Experimental Study of Drying Process of Porous Materials

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Abstract :

This work presents a study of a convection drying process of sand porous bricks under forced air with variable conditions to investigate the effect of drying conditions that is the air velocity, temperature and relative humidity on drying curves. Experimentally, a test rig constructed in the lab to study the influence of different conditions on drying curves as well as on heat and mass transfer characteristics associated with the drying process. The experimental results were presented and discussed. From the results obtained, it was found that the sand porous samples drying process is affected by drying conditions, where the drying rates increases with higher velocity and temperatures conditions.

Keywords : Drying - porous materials - drying conditions - heat and mass transfer

Nomenclature

A_p	Area exposed to the flow [m^2]	T_a	Ambient temperature [K]
H	Channel height [m]	T_{wb}	*Wet bulb* temperature [K]
h	Heat transfer coefficient [w (m^{-2} K^{-1})]	*t*	*time*
h	Sample height [m]	*W*	Moisture content [kg / kg dry basis]
h_{fg}	Latent heat of vaporization [J / kg]		
h_m	mass transfer coefficient [m/s]	*Greek Letter*	
k	Thermal conductivity [w (m^{-1} K^{-1})]	ε	Porosity
M_s	Mass of solid material [kg]	Φ	Relative humidity (%)
M_t	Total mass of the sample [kg]	ρ_a	Density [kg / m^3]
$\dot{m}_{evp}$	Evaporation rate [kg / m^2 s]	ρ_{wb}	Wet bulb density [kg / m^3]

Introduction:

Drying is a separation process in which the liquid contents is removed from solids in solid liquid systems, and its playing an important role in different industrial applications such food preservation, ceramic manufacturing, building materials, wood products, textile industry, chemical and pharmaceutical products. In most industrial drying operations, heat is supplied externally to a product by a drying medium to provide energy for moisture evaporation and removal. Drying of porous materials is a complex process of simultaneous heat and mass transfer characterized by external convective heat, and mass transfer to the drying medium, and internal transport within the wet solid. Internal transport is the less known of the drying process because of the complex interaction between the solid and different mechanisms of heat and mass transfer. Furthermore, the mechanisms of moisture migration is dominated by many physical variables at different drying stages, and the transport coefficients are function of moisture content and temperature within the porous body during drying operation. Generally, the drying process occurs mainly in two stages.

During the first stage of drying, that is, the constant rate period, the rate of evaporation from the material surface is independent of time, the evaporation rate being close to that from an open dish containing liquid, and the evaporation occurs at almost constant temperature which is wet bulb temperature. The resistance to internal movement of water is small compared with the resistance to removal of vapor from the surface, and so the surface is easily replenished. The constant rate period continues until critical moisture content is reached. After critical moisture content point, the drying in the falling rate period where the drying rate reduces progressively. Although the moisture is free moisture, but the surface of the porous material is no longer kept completely wetted because of depletion of water in the interior of the material and the moisture movement in the solid becomes insufficient to replenish the liquid being evaporated at the surface of the solid. Later in the falling rate period the plane of evaporation retreats into the interior of the material and a dry region is formed at the surface. Here the resistance to internal liquid movement becomes large compared to the total resistance to the removal of vapor, and evaporation occurs within the material and diffuses to the surface.

The drying process of different porous material was a subject of numerical and experimental investigation in order to study the effect of different internal and external conditions on the drying behavior of these materials as well as to obtain the optimum conditions for energy saving since drying is considered one of the most expensive operation in industry applications. CFD modeling of the drying process under different conditions studied by (Blocken, et al. [2], Defraeye, et. al [3,4], Chemkhi, et al. [6], Elhassen, A [7] and Younsi, et al. [11])

Also, experimentally the drying process studied and most researchers (Askari, et al. [1], Hamdami, et. al. [7], Kulasiri and Woodhead [8] Moropoulou et. al. [9], and Talukdar et. al. [10]) agreed that higher drying medium velocity and temperature and low relative humidity are favorable for drying process and lead to higher drying rates and hence shorter drying time. Material properties such as density, porosity, permeability and dimension of the material sample, exposed area to the flow, initial moisture content, and material temperature are the main parameters affecting the drying rate and time.

Experimental Installation:

Fig. (1) presents the experimental test rig developed in the laboratory. The tunnel has dimensions (0.15 m x 0.3 m x 1.5 m). The most important part of the installation is the drying chamber where the basic measurements and drying process occurs. Samples of sand porous bricks were placed in the dryer chamber where airflow parallel to the surfaces. The change in weight of the samples is controlled by a precision balance (Riselake 625, max 10000 gram, 0.05 gram precision) connected to a computer that allows storage of the values of the sample mass with time. Inlet air temperature and relative humidity are measured with a thermo-hygrometer (Testo 650). Air velocity is measured with vane probe (Testo 400). During the experiment the following parameters were controlled and recorded: drying time, inlet air velocity, inlet air temperature, inlet air relative humidity and sample mass.

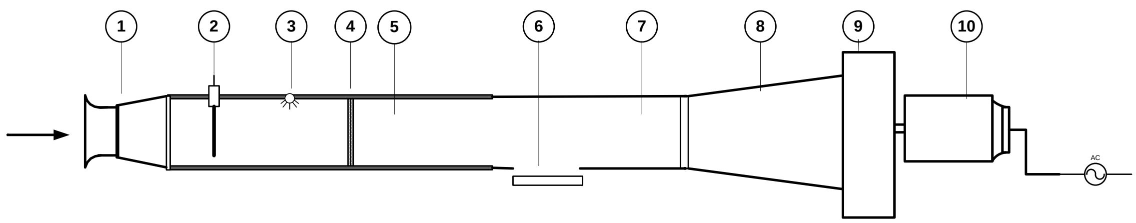

Fig. (1). Experimental test rig

1 - Inlet section	5 - First measuring point	8 - Extension duct
2 - Electric heater	6 – Digital mass balance.	9 - Blower
3 - Water spray	7 - Outlet measuring point	10 - Electric motor
4 – Perforated plate.		

Different experimental conditions were accomplished and drying behavior of sand porous bricks as well as the associated heat and mass transfer process where studied. Drying experiments carried out at different airflow speed, temperature and relative humidity of the drying medium, also the effect of sample size and porosity were tested.

The drying curves represents the moisture content loss with time during the drying process, the moisture content calculated using

$$W_t = \frac{M_t - M_s}{M_s} \quad \text{(kg of moisture / kg dry basis)} \tag{1}$$

Using the drying curve, the evaporation rate per unit area can be calculated by the equation :

$$\dot{m}_{evp} = \frac{M_s}{A_p} \left| \frac{dw}{dt} \right| \tag{2}$$

Since the major part of the drying process occurs close to the wet bulb conditions of the porous brick and most the moisture content within the brick is free moisture content. Hence, it is possible to define the heat and mass transfer coefficients with respect to a constant potentials (T_a - T_{wb}) and ($\rho_a - \rho_{wb}$) , such definition incorporates the coupled nature of heat and mass transfer during drying. Therefore, the heat and mass transfer coefficients can be calculated by the equations :

$$h_m = \frac{\dot{m}_{evp}}{\rho_a - \rho_{wb}} \tag{3}$$

$$h = \frac{\dot{m}_{evp} \; h_{fg}}{T_a - T_{wb}} \tag{4}$$

The heat flux due to evaporation is only included while the sensible heat is neglected, since it is very much smaller that latent heat.

Experimental Results:

The drying curves resulting from the experimental tests of the drying process under different drying conditions have the same trend and display mainly two drying periods. The constant drying rate exhibited by the linear part of the drying curve, and the non-linear or the concave portion of drying curve represents the falling rate period. The initial moisture content of porous materials is high enough, so that the surface is covered with a continuous layer of free water and evaporation takes place mainly at the surface. The movement of liquid is maintained mainly by capillary force. In this period, the internal moisture transfer to the surface and the evaporation at the surface are in equilibrium, and the free water on the surface will be evaporated steadily and continuously. As drying proceeds, the surface of the porous material is no longer kept completely wetted and starts to dry out due to reduction in moisture content in the interior of the sample. The moisture content at this point called the critical moisture content. Below this point, the drying in the falling rate period, where the drying process slows down and the evaporation rate decreases and the drying process controlled by internal diffusion and brick properties.

Based on the drying curves, the moisture content at the surface was higher than critical moisture content for most of the time corresponding to the constant drying rate period. During this period, the surface of the porous brick sample behaves like a wet bulb. Hence, the vapor concentration at the surface (ρ_s) and the surface temperature (T_s) is almost constant corresponding to wet bulb conditions of drying air. Consequently, the potential difference in temperature and concentration between the air and the brick surface (T_a -T_s) and ($\rho_s - \rho_a$) remain almost constant. Thus, the convective heat and mass transfer coefficients tends to remain constant. Later during drying, dry patches are formed at the surface which causes a reduction in evaporation rate causing the heat and mass transfer coefficients decrease with time due to reduction in moisture content at the surface, at the same time, brick surface temperature starts to converge towards the dry-bulb temperature of the drying medium.

1. *Effect of drying medium velocity :*

The drying curves of drying of porous bricks under different velocities are shown in Fig (2), the curves reveal that increasing air velocity resulting in increasing evaporation rate from the solid surface and hence increasing the heat and mass transfer coefficients. By increasing air velocity, the boundary layer thickness decreasing and therefore resistance to moisture flow due to the boundary layer would be negligible. Furthermore, an increase in air velocity increasing the convective transfer coefficients and consequently the moisture transfer between air and the surface of solid material, and hence improving conditions for evaporation. At a given temperature above critical moisture content, both heat and mass transfer coefficients tend to increase almost linearly with air velocity. During this period, the evaporation rate is constant, hence it can be increased by increasing the air velocity as long as water can move within the brick at a rate larger or equal to the surface evaporation. At the falling rate period that is below critical moisture content the heat and mass transfer coefficients for all velocities tend to decrease due to the reduction of evaporation rate from the surface and also the increase in surface temperature of the surface as shown in Fig (3) where the mass transfer coefficients increase with velocity and, at the same velocity, tend to remain constant at the constant rate period then decreases after critical moisture content, that is in the falling rate period. Similar trend can be observed in Fig. (4), where the results of local heat transfer coefficient is plotted.

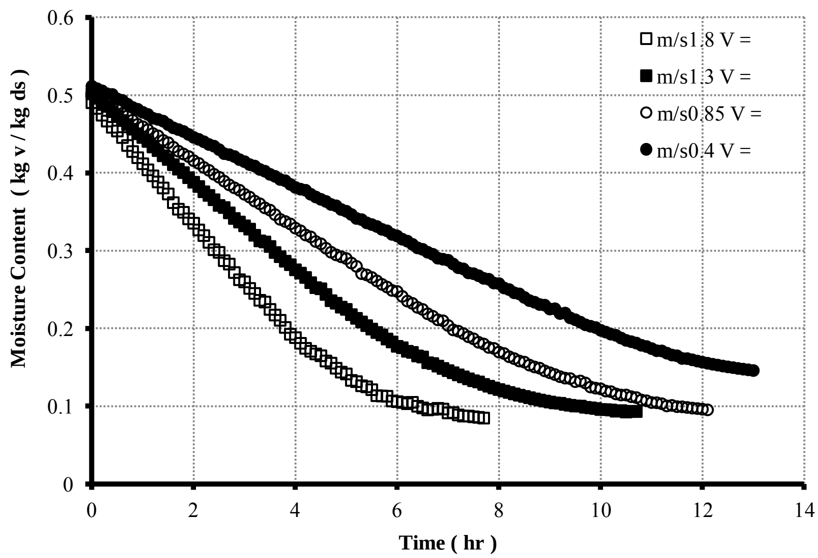

Fig. (2) Drying curves of brick drying at T = 50^{o}C and RH = 15% for different inlet air velocities

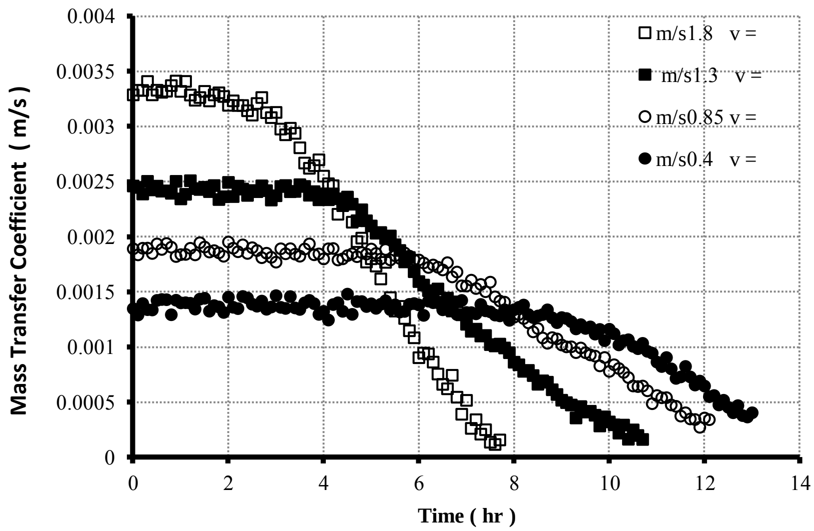

Fig. (3) Mass transfer coefficient at T = 50^{o}C and RH = 15% for different inlet air velocities

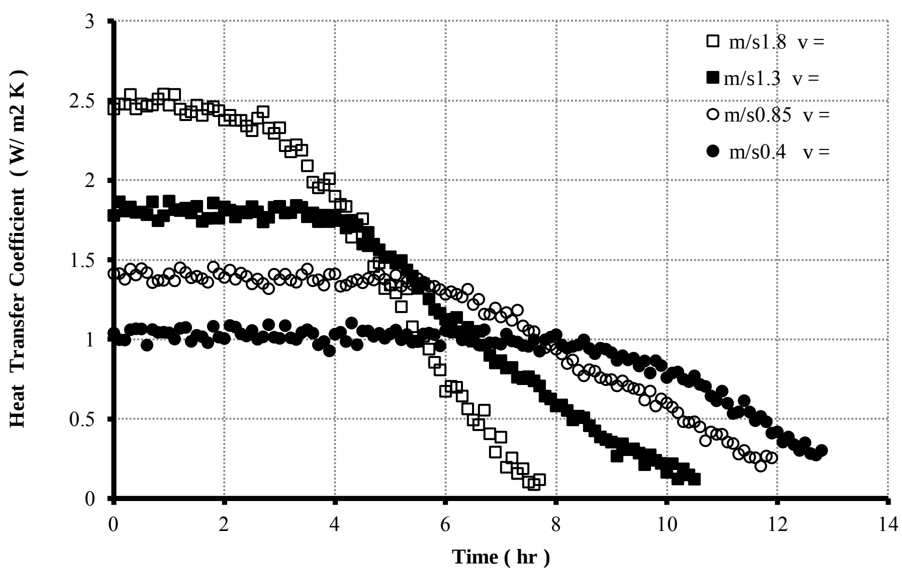

Fig. (4) Heat transfer coefficient of brick drying at T = 50^{o}C and RH = 15% for different inlet air velocities

2. ***Effect of drying medium temperature :***

Fig. (5) show the drying curve at different air temperature and as can be seen from the curve that increasing in air temperature, the drying process accelerated due to an increase in evaporation rate, also, increasing the difference in temperature between the brick surface and the surrounding air causes heat to be transferred from the air to the surface and this heat is used for evaporation at the surface. As the difference between the drying medium and surface temperatures increases, the evaporation rate increases, hence, increasing the air temperature and high temperature difference between the surrounding and the brick accelerates the heat and mass transfer process and consequently the drying process.

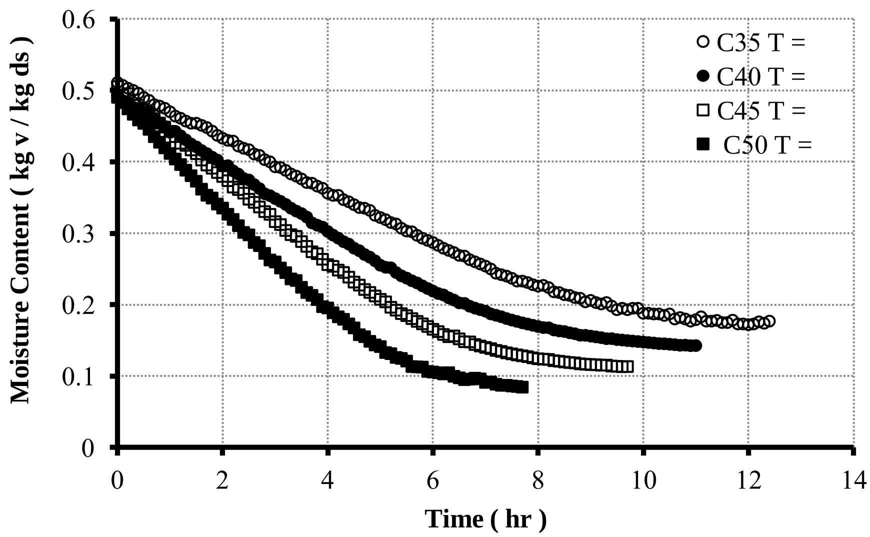

Fig. (5) Drying curve at V = 1.8 m/s and different air temperatures

3. ***Effect of drying medium relative humidity :***

The drying curve at different relative humidity and constant velocity and temperature is shown in Fig. (6). The relative humidity controls the rate of water vapor transport from the surface of the porous solid to the drying medium or air, so as relative humidity decreased the ability of air to absorb moisture content from the wet solid surface increased hence evaporation rate increases. Also, at constant air temperature, reducing the relative humidity decreasing the wet bulb temperature, therefore, the driving potential of heat transfer will be higher which accelerates the drying process. The variation of relative humidity of drying air changes the rate of moisture transfer between the surface and the flowing air. Hence lowering relative humidity increases the rate of moisture transfer and increases the evaporation rate, consequently increases heat and mass transfer coefficients.

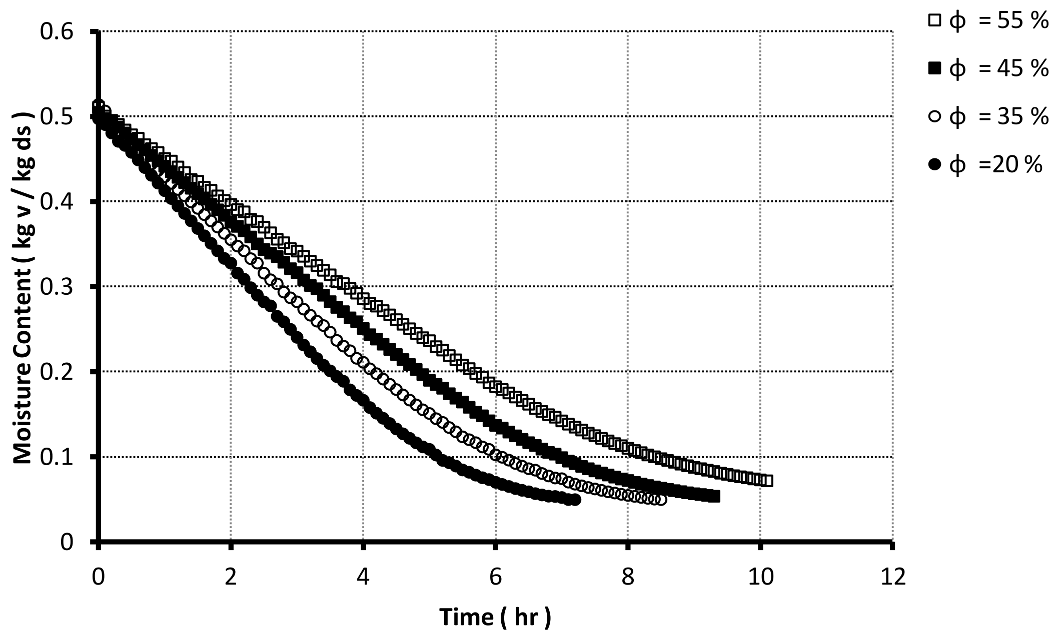

Fig. (6) Drying curves at V = 1.8 m /s and 55^{o}C

4. ***Effect of porosity :***

The porosity (ε) of a porous medium is defined as the fraction of the total volume of the medium that is occupied by void space. Thus $(1 - \varepsilon)$ is the fraction that is occupied by solid. Three different sample of sand bricks with different porosity are used to investigate the effect of porosity on the drying process. The drying conditions are kept almost the same during these tests. These conditions are v = 1.5 m/s , T = 40 ^{o}C and Φ =20 %. During drying the effect of porosity mainly observed during the constant rate period where the high porous sample has more void space and observes more moisture so, it has a longer constant rate period. This can be explained that at low porous sample it is difficult to pump out the moisture by capillary forces for longer time while at high porosity the free moisture content is more which allows the capillary forces to keep the surface wet above critical moisture content for longer time. At falling rate period higher porous sample has higher drying rate because the moisture diffusion and movement is easier and diffuse faster to the sample surface. This shown in Fig. (7) where the high porous sample dried faster than the other sample.

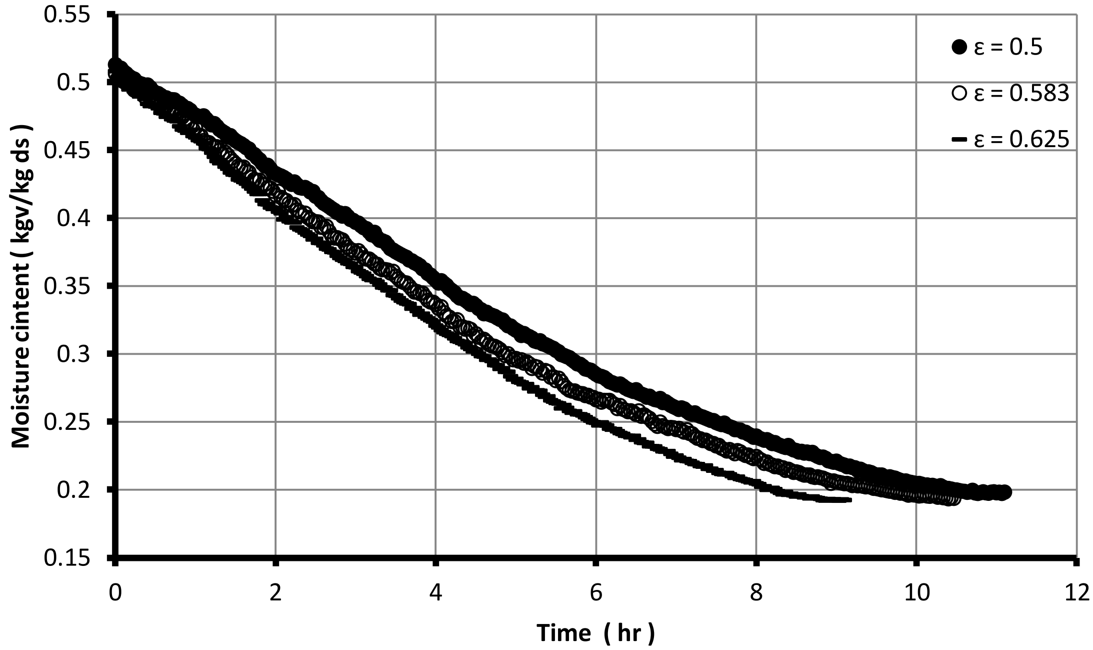

Fig. (7) Drying curves at v = 1.5 m/s , T = 40 ^{o}C and Φ =20 %. For different porosity samples

5. Effect of sample size :

It is easy to understand that under same drying conditions and samples properties, it takes more time to dry a larger sample. But it is not necessary that the relation between the total drying time and sample size is linear. Samples with same porosity and under same drying conditions of drying air, the effect of sample size was investigated by changing the sample height. As the height of the sample increased, the volume increased and hence more water content exist within the sample. The drying curves of this test are shown in Fig. (8). As can be seen from the drying curves that drying time increases considerably as the size of the sample increased indicating a long drying process. Also it is observed that for a larger value of sample size, the constant drying period is shorter indicating that the critical moisture content is higher, and the drying rate in the falling rate period is lower, therefore the drying process is slower. But for lower porosity the drying rate is low indicating long and slow drying rate.

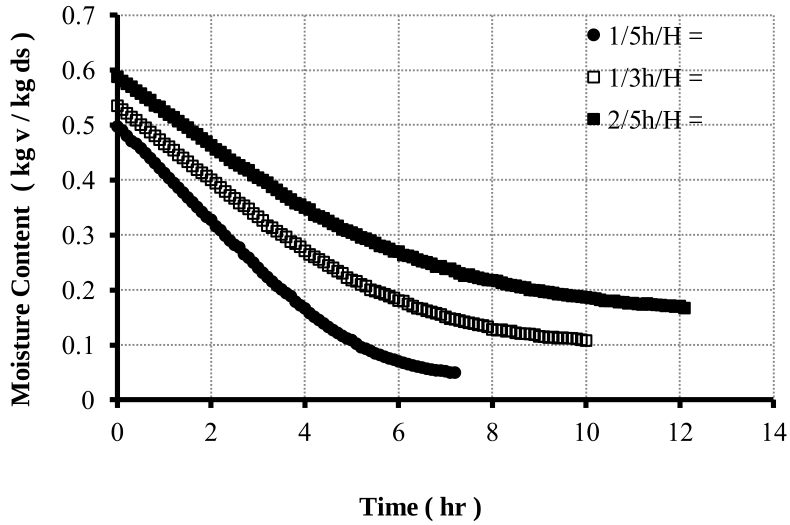

Fig. (8) Drying curves at V = 1.8 m /s , T= 55°C, and RH = 10 % for different sample heights

Conclusions

The drying process of porous materials under different drying conditions was experimentally investigated. From the results obtained, it can be concluded that :

- The heat and mass transfer coefficients are defined based on constant potential between inlet conditions and wet bulb conditions which more representive for the coupling nature of heat and mass transfer during drying process
- Temperature was found to be the most important factor of the drying rate for porous samples while the effect of air velocity and air humidity is considered lower than that of air temperature.
- Higher temperature and air velocity and low relative humidity are favorable conditions for drying process.
- Higher porous and small samples have shorter drying time.

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