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Thin-layer infrared drying characteristics of construction gypsum plaster and selection of a suitable drying model

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HIGHLIGHTS

- Infrared drying behaviour and modelling of construction gypsum plaster are investigated.
- The falling rate period at low drying temperatures, but all rate periods at the high drying temperatures.
- Due to porous structure disappears, the drying is not suitable at temperatures above 85 °C.
- The best fitting test result for multiple nonlinear regression analyses is obtained from derived diffusion equation.
- The effective diffusivities and activation energy of the drying process are determined.

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ABSTRACT

In this study, infrared drying behaviour of construction gypsum plaster samples was investigated. Experimental studies were carried out by using an infrared dryer at different temperatures (50–85 °C) and at atmospheric conditions. As a result, the falling rate period was the drying rate period for the drying of gypsum plaster samples at low temperatures studied (50 °C and 65 °C). But, three drying rate periods consisting of beginning, constant, and falling periods occurred at the high temperature studied (85 °C). FTIR and SEM analyses were performed to determine microstructural and surface properties of raw material and dried gypsum samples. A typical FTIR spectra for construction gypsum plaster samples have been obtained. It has been observed that dried gypsum plasters at the temperatures of 50 °C and 65 °C have a porous structure. On the contrary, raw material and dried gypsum at temperature of 85 °C were no almost porous structure according to the gypsum plasters at other temperatures studied. Thus, it may be said that the drying process for construction gypsum plaster sample should be performed at temperatures below 85 °C. In this work, the experimental drying data have also been fitted to various model equations by statistical testing. The most suitable model equations for drying of construction gypsum plasters have been determined by analysing the statistical test parameters such as chi-square, RMSE, and RSS at the temperatures studied. It has been founded that these models are Page and Diffusion equations. Also, derived forms of Page and Diffusion equations have been used to obtain an equation containing both drying time and temperature by multiple nonlinear regression analysis. As a result, it has been determined that a model derived Diffusion equation is the best representing the drying of CGP. Finally, the effective diffusivities and activation energy for the drying process of construction gypsum plaster samples have been calculated. The effective diffusivity values were $2.9920 \times 10^{-9}\ m^2/s$, $3.7527 \times 10^{-9}\ m^2/s$, and $3.9386 \times 10^{-9}\ m^2/s$ at temperatures of 50 °C, 65 °C, and 85 °C, respectively. The activation energy value was also 7.3795 kJ/mol.

1. Introduction

Drying is usually the final mass transfer process step before packaging in many industrial applications such as chemical, pharmaceutical, metallurgical, and agricultural operations. In the manufacturing of many building materials (for example, ceramic, bricks, and drywall), drying is one of the most important production process steps [1–3]. In the building envelopes, high moisture content may also lead to structural and/or aesthetic problems [4]. Thus, investigation of drying kinetics, characteristics, and modelling of building materials are required to improve the product

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Nomenclature

a, b, c, g, n, k	model constants
CGP	Construction Gypsum Plaster
DM	Derived Model
A_0	Arrhenius constant
$\overline{d}_{pore}$	Mean pore diameter (m)
$\overline{d}_p$	Mean particle diameter (m)
D_L	Liquid diffusion coefficient or effective diffusivity (m^2/s)
E_a	Activation energy (J/mol)
L	Diffusion distance for solid material (m)
M	Moisture content (g water/g dry solid material)
M_e	Moisture content at equilibrium (g water/g dry solid material)
MR	Dimensionless moisture ratio (–)
MR_{exp}	Experimental moisture ratio (–)
MR_{pred}	Predicted moisture ratio (–)
M_t	Moisture content at any time (g water/g dry solid material)
M_0	Moisture content at the initial (g water/g dry solid material)
N	Number of data obtained from experimental studies
R	Ideal gas constant (J/mol K)
S_g	BET surface area (m^2/g)
t	Time (s)
T	Temperature (°C or K)
w_d	Weight of the dry solid material (g)
w_t	The weight of the solid material at any time (g)
z	Axial direction (m)

Greek Letters

ρ_s	Solid density (kg/m^3)

quality and to enhance processing efficiency parameters like energy usage and time.

One of the most widely used materials in the construction industry is gypsum product obtained generally from gypsum rock having calcium sulphate chemically combined with water of crystallization ($CaSO_4 \cdot 2H_2O$) as based mineral. There are many advantages of gypsum product construction: Fast installation, fire resistance, sound control, durability, light weight, low installation cost, easily decorated, and versatility [5]. Gypsum products can be classified as gypsum board (or plaster board), gypsum lath, gypsum sheathing board, gypsum partition block, and gypsum plank [6]. Gypsum boards are produced by a continuous process simply consisting of plaster preparation, cutting to length, drying, prefinishing, and packaging and are mostly used in drywall construction [1,6]. As seen, since the drying is an important phenomenon in the gypsum board production technology, it should be investigated in detail.

Due to the physical and chemical properties (particularly porous structure) of gypsum board materials, the drying method should be well chosen. Because, it has commercially significant impact on the product quality, drying time, and the process economy. The most primitive method in the drying technology is the traditional drying carried out by using solar energy in the outdoor air. The disadvantages of such drying are weather and climate dependency, long drying time, and difficulties of process control. One the most extensively used drying method in the industrial applications is the drying convectively performed by using hot air. The convective drying has also some limitations such as high energy use and long drying time. Recently, the radiative drying (infrared or microwave) has been developed as an alternative method to conventional drying techniques and has been used in numerous studies on many materials, especially food and bioproducts [7–12].

There are a great number of articles published about convective and microwave drying of various building materials [3,4,13–23]. But, according to the author' knowledge, there is no almost work on infrared (IR) drying of these materials.

The mechanisms of electromagnetic radiation extinction occur by two main ways: scattering and absorption. The scattering mechanism is redirection of the radiation energy by means of reflection, refraction, and diffraction. The absorption of radiation energy is conversion of the electromagnetic radiation to another forms of energy or some other spectral distributions [24]. The fundamental of IR drying is the latter mechanism, which IR energy is converted to sensible heat energy. IR radiation energy can be obtained from a monochromatic source (laser) or a polychromatic source (quartz-tungsten-halogen lamp) [25]. The amount of radiation absorbed can be measured by Beer's Law. According to Beer's Law for non-homogeneous systems, for example emulsions and dispersions or porous solids, the transmission of spectral irradiance depends on the original spectral irradiance, the mass of absorbing medium per unit area, and spectral extinction coefficient. Nonporous solid materials usually absorb the IR radiation in a thin layer surface. But, the radiation penetrates into deeper points in porous materials. The radiation transmissivities of porous bodies relate to their moisture content. During IR drying, the radiation property changes due to decreasing of the moisture content. While the short wavelength IR radiation is transmitted in water, the long wavelength IR radiation is absorbed. Dryer equipment for IR drying is compact and has easily controllable feature [11,24,26].

To design, scale up, and improve the drying systems, mathematical models developed and numerical approaches for drying of the solid materials have been used in many studies [11,22,27–29]. However, there are a few papers that those mathematical model equations for the gypsum plaster drying processes have been fitted to the experimental data [3,19].

In this paper, thin layer IR drying kinetics and characteristics of construction gypsum plaster (CGP) have been investigated at different temperatures. Also, the experimental moisture ratio values changing with time were fitted to some mathematical models in literature.

2. Drying rate, water diffusion, and mathematical modelling of drying curves

2.1. Drying rate curves

Experimental data required for drying calculations are obtained by measuring the weight of the wet solid material with the time throughout the drying process. To introduce the type of the drying rate, these data should be converted to the rate of drying data. For this purpose, the moisture content values are firstly calculated by the following equation:

$$M = \frac{w_t - w_d}{w_d} \tag{1}$$

where M is the moisture content (g water/g dry solid material) of the solid material, w_t is the weight (g) of the solid material at any time, and w_d is the weight (g) of the dry solid material [2,7,11].