International Journal of Heat and Mass Transfer 52 (2009) 3842–3849

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Low pressure evaporative cooling of micron-sized droplets of solutions and its novel applications

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ARTICLE INFO

Article history:
Available online 7 April 2009

Keywords:
Free molecular regime
Air cooler
Colloid solution
Nanoparticles growth

ABSTRACT

For free molecular regime the mathematical model of low pressure evaporative cooling of binary droplets in gas flow is developed. The model includes five ordinary differential equations and takes into account effects such as the release of the latent heat of condensation of both components and the release of the latent heat of dissolution. Simulations were made for weak aqueous solutions of ammonia. It was discovered that compositions of gas flow and the aqueous solution affect the rate of evaporative cooling of droplets. The ratio of mass flow of solution and gas flow is also an important parameter. The cooling rate of such binary droplets can reach the value of about 2×10^5 K/s.

As first applications we consider the air cooler based on evaporative cooling of droplets. For pressure of 20–80 Torr in aerosol reactor, it is shown that in the cooler with length of about 1 m temperature of air flow may drop to about 10–15 °C.

The second application is the formation of nanoparticle in evaporating multicomponent droplet with two volatile components. Simulation was made for aqueous solution of ammonia which is widely used by experimentalists and engineers now. Effects of the number of precursors in droplet and supersaturation in droplet on the final size of nanoparticles were investigated.

1. Introduction

Evaporative cooling of micron-sized droplets at a low pressure in a flow aerosol reactor can give new perspectives for a number of modern technologies. In particular, in this paper we will show that this phenomenon can be used for the creation of ecologically friendly ventilation and air conditioning systems. It is already known that the evaporative cooling of micron-sized droplets of solutions plays an important role in the novel method of nanoparticles production: a low pressure pyrolysis of droplets of solutions in a flow aerosol reactor [1]. There are no doubts that new applications of evaporative cooling of micron-sized droplets will be found soon! To mention only the application of it at the mass spectroscopy [2]!

Recently, experimental data and simulation results devoted to the evaporative cooling of micron-sized droplets of pure water have been published in [3]. In particular, it was discovered that the rate of cooling of pure water droplets reaches 2000 K/s at total pressure of 20 Torr in the flow aerosol reactor. For description of heat and mass transfer of evaporating droplets under low pressure we have to use the free molecular (kinetic) approach. Some fundamentals of the kinetic description of the evaporation–condensation of droplets are given in the famous classic book [4]. Recently, important applications of kinetic approach to evaporation have been presented in publications [5–6] and references therein. It is worth to mention that the evaporation of binary droplets was considered at the diffusion approximation in [7].

The evaporation of two and more volatile substances from droplets gives additional possibilities for the control of the cooling rate of droplets. For the control of the production of semiconductor nanoparticles in multicomponent droplets the evaporation of two volatile substances already has been used in the flow aerosol reactor [8].

Besides we consider that the evaporative cooling of micron-sized droplets could find application in coolers of gas flows [9]. High cooling rates of micron-sized droplets permit to design some compact heat exchangers. Cooling of stagnant air, based on the effect of evaporative cooling of water droplets, is widely used in greenhouses now.

The aim of this work is the development of the mathematical model of the evaporative cooling of micron-sized droplets with two volatile substances in gas flow. Additionally we give example of the calculation of performance of the air cooler based on a low pressure evaporative cooling of micron-sized droplets. We consider water and ammonia as two volatile substances. It is worth to emphasize again that developed mathematical model can be applied only for relatively low pressure in aerosol reactor; in other words at the free molecular approximation.

The paper is organized as follows. First we discuss the kinetics of evaporative cooling of binary droplets of a micron size in a flow

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doi:10.1016/j.ijheatmasstransfer.2009.02.017

Nomenclature

A	energy flow (W/m^2)
$c(x)$	specific heat capacity of solution (J/(kg K)
c	heat capacity per one molecule in gas phase (J/K)
D	diffusion coefficient (m^2/s)
E	droplet enthalpy (J)
H	the Henry constant (Pa^{-1})
I	source term
k	Boltzmann's constant (J/K)
L	characteristic length of cooler (m)
M	mass soluble impurity in droplet (kg)
m	mass of molecule (kg)
N	the number of something in droplet
P	pressure (Pa)
Q	mass flow rate per unit cross-section (kg/m^2 s)
R	radius (m)
r	radius of hole in the atomizer (m)
Re	the Reynolds number
S	supersaturation of solution in droplet
T	temperature (K)
t	time (s)
u	velocity (m/s)
U	heat per one molecule (J)
x	molar fraction of ammonia
z	distance (m)

Greeks

α	heat transfer coefficient of air flow (W/m^2 K)
λ	hear conductivity coefficient (W/m^2 K)
ρ	density (kg/m^3)
μ	dynamic viscosity (m^2/s)
σ	surface tension (J/m^2)

Subscripts

0	initial air in the clearance
1	aerosol reactor
2	clearance
A	ammonia
ag	ammonia in gas phase
as	saturated ammonia over aqueous solution of ammonia
av	ammonia vapor
c	colloid
cl	clearance
d	droplet
dis	dissociation
g	carrier gas
m	gas mixture
st	steady state
w	water
ws	saturated water vapor over solution
wv	water vapor

aerosol reactor. We apply kinetic approach based on the free molecular approximation because for low pressure the mean free paths of vapor molecules are significantly larger than droplet diameter. Next, we use our mathematical model of evaporative cooling for the description of the performance of an air cooler. In Section 4 we briefly discuss nanoparticles production in an evaporating multicomponent droplet. This process is greatly accelerated if there is a colloid solution in a droplet. Some preliminary results of this research have been published in [10] and reported in [11].

2. Mathematical model

The sketch of the flow aerosol reactor is shown in Fig. 1. The constant pressure is contained by vacuum pump and a controller with good accuracy. After the atomizer at the inlet of the aerosol reactor, the temperature of droplets is equal to that of the gas flow one. The composition of gas flow in the aerosol reactor is the same one as before aerosol reactor. The molar fraction of ammonia in droplets and one in gas flow may differ. We consider nitrogen as the carrier gas below.

For relatively low mass flow rates of solution the average distance between the droplets in the aerosol reactor is much larger than a droplet diameter. Therefore heat and mass transfer processes, related to evaporation, can be considered just for one droplet. Let us consider the droplet that has N_w of water molecules and N_a of ammonia molecules; to denote the droplet temperature as T_d. Then for radius R_d of this droplet we have algebraic equation

$$\frac{4\pi R_d^3}{3}\rho(x) = m_a N_a + m_w N_w, \tag{1}$$

where m_aиm_w are, respectively, molecular mass ammonia and water, $\rho(x)$ is the mass density of aqueous solution of ammonia. The molar fraction of ammonia x is determined by the following expression:

$$x = \frac{N_a}{N_a + N_w},$$

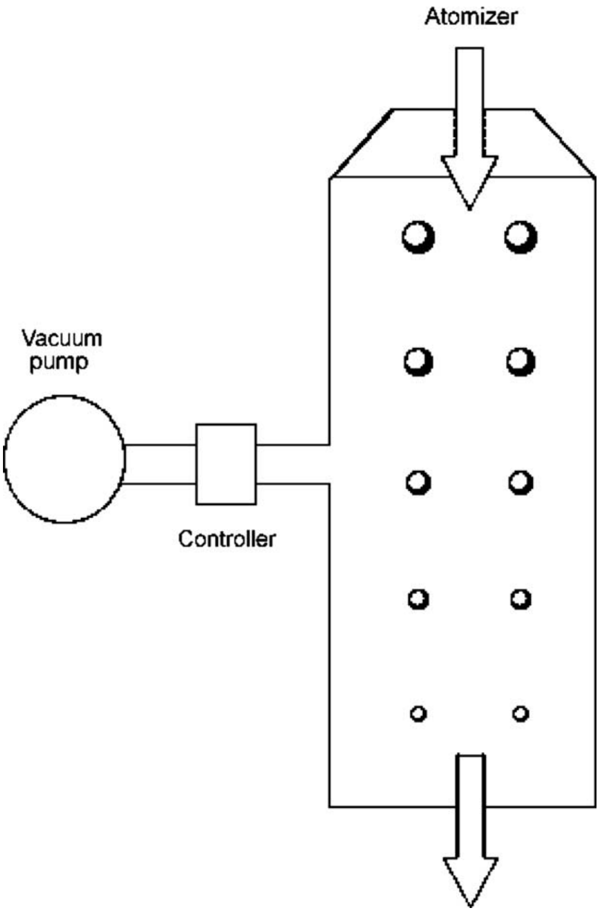

Fig. 1. Sketch of a low pressure aerosol reactor.