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Theoretical and experimental study of heat and mass transfer mechanism during convective drying of multi-layered porous packed bed☆

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ABSTRACT

In this paper, the experimental validation of a combined mass and thermal model for a convective drying of multi-layered packed beds composed of glass beads, water and air is presented. The effects of the drying time, particle size and the layered structure on the overall drying kinetics are clarified in detail. Based on a completed model combining the temperature, total pressure and moisture equations, the results show that the convective drying kinetics strongly depend on the particle size as well as hydrodynamic properties and layered structure, considering the interference between capillary flow and vapor diffusion in the multi-layered porous packed bed. The predicted results are in a good agreement with the experimental results.

1. Introduction

From a theoretical standpoint, the drying process of porous media is a complicated process involving simultaneous, coupled heat and mass transfer phenomena. Modeling simultaneous heat and mass transport in porous media is of growing interest in a wide range of new technology. In order to improve process performance and energy utilization for new technologies related to tertiary oil recovery processes, medical application, geothermal analysis, freeze drying processes, forest product, building materials, food stuffs and microwave drying process have been applied. Knowledge of heat and mass transfer that occurs during convective drying of porous materials is crucial to reduce energy cost of drying, equipment and process design, and preserve the quality of products.

The analysis of heat and mass transfer in porous materials has been the subject of theoretical and experimental work for several decades. Most theories have been proposed to explain the physical phenomena of drying process in porous materials: the diffusion theory, the capillary flow theory and the evaporation–condensation theory. A convenient starting point of drying theory is found, in the work of Whitaker [1] who has derived appropriate local volume averaged conservation equations for two-phase capillary flow in porous media. The mathematical models for simultaneous heat and mass transfer during convective drying of porous media have been studied by many authors [2–9]. These previous models are based on Whitaker's theory, taking into account the thermal and mass transfer as well as the total gaseous pressure. Recently, the evolution of phase distributions within the network during drying in capillary-porous media are visualized and compared to numerical discrete simulations [10]. Also many researchers such as Bae [11], Lamnatou [12], Bubnovich [13,14], Kaya [15,16] and Kim [17] have used mathematical principles to analyze heat and mass transfer in porous materials. This does not explain the mechanism of heat and mass transfer clearly. However, most of the previous works deal with the drying of uniform materials. Indeed, little effort has been reported on the study of drying process of non-uniform material i.e., multi-layered material especially a complete comparison between mathematical model and experimental data.

Typical applications of non-uniform material include the tertiary oil recovery process, geothermal analysis, asphaltic concrete pavement process and preservation process of food stuffs. Therefore, knowledge of heat and mass transfer that occurs during convective drying of multi-layered porous materials is necessary to provide a basis for fundamental understanding of convective drying of non-uniform materials. There is one published study of heat and mass transport in non-uniform material, that by Plumb [18]. This paper contains a useful review, an experimental study of heat and mass transfer in non-uniform material, and supporting numerical work.

From a macroscopic point of view, the effects of the particle sizes, hydrodynamic properties, and the layered location on the overall drying kinetics must be clarified in detail. Therefore, the specific objectives of this work are to: (1) solve the mathematical model numerically, (2) compare the numerical results with experimental measurements and (3) discuss the effect of particle size and the layered location on the overall drying kinetics.

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