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The Lewis factor and its influence on the performance prediction of wet-cooling towers

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Abstract

The effect of the Lewis factor, or Lewis relation, on the performance prediction of natural draft and mechanical draft wet-cooling towers is investigated. The Lewis factor relates the relative rates of heat and mass transfer in wet-cooling towers. The history and development of the Lewis factor and its application in wet-cooling tower heat and mass transfer analyses are discussed. The relation of the Lewis factor to the Lewis number is also investigated. The influence of the Lewis factor on the prediction of wet-cooling tower performance is subsequently investigated. The Poppe heat and mass transfer analysis of evaporative cooling are considered as the Lewis factor can be explicitly specified. It is found that if the same definition or value of the Lewis factor is employed in the fill test analysis and in the subsequent cooling tower performance analysis, the water outlet temperature will be accurately predicted. The amount of water that evaporates, however, is a function of the actual value of the Lewis factor. If the inlet ambient air temperature is relatively high, the influence of the Lewis factor, on tower performance diminishes. It is very important, in the view of the Lewis factor that any cooling tower fill test be conducted under conditions that are as close as possible to the conditions specified for cooling tower operating conditions.

Keywords: Lewis factor; Lewis number; Wet-cooling tower; Evaporation; Poppe

1. Introduction

The Lewis factor, Le_f, appears in the governing equations of the heat and mass transfer processes (evaporative cooling) in a wet-cooling tower according to Merkel [1] and Poppe and Rögener [2]. Merkel [1] assumed that the Lewis factor is equal to 1 to simplify the governing equations while Poppe and Rögener [2] used the equation of Bosnjakovic [3] to express the Lewis factor in their more rigorous approach. This approach is commonly known as the Poppe method and will be referred as such in this paper. The analysis of Poppe [2] is employed in the current investigation as the value of the Lewis factor can be explicitly specified. The influence of the Lewis factor on wet-cooling tower performance can therefore be critically evaluated under a wide range of ambient conditions.

There is a common misconception among researchers who refer to the Lewis number, Le, as the Lewis factor, Le_f. The relation between the Lewis number and the Lewis factor is explained.

2. Lewis number

The derivation and significance of the Lewis number, Le, is explained by its analogy to the derivation of the Prandtl, Pr, and Schmidt, Sc, numbers.

The rate equation for momentum transfer is given by Newton's law of viscosity, i.e.,

$$\frac{F}{\mathrm{A}} = -\mu \frac{\partial u}{\partial y} = -\nu \frac{\partial (\rho u)}{\partial y} \tag{1}$$

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Nomenclature

A	area	m^2
C	coefficient	
c_i	concentration	$kg{\cdot}m^{-3}$
c_p	specific heat at constant pressure	$J{\cdot}kg^{-1}{\cdot}K^{-1}$
D	diffusion coefficient	$m^2{\cdot}s^{-1}$
d	molecular weight ratio $= 0.622$	
F	force	N
h	heat transfer coefficient	$W{\cdot}m^{-2}{\cdot}K^{-1}$
h_m	mass transfer coefficient	$kg{\cdot}m^{-2}{\cdot}s^{-1}$
k	thermal conductivity	$W{\cdot}m^{-1}{\cdot}K^{-1}$
L	length, m, or length scale	
$\dot{M}$	mass flow rate	$kg{\cdot}s^{-1}$
Q	heat transfer rate	W
T	time scale	
u	velocity	$m{\cdot}s^{-1}$
w	humidity ratio	(kg water vapor)·(kg dry air)$^{-1}$
y	coordinate	

Greek symbols

α	thermal diffusivity, $k/\rho c_p$	$m^2{\cdot}s^{-1}$
μ	dynamic viscosity	$kg{\cdot}m^{-1}{\cdot}s^{-1}$
ν	kinematic viscosity	$m^2{\cdot}s^{-1}$
ρ	density	$kg{\cdot}m^{-3}$

Dimensionless numbers

Le	Lewis number, $k/(\rho c_p D)$, or Sc/Pr, or α/D
Le_f	Lewis factor, $h/(c_p h_m)$
Nu	Nusselt number, hL/k
Pr	Prandtl number, $c_p\mu/k$
Re	Reynolds number, $\rho uL/\mu$
Sc	Schmidt number, $\mu/(\rho D)$
Sh	Sherwood number, $h_m L/D$
St	Stanton number, $h/(\rho u c_p)$, or $Nu/(Re\,Pr)$
St_m	mass transfer Stanton number, $h_m/(\rho\nu)$ or $Sh/(Re\,Sc)$

Subscripts

a	air
i	inlet
m	mass transfer, or mean
o	outlet
s	saturation
w	water

The rate equation for heat or energy transfer is given by Fourier's law of heat conduction,

$$\frac{Q}{A} = -k\frac{\partial T}{\partial y} = -\alpha\frac{\partial(\rho c_p T)}{\partial y} \tag{2}$$

The rate equation for mass transfer is given by Fick's law of diffusion, i.e.,

$$\frac{\dot{M}}{A} = -D\frac{\partial c_i}{\partial y} \tag{3}$$

The diffusivities ν, α and D in Eqs. (1)–(3) have dimensions of $[L^2/T]$, where L and T refer to the length and time scales respectively. Any ratio of two of these coefficients will result in a dimensionless number. In systems undergoing simultaneous convective heat and momentum transfer, the ratio of ν to α would be of importance and is defined as the Prandtl number, i.e.,

$$Pr = \frac{\nu}{\alpha} = \frac{c_p\mu}{k} \tag{4}$$

In processes involving simultaneous momentum and mass transfer the Schmidt number is defined as the ratio of ν to D, i.e.,

$$Sc = \frac{\nu}{D} \tag{5}$$

In processes involving simultaneous convective heat and mass transfer, the ratio of α to D is defined as the Lewis number, i.e.,

$$Le = \frac{\alpha}{D} = \frac{k}{\rho c_p D} = \frac{Sc}{Pr} \tag{6}$$

From Eq. (6) it can be seen that the Lewis number is equal to the ratio of the Schmidt to the Prandtl number and is relevant to simultaneous convective heat and mass transfer. The relative rate of growth of the thermal and concentration boundary layers are determined by the Lewis number. The temperature and concentration profiles will coincide when $Le = 1$.

3. Lewis factor

In addition to the Lewis number, Le, the Lewis factor, or Lewis relation, Le_f, can be defined: it gives an indication of the relative rates of heat and mass transfer in an evaporative process. In some of the literature encountered there seems to be confusion about the definitions of these dimensionless numbers and the Lewis factor is often incorrectly referred to as the Lewis number.

The Lewis factor, Le_f, is equal to the ratio of the heat transfer Stanton number, St, to the mass transfer Stanton number, St_m where

$$St = \frac{Nu}{Re\,Pr} = \frac{h}{\rho u c_p} \tag{7}$$

$$St_m = \frac{Sh}{Re\,Sc} = \frac{h_m}{\rho u} \tag{8}$$

where Nu is the Nusselt number, or dimensionless heat flux, and Sh is the Sherwood number, or dimensionless mass flux.