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Unsteady multi-phase mass transfer modeling and analysis for the process of the ammonia volatilization from yarn bobbin

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ABSTRACT

An unsteady multi-phase mass transfer model is developed to analyze and discuss the mass transfer characteristics in the process of the ammonia volatilization from yarn bobbin. The model considers the mass diffusion in the porous material, concentration distribution in boundary layer and the mass convection diffusion in the air flow. The five key parameters of the model are solved by giving the analytic expressions and calculating formulas expectively. With the experimental results from lattice distortion modification production equipment, the two main unknown parameters of the concentration partition coefficient and the diffusion coefficient were determined by data fitting method based on the proposed mass transfer model. The mass transfer model was used to investigate the ammonia medium mass transfer characteristics. The results show that the concentration distribution in the yarn bobbin is mainly related to the air flow velocity and the volatilization time. The concentration gradient between the center and the surface enhances with the increasing of the air flow velocity. But the impact of the air flow velocity on the concentration gradient decreases with the volatilization time extension. The mass transfer rate improves with the air flow velocity increasing, and decreases with the yarn bobbin radius increasing. The normalized concentration and the normalized volatilized mass have no relation with the initial concentration, but are just determined by the inherent mass transfer properties of the ammonia medium in yarn bobbin.

1. Introduction

Lattice distortion modification technology is a kind of natural fabric finishing process. It uses the liquid ammonia which has small molecular weight and high viscosity characteristics as the medium to fully contact with fiber tissue in reaction kettle. This process can generate crystal distortion effect. As a result, the performance of raw textile is significantly improved to achieve the advantages of easy to dye, easy to weave and easy to spin [1]. After lattice distortion modification, the yarn bobbin is full of the residual ammonia medium [2]. The air flow is fed into the kettle from the bottom to enhance the residual ammonia volatilization from the yarn bobbin. Thus research on the mass transfer characteristics of the ammonia medium plays a very important role in developing better ammonia removal process.

Physical model based on the fundamentals of mass transfer is the most common method to solve mass transfer problem. One research hotspot is mainly focused on the study of mass transfer process in porous material, which is mainly related to the engineering practice. Crank [3] discussed the mass transfer process in detail and built the mass transfer model using the mathematical analysis method. Huang and Haghighat [4] developed a plate mass transfer model to predict the volatile organic compounds emission from dry building materials. Yan et al. [5] proposed a new analytical solution for the wall film heating up and evaporation with consideration of the unsteady. These studies put the specific process to be equivalent to an infinite plate mass transfer [6–10]. The established models are usually the two order partial differential equations with the second or three kind of boundary conditions [11–14]. The ammonia volatilization from the yarn bobbin is an unsteady multi-phase mass transfer ignored the temperature and other factors, which contains three processes of the diffusion mass transfer within the material, the concentration distribution in boundary layer and the convection diffusion in the air. The infinite plate mass transfer modeling method is not suitable for this process. The modeling and analysis of the mass transfer process of the ammonia volatilization from yarn bobbin is a challenging research target.

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Nomenclature

Symbols	
A, m, n	parameters in relational expression of Sh, Re and Sc [–]
C	medium concentration [g m^{-3}]
C_0	initial medium concentration [g m^{-3}]
C_a	gas medium concentration in air flow [g m^{-3}]
C_{as}	gas phase medium concentration in boundary layer [g m^{-3}]
C_{avg}	average concentration [g m^{-3}]
C^*	normalized concentration [–]
D	diffusion coefficient [m^2 s^{-1}]
D_a	diffusion coefficient of gas medium in the air [m^2 s^{-1}]
h	time [h]
k_a	convective mass transfer coefficient [m s^{-1}]
l	length along air flow direction [m]
M_0	initial mass of medium in cylinder [g]
M_1	initial weight of cylinder contained medium [g]
M_{all}	weight of cylinder contained medium [g]
M_d	weight of dry cylinder [g]
M_p	medium volatilized mass [g]
M_h	medium mass in cylinder at time h [g]
M^*	normalized volatilized mass [–]
P_0	standard atmospheric pressure [Pa]
P_{air}	air flow pressure [Pa]
Re	Reynolds number [–]
r	coordinate value on the r axis [m]
r_0	radius of cylinder [m]
r - θ - z	cylinder coordinate system [–]
$\dot{r}$	medium generation rate [g m^{-3} s^{-1}]
S	contact area [m^2]
Sc	Schmidt number [–]
Sh	Sherwood number [–]
T_0	standard temperature [K]
T_{air}	air flow temperature [K]
t	time [s]
t_p	time step [h]
u_a	air velocity over cylinder surface [m s^{-1}]
u_r, u_θ, u_z	medium velocity in r-, θ-, z-direction [m s^{-1}]
w	unit conversion ratio between hour and second [–]
z	coordinate value on the z axis [m]
z_0	length of yarn bobbin [m]
Greek letters	
ΔC_{avg}	average concentration step [g m^{-3}]
Δr_0	radius step [m]
ζ	liquid and gas partition coefficient [–]
θ	coordinate value on the θ axis [rad]
μ	equation variable [–]
ν	kinematic viscosity of air [m^2 s^{-1}]
τ	mass transfer time [s]
Subscripts	
n	referring to a eigenvalue element

This paper developed a mass transfer model to analysis and discuss the process characteristics of the special process. The structure of this paper is organized as follows. In Section 2, the model was developed based on fundamentals of the mass transfer, and the analytical solution was obtained by variable separation method. The five key parameters were discussed and determined. In Section 3, through the experiment based on the lattice distortion modification production equipment, the partition coefficient and the diffusion coefficient in the model were determined. In Section 4, the medium concentration in yarn bobbin was calculated and simulated by the proposed mass transfer model. The mass transfer characteristics were analyzed and discussed. Finally, the conclusions were given in Section 5.

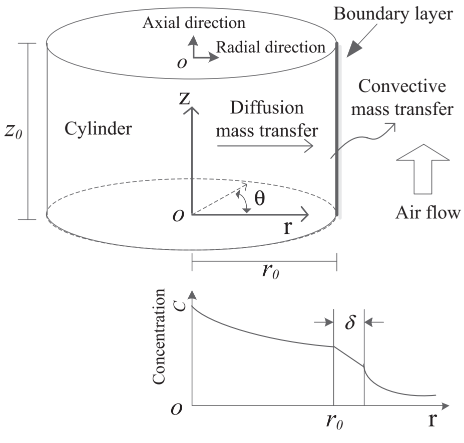

Fig. 1. Schematic diagram of the mass transfer process.

2. Development of the mass transfer model

As to the cylinder unsteady mass transfer problem, suppose there is a porous material infinite cylinder, and the internal liquid medium diffuses along the radial direction, and transfers into gas phase in the boundary layer. The convective mass transfer exists between the cylinder surface and the air flow outside the cylinder. The air flow direction is parallel to the axial direction of the cylinder. Before modeling for the mass transfer process, there are several assumptions. First, the cylinder temperature is assumed to be stationary, in other words, heat exchange in the cylinder is ignored. Second, one-dimensional mass transfer from the central to the surface in the cylinder is only considered, and the axial mass transfer is ignored. Third, the lateral surface of the cylinder is considered as the only contact area with the outside. Fig. 1 shows the schematic diagram of the mass transfer process.

As seen in Fig. 1, the cylinder coordinate system r-θ-z is set up at the central axis of the cylinder, and the cylinder unsteady mass transfer is composed of three main processes: the diffusion mass transfer inside the cylinder, the concentration distribution in boundary layer and the convection diffusion outside the cylinder.

2.1. Diffusion mass transfer in the cylinder

Considering that the concentration gradient is the only driving force for the diffusion mass transfer. For the medium with homogeneous diffusivity in the cylinder, the diffusion mass transfer process can be described by the unsteady diffusion equation [6] in the cylindrical coordinate system as

$$\frac{\partial C}{\partial \tau} + u_r \frac{\partial C}{\partial r} + \frac{u_\theta}{r}\frac{\partial C}{\partial \theta} + u_z \frac{\partial C}{\partial z} = D\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 C}{\partial \theta^2} + \frac{\partial^2 C}{\partial z^2}\right] + \dot{r} \tag{1}$$