The cooling tower model is simple but has necessary precision for the packing design and outlet conditions forecast of the humidifier, especially under the pressure and temperature level of micro humid air turbine. This research focuses on developing a mass transfer correlation of the novel ceramic foam packing, which has the potential to be used in humidification. The heat and mass transfer properties of the packing are investigated with the mass transfer coefficients calculated from 105 groups of experimental data, and the effects of pressure, water/air mass flow ratio, inlet water temperature and inlet air enthalpy are analyzed. It is shown that the mass transfer coefficient increases with the increase of water/air mass flow ratio, but decreases with the increase of inlet water temperature and inlet air enthalpy. The effect of pressure on heat and mass transfer is related with air mass flow. A dimensionless group correlation of mass transfer coefficient is developed and evaluated. It is shown that the deviations between the predicted and experimental values are estimated within ± 12% for 75% experimental conditions. The developed correlation can be used to predict the packing height and the water/air outlet conditions of the ceramic foam packing humidifier.

1. Introduction

In past decades, microturbine was considered as a promising technology for small-scale Combined Heat and Power (CHP) [1]. However, it is uneconomical when the heat load is absent for the relatively low electrical efficiency of microturbines. A possible solution for this problem is to develop advanced cycle instead of the recuperated cycle. In the literature, the Humid Air Turbine (HAT), proposed by Rao [2], had the highest efficiency of all developed gas turbine cycles [3]. More recently, several research work has already been performed on converting the microturbine into micro Humid Air Turbine (mHAT) [4–8].

In mHAT cycle, the humidifier is a key component, which introduces water into the compressed air at temperatures below the boiling point. Several different types of humidifier, such as tubular humidifier [9], spray humidifier [10,11] and packed humidifier [12–14], are proposed in practices. Due to uniform contact area all over the volume and mature design method, packed humidifier seems most likely to be applied in commercial mHAT package.

The principles of humidifier are similar to the cooling tower. The simultaneous heat and mass transfer process analysis on the cooling tower has been presented by different methods. Merkel [15] developed the theory based on three critical assumptions that the Lewis factor was equal to1, the existing air was saturate and the evaporated water into the air was neglected. The numerical approach based on the mass and energy balances without Merkel assumptions was presented by Bourillot [16]. Jaber and Webb [17] presented the effectiveness-NTU analytical method for countercurrent cooling towers. The Merkel assumptions have reasonable accuracy for cooling tower, but its applicability to humidifier should be verified for the different pressure, temperature and humidity level. Parente et al. [18] compared the Merkel model and

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Nomenclature

a	volumetric contact area ($m^2 \cdot m^{-3}$)
A	cross sectional area (m^2)
C_p	specific heat at constant pressure ($kJ \cdot kg^{-1} \cdot K^{-1}$)
D	mass diffusivity coefficient ($m^2 \cdot s^{-1}$)
d_{eq}	equivalent diameter of packing (m)
G	air mass flow rate ($kg \cdot m^{-2} \cdot s^{-1}$)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$)
H	specific enthalpy ($kJ \cdot kg^{-1}$)
k	mass transfer coefficient ($kg \cdot m^{-2} \cdot s^{-1}$)
L	water mass flow rate ($kg \cdot m^{-2} \cdot s^{-1}$)
Le	lewis number
R	water/air mass flow rate ratio
t	temperature (°C)
X	humidity ratio ($kg \cdot kg^{-1}$)
Z	packing height (m)

Greek letters

ρ	density ($kg \cdot m^{-3}$)
ε	relative error
π	dimensionless groups

Subscripts

a	air
w	water
i	inlet
if	interface
o	outlet
v	water vapor

the one-dimensional numerical model for humidifier. The result shows that computing error between the two models is fewer than 4% for operating pressure up to 16 bar, i.e., the Merkel model is suited for the engineering design of humidifier especially used in the mHAT.

Solving Merkel model and predicting the outlet conditions of the water and air need the heat and mass transfer correlations. Under the assumption that Lewis factor is equal to1, the heat transfer correlation and the mass transfer correlation are equivalent. Many researchers have measured the mass transfer correlations in cooling tower [19,20], but these correlations don't consider the effect of the packing type and mass transfer driving force. In addition, it is absent for the humidifier at the operating pressure and temperature level in mHAT. In our previous work, a ceramic foam corrugated packing is developed to improve the compactness of the humidifier, and its heat and mass transfer performances have been proved to be superior to the traditional structured packing [21]. This research focuses on developing a mass transfer correlation for the ceramic foam corrugated packing, using the experimental data of a countercurrent humidifier. The effects of operating pressure, water/air mass flow ratio, inlet water temperature and inlet air enthalpy on the heat and mass transfer are investigated. The developed correlation can be used along with the Merkel theoretical model to predict the packing height and the water/air outlet conditions of the ceramic foam packing humidifier.

2. Experimental setup

The humidification experiments are carried out on a test facility of pressurized packing humidifier, whose schematic is shown in Fig. 1. It mainly includes water system, pressured air system, a packing humidifier and test instruments. The air is introduced by a gas distributor in the bottom, passes through the packing and exits from the top. The water is distributed over the packing with a nozzle, falls down and countercurrent contacts with the air at the surface of the packing. In the humidifier, three packing modules are equipped and the total height is 0.24 m. The inner diameter and height of the humidifier are 0.125 m and 1.5 m, respectively. The ceramic foam corrugated packing in this research has similar geometric shape and flow channel with traditional perforated corrugated packing (see also in Fig. 1), but better mass transfer performance [21,22]. Since the imbibition effect of interconnect net-shape structure allows better fluid dispersion ability and more effective air-water contact area. In order to improve mass transfer performance, microporouses are added to the framework of Sic-foam by surface treating, thus the liquid hold-up and wettability increase obviously. In order to avoid transferring the pollutant in the water into the air, a mesh mist eliminator is installed above the nozzle. The test result shows that more than 95% of the droplets in the outlet air can be removed. The parameters of the ceramic foam corrugated packing sheets and module are shown in Table 1.

The air temperature, air moisture content and water temperature

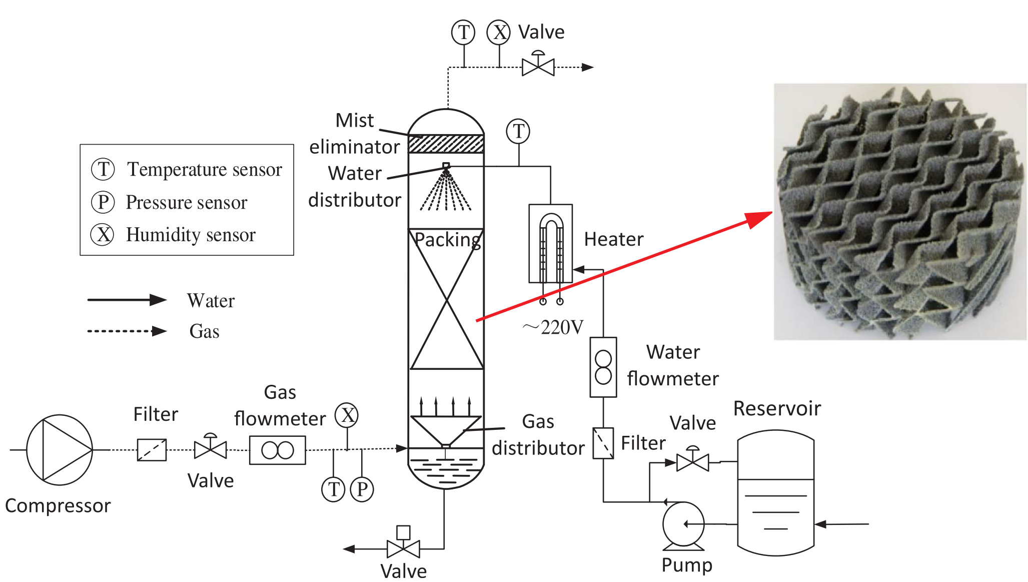

Fig. 1. Experimental facility of pressurized packing humidifier and ceramic foam corrugated packing.