Reynolds's Number Effect on Heat and Mass Transfer Characteristics Associated with Drying Process of Porous Materials

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Abstract:

An experimental study for forced convection drying process of sand porous bricks under forced air with variable inlet velocity conditions are reported. The study investigates the effect of Reynolds number on the heat and mass characteristics associated with the drying process of sand porous bricks. The inlet air temperature, relative humidity and porosity of the brick are kept constant. A test rig constructed in the lab to test different values of air velocities on drying curves as well as on heat and mass transfer coefficients of the drying process. The experimental results were presented and discussed. Results reveal that the drying curves consisted of two drying periods where the heat and mass coefficients notices to be constant at the constant rate period and decreasing at the falling rate period. The Nusslet and Sherwood numbers found to be increasing as the Reynolds number increased.

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

Nomenclature

A_p	Area exposed to the flow [m^2]
D	*Diffusion coefficient of vapor in dry air [m^2/ s]*
H	Porous material sample height
h	*Convection heat transfer coefficient [W / m^2 K]*
h_{fg}	*Latent heat of vaporization [J / kg]*
h_m	*Convection mass transfer coefficient [m / s]*
k	*Thermal conductivity[W / m K]*
m_s	Mass of dry solid sample [kg]
m_t	Mass of the sample at a certain time [kg]
$\dot{m}_{ev}$	Evaporation rate
Sh	*Sherwood number*
T_a	Ambient temperature [K]
T_{wb}	*Wet bulb* temperature [K]
t	*Time [s]*
u	Air velocity [m / s]
W	Moisture content [kg / kg]

Greek Letter

Φ	Relative humidity (%)
ρ_a	Dry air density [kg / m^3]

Nu	Nusselt number	ρ_{wb}	Wet bulb density [kg / m^3]
Re	Reynold number	ν	Kinematic viscosity [m^2/ s]

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 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.

Most researchers (Elhassen et. al. 2018 [1], Chen, et al. 2017 [2], Defraeye et al 2012 [3], Defraeye et al 2010 [4], Kaya et. al. 2009 [5], Oztop and Akpinar 2008 [6], and Talukdar et al. 2007 [7]) 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 wet material, exposed area to the flow, initial moisture content, and material temperature are the main parameters affecting the drying rate and time.

Experimental Installation:

Figure (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.

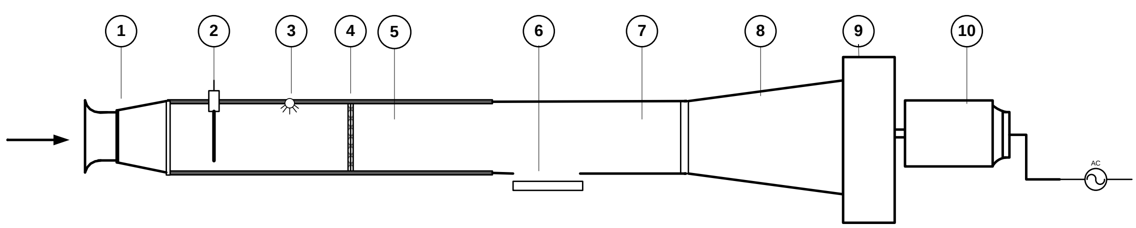

Fig. (1). Experimental Test Rig

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, evaporation curves and the average heat and mass transfer coefficients and in turn the local and average Nusslet and Sherwood numbers under different drying conditions were calculated, presented and discussed. 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 drying rate curves can be calculated hence the evaporation rate per unit area can be calculated by the equations:

$$\left|\frac{dw}{dt}\right| = \left|\frac{w_2 - w_1}{\Delta t}\right| \tag{2}$$

$$\dot{m}_{evp} = \frac{M_s}{A_p} \left|\frac{dw}{dt}\right| \tag{3}$$

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 [8 , 9]. Therefore, the local heat and mass transfer coefficients can be calculated by the equations:

$$h_m = \frac{\dot{m}_{evp}}{\rho_{wb} - \rho_a} \tag{4}$$

$$h = \frac{\dot{m}_{evp} \ h_{fg}}{T_a - T_{wb}} \tag{5}$$

The heat flux due to evaporation is only included while the sensible heat is neglected, since it is very much smaller that latent heat. The average values of heat and mass transfer coefficients at certain conditions can be calculated by the integration with time along the drying process

$$\bar{h} = \frac{1}{t_d} \int_0^{t_d} h(t)\, dt \tag{6}$$

$$\overline{h_m} = \frac{1}{t_d} \int_0^{t_d} h_m(t)\, dt \tag{7}$$

The average coefficients used to calculate the Nusslet and Sherwood numbers by:

$$Nu = \frac{\bar{h}\ H}{k_a} \tag{8}$$

$$Sh = \frac{\overline{h_m}\ H}{D_a} \tag{9}$$

Experimental Results:

The drying curves from the experimental tests mass measurements and equation (1) were evaluated and plotted under different drying air velocities as shown in figure (2). In these tests the air temperature and relative humidity were kept constant, that is, 50ºC and 15% respectively. The figure shows that the curves 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.

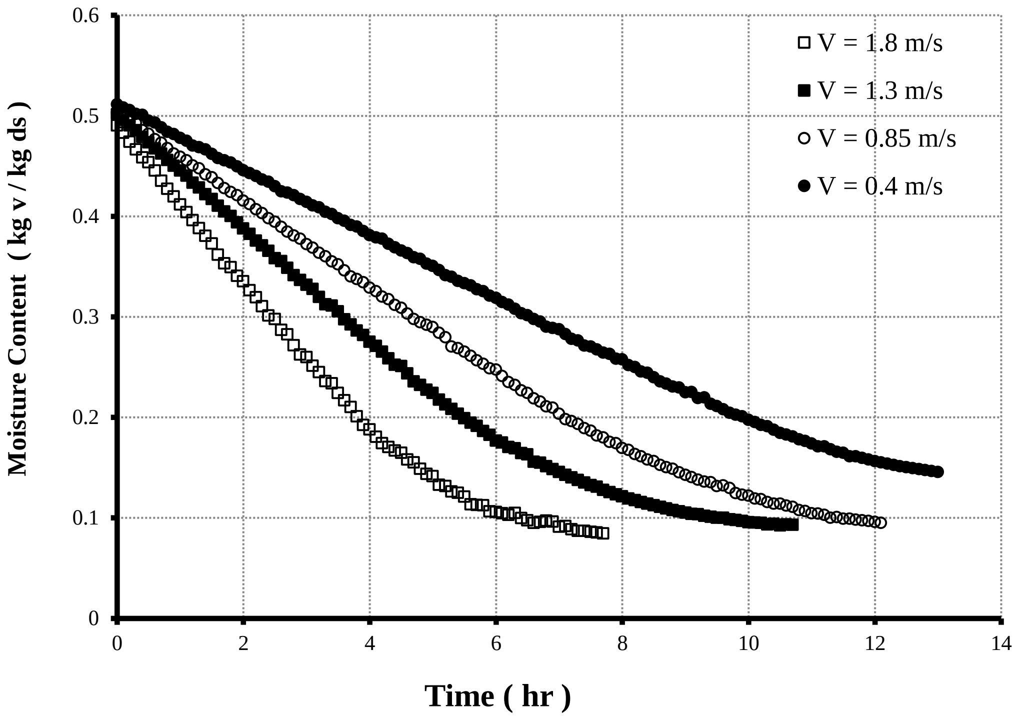

Fig. (2) Drying curves at T = 50^{o}C and RH = 15%

For different inlet air velocities

Based on the drying curves, the evaporation rate at each measuring time is calculated by equations (2) and (3) then plotted as shown in figure (3). Initially, the moisture content at the sample surface was higher than critical moisture content indicating constant drying rate period, during this period, the surface of the porous brick sample behaves like a wet bulb conditions. Hence, 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. 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.

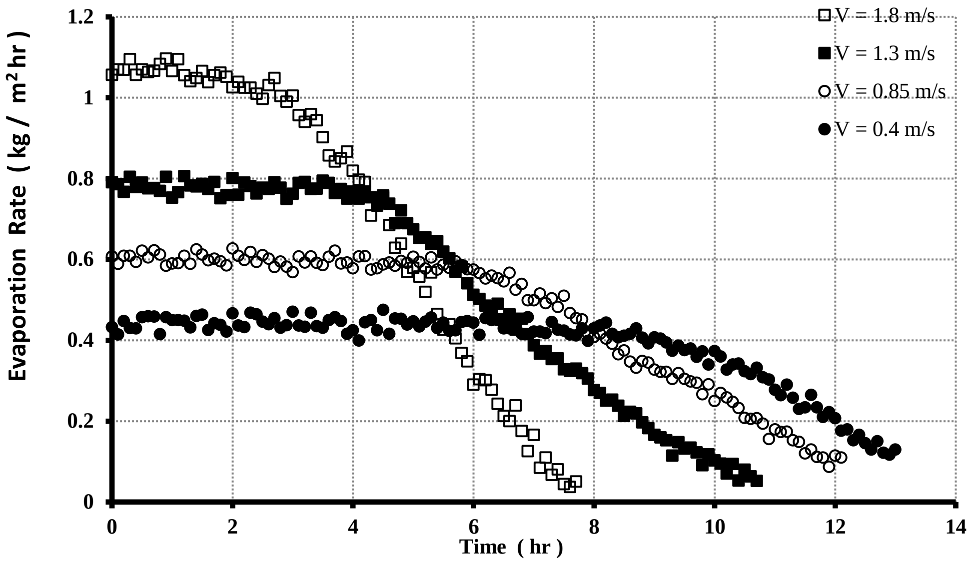

Fig. (3) Evaporation rate curves at T = 50^{o}C and RH = 15%
For different inlet air velocities

Using evaporation rate data curves, the time local heat and mass transfer coefficients are calculated and plotted as shown in figures (4 and 5) respectively. These curves show that an, increasing air velocity resulting in increasing evaporation rate from the solid sample surface and hence increasing the heat and mass transfer coefficients, hence improving conditions for drying.

During the constant rate 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. Later during the falling drying rate period, 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.

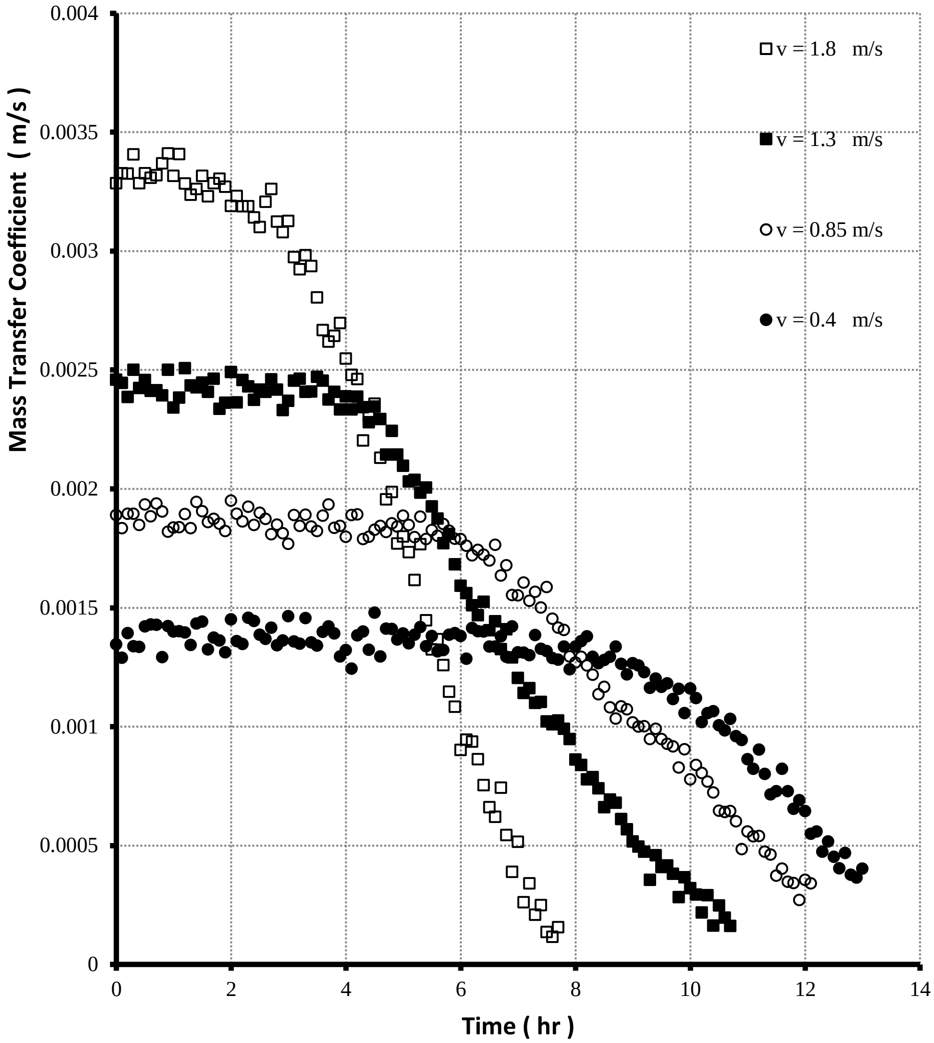

Fig. (4) Mass transfer coefficient at T = 50^{o}C and RH = 15%

For different inlet air velocities

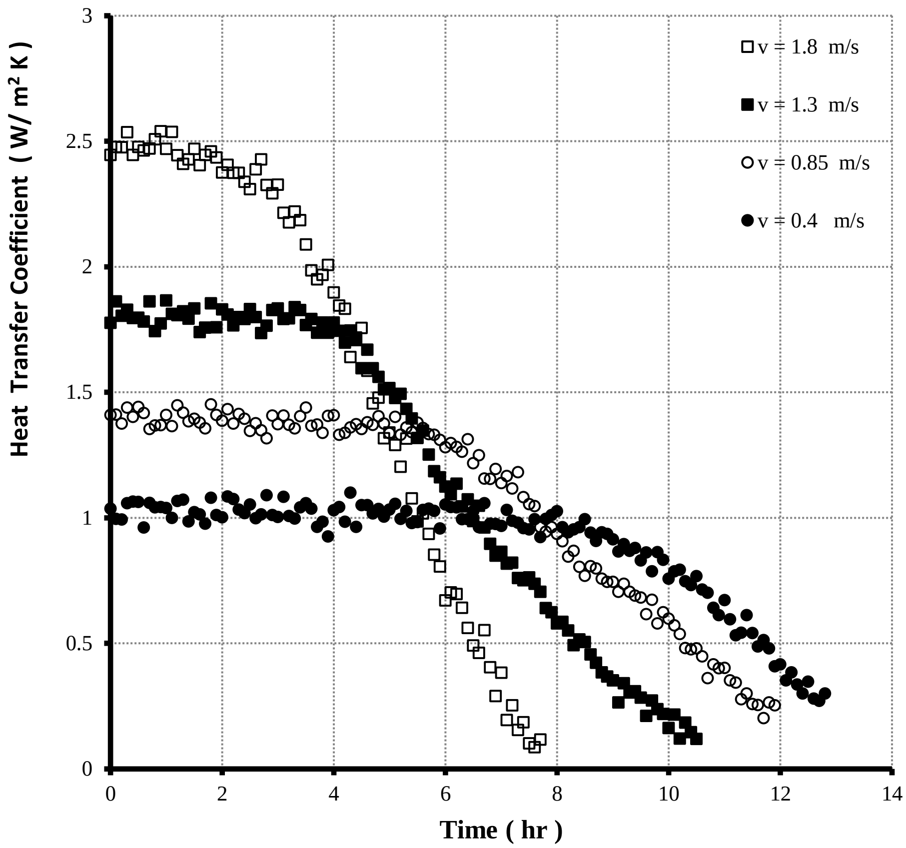

Fig. (5) Heat transfer coefficient at T = 50ºC and RH = 15%

For different inlet air velocities

The average Nusslet and Sherwood numbers for the total drying time is calculated using equations (8 and 9) and plotted against the Reynolds number as shown in figure (6) and it shows that there is almost increasing relation between the Re number and Nu and Sh numbers, whereas the Reynolds number ingresses both Nusslet and Sherwood number increase.

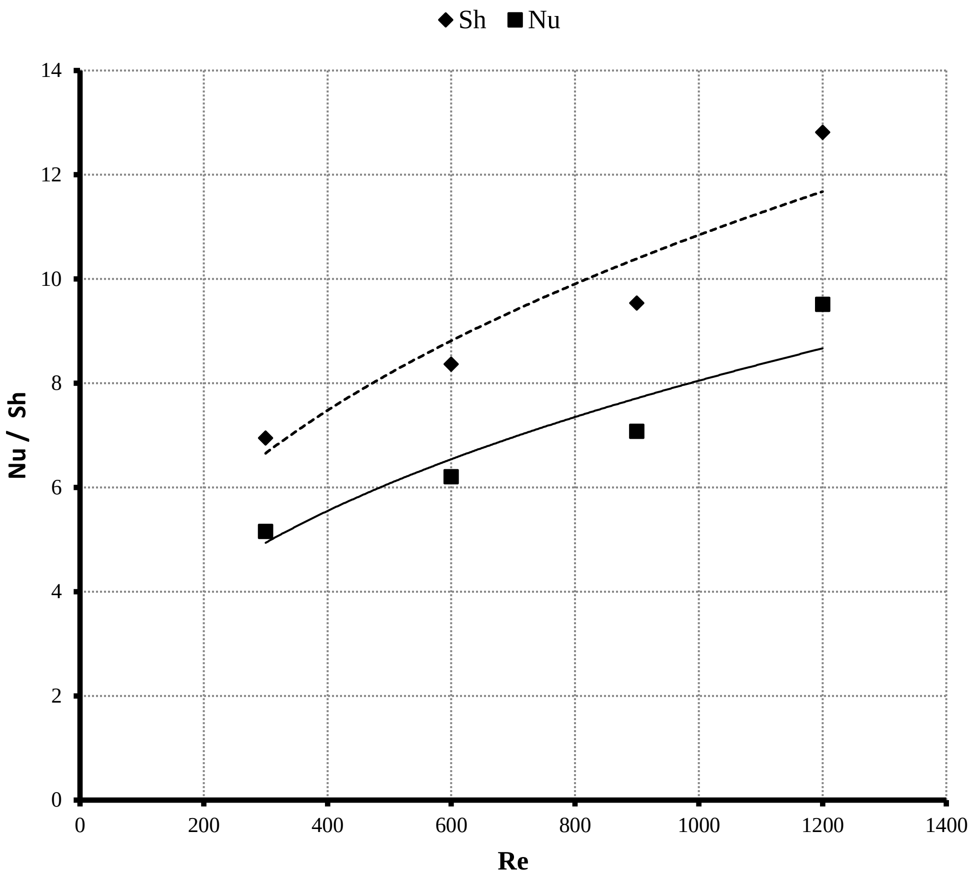

Fig. (6) Average Nusslet and Sherwood numbers at T = 50°C and RH = 15%

Conclusions

The drying process of samples of porous bricks under different flow velocity of hot air drying conditions was experimentally investigated. The following conclusions are obtained:

1. The drying curves reveal two drying periods, constant rate period where heat and mass transfer coefficients are constant and falling rate periods where the heat and mass transfer coefficients are decreasing.

2. Results obtained indicate that the heat and mass transfer coefficients are improved as the air velocity increased.
3. Nusslet and Sherwood numbers are increasing with the Reynolds number.

References:

1. Elhassen. O., Twier, A., Almadani R., Jurnaz, M., and Houssein, A., "Experimental study of drying process of porous materials ", Twentieth annual conference YUCOMAT 2018, Herceg Novi September 3-7, 2018.
2. Chen, K., Bachmann, P., Bueck, A., Jacob, M., and Tsotsas, E., "Experimental study and modeling of particle drying in a continuously-operated horizontal fluidized bed" Particuology, vol. 34, pp. 134–146, 2017.
3. Defraeye T., Blocken B., Carmeliet J. "Analysis of convective heat and mass transfer coefficients for convective drying of a porous flat plate by conjugate modeling", International Journal of Heat and Mass Transfer 55 (1-3), 112-124, 2012.
4. Defraeye T., Blocken B., Carmeliet J. "CFD analysis of convective heat transfer at the surfaces of a cube immersed in a turbulent boundary layer, International Journal of Heat and Mass Transfer 53 (1-3) 297-308. 2010
5. Kaya, A., Aydın, O. and Demirtaş, C. "Experimental and theoretical analysis of drying carrots", *Desalination*, Vol. 237 1-3, pp. 285–295, 2009.
6. Oztop, H.F. and Akpinar, E.K. "Numerical and experimental analysis of moisture transfer for convective drying of some products", *International Communications in Heat and Mass Transfer*, Vol. 35 No. 2, pp. 169–177, 2008.
7. Talukdar, P., Olutmayin, S., Osanyintola, O., . Simonson, C. J., "An experimental data set for benchmarking 1-D, transient heat and moisture transfer models of hygroscopic building materials. Part I: Experimental facility and material property data", International Journal of Heat and Mass Transfer 50 (23-24) 4527-4539, 2007.
8. Moropoulou A., Karoglou M., Giakoumaki A., Krokida M., Maroulis Z. and Saravacos, Z " Drying kinetics of some building materials " Brazilian Journal of Chemical Engineering, Vol. 22, pp. 203-208. 2005.
9. Sander A., Skansi D. and Bolf N. " Heat and mass transfer models in convection drying of clay slabs " Ceramics International, Vol. 29 pp. 641-653, (2003).