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International Journal of Refrigeration 30 (2007) 1207–1214
REVUE INTERNATIONALE DU FROID
INTERNATIONAL JOURNAL OF
refrigeration
www.elsevier.com/locate/ijrefrig

Heat and mass transfer characteristics in a spray chamber

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Received 15 August 2006; received in revised form 15 February 2007; accepted 19 February 2007
Available online 12 March 2007

Abstract

This paper presents a one-dimensional mathematical model for heat and mass transfer of water droplets in a spray chamber. The model includes drop size distribution and velocity of the droplets generated by a nozzle of inlet diameter 3.2 mm. By using the conservation of mass and energy, the changes in water temperature, air temperature and humidity along the spray cone in the spray chamber can be calculated. This model is tested with two different water mass flows. The results look reasonable from practical point of view and they also show that higher water mass flow results in a higher air temperature drop and higher humidity.

Keywords: Air conditioning; Humidifier; Modelling; Heat transfer; Mass transfer; Drops; Parameter; Geometry; Speed

Caractéristiques de transfert de chaleur et de masse dans une chambre de pulvérisation

Mots clés : Conditionnement d'air ; Humidificateur ; Modélisation ; Transfert de chaleur ; Transfert de masse ; Gouttelettes ; Paramètre ; Géométrie ; Vitesse

1. Introduction

Sprays play an important role in many engineering applications, for example, in combustion of liquid fuels, agricultural applications, painting, direct injection condensers and cooling. Detailed knowledge of drop size and velocity distributions of the spray is of ultimate importance for the estimation of heat and mass transfer from droplets in practical spray systems. The purpose of such sprays is to increase the surface area of the injected liquid, thereby increasing the heat and mass transfer rates.

The theory most often used to obtain the droplet size distribution is known as the maximum entropy principle (MEP) [1–5] which draws together concepts from information theory, statistical inference, optimization and a precise knowledge of the practical information about a physical system. The MEP formalization together with the principle of momentum, energy and mass conservation allow one and only one droplet size distribution, given the properties of the spraying nozzle, liquid, surrounding gas and mass flow of liquid.

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doi:10.1016/j.ijrefrig.2007.02.013

Nomenclature

A	cross-sectional area (m^2)
A_i	surface area of droplet of diameter D_i (m^2)
c_p	specific heat (kJ kg^{-1} K^{-1})
c_D	drag coefficient
D	diameter of droplet (m)
D_{aw}	diffusion coefficient of air−water vapor (m^2 s^{-1})
D_{30}	volume mean diameter (m)
D_{32}	Sauter mean diameter (m)
d_o	diameter of nozzle hole (m)
$\boldsymbol{e}_z$	unit vector in z-direction
$\mathbf{F}_D$	drag force (N)
h_i	convection heat transfer coefficient for droplet of size D_i (W m^{-2} K^{-1})
h_{mi}	mass transfer coefficient for droplet of size D_i (kg m^{-2} s^{-1})
i''_v	specific enthalpy of saturated vapor (kJ kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
l	length (m)
M_a	molecular weight of air (kg mol^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N_i	number of droplets of diameter D_i
N_{tot}	total number of droplets
Nu_{D_i}	Nusselt number for droplet of diameter D_i
$\tilde{N}(D)$	fractional proportion of droplets smaller than D
Pr	Prandtl number
p	pressure (Pa)
q	heat transfer rate (W)
R	universal gas constant (kJ kg^{-1} K^{-1})
Re_{D_i}	Reynolds number for droplet of diameter D_i
Sc	Schmidt number
t	temperature (K)
Δt	time range (s)
U	velocity of droplets (m s^{-1})
U_o	velocity of liquid at nozzle outlet (m s^{-1})
We	Weber number
z	length coordinate (m)
z^*	non-dimensional coordinate

Greek symbols

α_i	fractional proportion of droplets of size D_i
β	spray cone angle (°)
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})

Subscripts

a	air
m	mean
d	disintegration
g	gas
l	liquid
p	psychrometric
s	surface
tot	total
v	vapor
w	water

Superscripts

$''$	saturated state

Up to now, the calculation of heat and mass transfer from droplets in a spray chamber system (for instance in cooling towers) has been used based on the unit volume coefficient [6−11]. However, neither much information has been derived about how this coefficient can be calculated nor about its values.

In the following section, we will present a mathematical model about heat and mass transfer from droplets in a spray chamber. The size distribution of droplets and their velocity distribution is based on MEP. No unit volume coefficient is needed, hence the heat and mass transfer can be calculated directly without using that concept.

2. Droplet size distribution and velocity

Liquid is delivered to the spray chamber through a nozzle. Since the pressure of the liquid is high and the hole in the nozzle is very small, the continuous flow of liquid will disintegrate into small droplets. The schematic diagram of the spray chamber is illustrated in Fig. 1. In order to mathematically predict what happens to the water flow temperature, air temperature and humidity in the spray chamber, the droplet size distribution and its corresponding velocity distribution must be first determined. The water temperature,

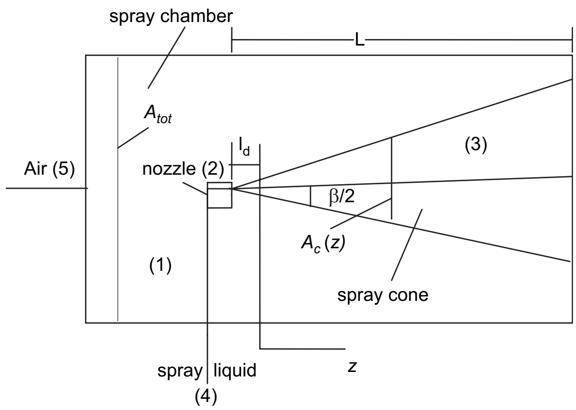

Fig. 1. Schematic diagram of a spray chamber: (1) spray chamber, (2) nozzle, (3) spray cone where the droplets are generated, (4) spray liquid to the nozzle and (5) air flow to the spray chamber.