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A new and practical ε-NTU correlation for the humidification process under different Lewis number

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HIGHLIGHTS

- An explicit novel correlation of ε-NTU for air humidifier was presented.
- The novel correlation can be used for humidifier under different Lewis numbers.
- The novel correlation can be implemented for sizing/rating design of the humidifier.
- The novel correlation's accuracy was tested via comparison with the previous work.

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ABSTRACT

The main objective of this article is to present a new and practical correlation associating the effectiveness (ε) with its number of transfer unit (NTU) and vice versa of the humidification process. This correlation is featured by its simplicity in use and has non-iterative procedure to implement as the traditional published correlations in the literature. The new correlation can predict the thermal performance/design of the humidifier at different Lewis numbers (both unit and non-unit) with a reasonable accuracy. General integral equation, which is similar to that of Merkel equation, is developed and used in the present humidifier simulation model. The validity of the new correlations was tested against the available experimental and numerical data reported in literature for an industrial air humidifier. In addition, the comparison was conducted with the traditional numerical model at different Lewis numbers. The simulated results of the present correlation show a good agreement with those obtained from the experimental work within 10% accuracy. The main benefits of this new correlation are: (1) its simplicity to be implemented through simple calculations of input parameters and (2) it provides helpful guidelines for developing of humidification-dehumidification HDH desalination cycle simulation program.

List of symbols

$a_{v.}$	surface area per unit volume of the humidifier, m^2/m^3
A_i	inner surface area, m^2
A_o	outer surface area, m^2
b	slope of saturation air enthalpy line or fictitious specific heat, kJ/kg·K
C_w	water specific heat, kJ/kg·K
Cpa	air specific heat, kJ/kg·K
$Cpra$	ratio between fictitious specific heat b and water specific heat
H	Total height of the humidifier, m
h_a	specific air enthalpy, kJ/kg
h_s	saturated specific air enthalpy, kJ/kg
h_{sw}	saturated specific air enthalpy at the feed water temperature, kJ/kg
h_{swin}	saturated specific air enthalpy at the feed water inlet temperature, kJ/kg
h_{swout}	saturated specific air enthalpy at the feed water outlet temperature, kJ/kg
K	mass transfer coefficient, m/s
Le	Lewis number, defined as a ratio between thermal diffusivity and mass diffusivity of humid air
m_a	air mass flow rate, kg/s
m_w	feed water mass flow rate, kg/s
mra	ratio between mass flow rate of air and water
NTU	number of transfer unit, –

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Q	heat transfer rate, kW
SHF	sensible heat factor, –
T	temperature, °C
T_w	feed water temperature, °C
T_{wm}	feed water mean temperature, °C
T_{win}	feed water inlet temperature, °C
T_{wout}	feed water outlet temperature, °C
T_s	feed water surface temperature, °C
T_{sm}	mean water surface temperature, °C
T_{wbi}	inlet air wet-bulb temperature, °C
U	overall heat transfer coefficient, $W/m^2 \cdot °C$
V	humidifier volume, m^3
W_a	air humidity ratio, Kg/Kg_a
W_s	saturated air humidity ratio, Kg/Kg_a
W_{sw}	saturated air humidity ratio at the feed water temperature, Kg/Kg_a
W_{swin}	saturated air humidity ratio at the feed water inlet temperature, Kg/Kg_a

Greek symbols

ε	effectiveness
α	heat transfer coefficient, $W/m^2 \cdot K$

Subscripts

a	air or ambient
ai	air inlet
ao	air outlet
i	inner
in	inlet
j	properties at arbitrary control volume
m	mean
o	outer
out	outside
ref	reference
s	saturated or surface
swin	saturated water inlet property
swout	saturated water outlet property
sm	air mean saturated condition
w	water
wm	water mean

1. Introduction

Humidification process is widely applied in different industrial components as in wet cooling towers, evaporative cooler, or generally direct-contact heat exchangers. On the other hand, humidification-dehumidification (HDH) process is widely used particularly in the desalination field as a simple and reliable system of fresh water production. In the humidification process, the saline water is sprayed over a stream of inlet air through the humidifier tower. Heat and mass transfer occurs between the spray saline water and the air passing the tower packing.

The prediction of the humidifier's thermal performance during its operation is paramount for the process and design engineer either for sizing or rating predictions. The simpler and reliable relationship that describes the heat and mass transfer process, the more attractive tool to be used at the practical site or in the theoretical analysis particularly for carrying-out an optimization exercise for the HDH performance or developing energy simulation program.

In modeling simultaneous heat and mass transfer of the humidification process, it introduces complexities in the heat and mass transfer calculations. Goodman [1] developed and presented the potential enthalpy approach to solve the simultaneous heat and mass transfer problem. Threlkeld [2] detailed the enthalpy potential method and presented the LMED (logarithmic mean enthalpy difference) which is analogous to LMTD (logarithmic mean temperature difference) for dry heat exchanger. However, the enthalpy difference is the driving force in wet heat exchangers such as air humidifier of HDH cycle. Extensive researches have been directed towards the thermal analysis of the HDH system. Muthusamy et al. [3] simulated the sensible and latent process which takes place in the humidifier by balancing the heat and mass transfer equation with the energy equation. The heat and mass transfer equation was represented by applying the LMED equation between the air at the free stream and the saturated air at the interfacial layer between the hot water and the air. The inlet air and water conditions are known, the outlet conditions must be assumed to execute the solution using the LMED method. In similar way, other previous researches [4–8] have used LMED method and energy balances to predict the thermal performance of the humidifier.

A second simplified method to simulate the wet heat exchanger is the effectiveness-NTU (ε-NTU) method. One of the benefits of the ε-NTU method for dry heat exchanger is that it can be solved explicitly without iteration. Only the inlet conditions are needed to solve for the heat transfer rate and outlet conditions. Alternatively, ε-NTU method for wet heat exchanger is, unfortunately, still an iterative process. Braun [9] developed "effectiveness models" for cooling coils and cooling towers, which utilized the assumption of a linearized air saturation enthalpy and the modified definition of NTU. The models were useful for both design and system performance simulation. However, Braun's model needs also iterative computation to obtain the output results and is not suitable for online optimization.

According to the authors' knowledge, and the available literature review, the researches which have been conducted on mathematical modeling of the humidification process in HDH cycle, have not been treated using traditional ε-NTU. The reason may be attributed to the iterative solution associated with this method. Iterative method needs a relatively lengthy computational time and cost which causes a fastidious solution to be implemented. In addition, for process design engineer, non-iterative method simplifies his/her design process.

On the other hand, all the previous researches have been carried out their simulation process assuming unity value of Lewis number. And, as revealed by the Xia and Jacobi [10] that the assumption of Lewis number of unity is the major source of error in LMED method. A difference of 8% could be introduced in evaluating the total heat transfer rate, under the operating condition of a sensible heat ratio of 50%, as the value of Lewis Factor changed from 1 to 1.16. Recently, Xia et al. [11] suggested the relative calculation error for the total heat transfer rate could be as high as 20% as a result of assuming Lewis number of unit value.

It can be concluded from this introduction that the determination of the air humidifier performance was done using LMED only with a unity value of Lewis number.

In this work, a novel simplified correlation for ε-NTU of counterflow air humidifier operating under both unit and non-unit Lewis number is developed and presented. This correlation is handy to be used by the process engineer or humidifier designer and they is featured by direct input parameters while no need for iterative process.

2. Mathematical modeling and correlation development

A schematic diagram of a counterflow humidifier considers an increment of a heating and humidification process as in control volume (dv) is shown in Fig. 1. Feed hot water mass flow rate $m_w$and air mass flow rate m_a are uniformly distributed along plane area. All vertical sections are assumed to be the same, in which both streams move in an opposite direction.

The major assumptions that are used to derive the basic modeling equations are: