# EXPERIMENTAL STUDY OF HEAT AND MASS TRANSFER IN POROUS SPHERES DURING DRYING

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## ABSTRACT

The heat and mass transfer was studied in case of porous material. The models were spheres which were made in different sizes from gypsum and the mixtures of gypsum and paper. The weight loss, the water content and the temperature of the product were tested on different air velocities during each experiment. The physical properties of the samples were measured in the interest of determination of heat transfer data.
The calculated heat transfer coefficients on the basis of measured data have shown a difference from the results of heat transfer data – including dimensionless equations - derived from literature. The mass transfer was studied during the steady-state period and the results confirm the tendency the dimensionless Sh equations suggested in the literature.

## 1. INTRODUCTION

Drying means the removal of the moisture content from a wet, solid material by turning a part of this moisture into gas state. The drying conditions influence the quality of the dried product. These conditions are the gas velocity, the inlet gas temperatures and humidity and the drying time. In analyses of the drying, convective transfer coefficients are important parameters for the prediction of drying rates and temperatures.
Some studies presented experimental results about the coupling heat and mass transfer phenomena around different shaped materials. After considering the transport coupling effects, experimental results from loss of moisture and surface temperature indicate several ways to calculate the heat transfer coefficients using dimensionless numbers. The coupled heat and mass transfer results are correlated in terms of the dimensionless Nusselt and Sherwood numbers. The simple shapes of the dried materials were plates and cylinders made of porous material.
Some research carried out that the free stream turbulence has an effect on the heat transfer coefficients in case of plate, circular cylinder and elliptical cylinders. (Kondjoyan et al., 2002; Kondjoyan and Daudin, 1995). Fig. 1. shows four experimental results of the effect of turbulence intensity on heat transfer. The transfer coefficient increases according to the free stream turbulence level either in the laminar boundary layer or in the turbulent boundary layer (Kondjoyan and Daudin, 1993).

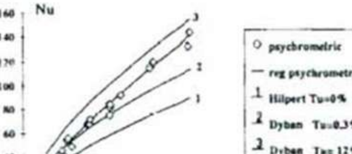


*Figure 1. The effect of turbulence on heat transfer Nu at cylinder (Kondjoyan and Daudin, 1993)*

Others found that the measured heat transfer coefficient is twice larger than the coefficient predicted for heat transfer only (Szentgyörgyi et al., 2000; Sun and Marerro, 1996). See Figs. 2 and 3.

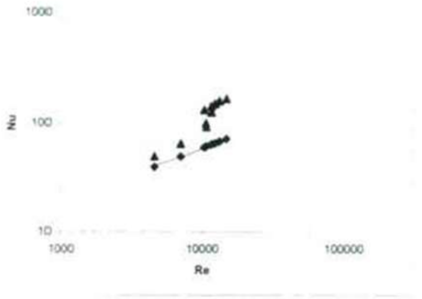


*Figure 2. Nu numbers derived from experiment (▲) and calculated from literature (♦) for plates [4]*

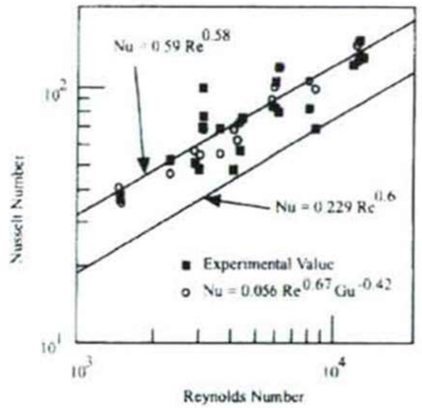


*Figure 3. Nu numbers derived from experiment ($Nu=0,59Re^{0,58}$) and calculated from literature ($Nu=0,229Re^{0,6}$) and a corrected Nu for cylinder [5]*

The aim of our work was to study the heat and mass transfer around single spheres during convective drying using a correction method with a dimensionless number.

## 2. MATERIALS AND METHODS

*Apparatus and drying conditions*

The experimental way used in this study adopted from (Kondjoyan and Daudin,1993). A horizontal drying chamber was made for this study. The cross-section of the chamber was 0.1 $m^2$. The chamber operated with a fan. The fan was placed in the inlet pipe, and this inlet pipe contained filaments to warm up the drying air. The air temperature was kept on a constant level at each experiment. The air velocity was controlled on a constant level. The experiments were repeated four or five times with the same sized sphere on a different velocity level.

The drying material was placed onto a special frame in the area of free stream. The frame had tripod standing outside of the chamber on a balance. By this way, the weight loss of the sphere was under on-line control. The inlet air temperature, humidity and the pressure-drop were measured at the inlet pipe. The air temperature in the drying chamber and the inside temperature of the sphere were measured by a sensor and thermocouples. All parameters were registered on a computer.

*Material*

The materials used in the experiments were different size of spheres which diameter was 29 mm; 38 mm; 41 mm. These spheres were made of gypsum and gypsum mixed with paper. Three thermocouples were inserted into the spheres: into the middle, near the surface and one between these. The prepared spheres were put under water to hydration for eight hours before the experiments.

*Theoretical analysis*

During convective drying, simultaneous heat and mass transfer exist. The drying process consists of three main periods: the first is the 'developing' period; the second is the 'constant rate' period and the third one is the 'falling rate' period. This study pays attention on the constant rate period.

The correction method was used to define the heat and mass transfer coefficients in the constant rate period of the drying. In this period, the surface of the material is supposed to be covered totally by water. Therefore, the surface temperature is equal to the wet bulb temperature at any point of the body. The wet bulb temperature depends on the air temperature and the humidity.

In coupling transport phenomena, the heat flux coming from the hot, ambient air turns into the phase change of the moisture content of the material and otherwise increases the temperature of the drying material.

In the constant rate period, the heat is assumed to turn into evaporation of the moisture content of the material and the increase of the temperature inside the material is negligible:

$$\phi_h = \phi_m \cdot L_{vap} \tag{1}$$

Where:

$$\phi_h = h \cdot (T_G - T_{sp}) \tag{2}$$

$$\phi_m = k' \cdot \rho_G \cdot (Y_s - Y_G) \tag{3}$$

The moisture flux across the sphere can be estimated from the weight changes during the constant rate period:

$$\phi_m = \frac{1}{A_{sp}} \cdot \frac{dm}{dt} \tag{4}$$

Using the Eqs. (2) and (4), the heat transfer coefficient can be calculated.

$$h = \frac{\phi_m \cdot L_{vap}}{T_G - T_{sp}} \tag{5}$$

With the heat transfer coefficient derived from the measured data, the Nusselt number is:

$$Nu = \frac{h \cdot D_{sp}}{\lambda_G} \tag{6}$$

There are Nusselt numbers proposed by (Inncoropera and DeWitt, 1995) and (Környey, 1999) with which the heat transfers could be described around a single sphere.

$$Nu_{lit,1} = \left[2 + \left(0{,}4 \cdot \mathrm{Re}^{1/2} + 0{,}06 \cdot \mathrm{Re}^{2/3}\right) \cdot \mathrm{Pr}^{0{,}4}\right] \cdot \left(\frac{\eta_G}{\eta_{sp}}\right)^{0{,}24} \tag{7}$$

A special case of convection heat transfer from spheres relates to the heat transport from freely falling drops. The Eq. (8) is suggested by (Inncoropera and DeWitt, 1995).

$$Nu_{lit,2} = 2 + 0{,}6 \cdot \mathrm{Re}^{0{,}5} \cdot \mathrm{Pr}^{0{,}33} \tag{8}$$

Introducing a dimensionless group, the Eq. (7) and (8) can be improved. The Gukhman number, see Eq. (9), is published by (Luikov, 1964).

$$Gu = \frac{T_{G\infty} - T_{wb}}{T_{G\infty}} \tag{9}$$

The suggested dimensionless Nu-relation:

$$Nu_{Cor} = Nu_{lit} \cdot Gu^{n} \tag{10}$$

The mass transfer coefficient was determined by Eqs. (3) and (4) without using any analogy to estimate it from the heat transfer.

The Sherwood number was calculated by:

$$Sh = \frac{k' \cdot D_{sp}}{D} \tag{11}$$

There are Sherwood numbers proposed by (Inncoropera and DeWitt, 1995) and (Szentgyörgyi et al., 1986) with which the mass transfers could be described around a sphere. Eq. (12) describes the mass transfer around a single porous sphere:

$$Sh = \left[2 + \left(0{,}4 \cdot \mathrm{Re}^{1/2} + 0{,}06 \cdot \mathrm{Re}^{2/3}\right) \cdot Sc^{0{,}4}\right] \cdot \left(\frac{\eta_G}{\eta_{sp}}\right)^{0{,}24} \tag{12}$$

Eq. (13) can be used to predict the mass transfer around freely falling drops.

$$Sh = 2 + 0{,}6 \cdot \mathrm{Re}^{0{,}5} \cdot Sc^{0{,}33} \tag{13}$$

Eq. (14) predicts nearly the same for sprayed liquid drops or sphere shaped solids.

$$Sh = 2 + 0{,}55 \cdot \mathrm{Re}^{0,5} \cdot \mathrm{Pr}^{0,33} \tag{14}$$

## 3. RESULTS

The constant rate period is well observable from the weight loss of the sphere. The weight of the wetted, gypsum sphere decreases consistently until 30 minutes, see Fig. 4, marked with ♦-line. As assumed before, the evaporation is characteristically for the constant rate period therefore the temperature of the material is constant. This shows well the Δ ○ ◊-marked lines on the Fig. 4.

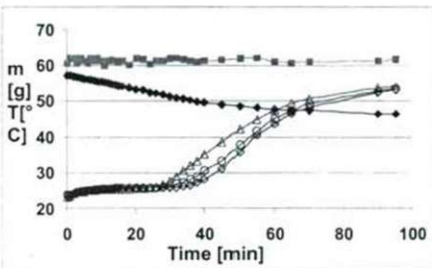


*Figure 4. Drying parameters of the sphere*

*(diameter 41 mm and air velocity 2,39 ms$^{-1}$ ; ■ air temperature 60°C): ♦ m-weight loss;*

*Δ ○ ◊: Ts-inside temperature of the sphere*

The calculated Nusselt numbers are significantly higher than the Nusselt numbers predicted by the equations found in the literature. The same discrepancy was found earlier in case of green peas during fluid bed and tray drying. (Simon, 2007) The Nusselt numbers published before took into consideration the heat transfer only. The calculated Nusselt numbers denote here the simultaneous heat and mass transfer. Introducing the dimensionless Gukhman number, suggested by Luikov, the corrected Nusselt number taken from the literature can be improved, see Eq. (9). After determination the exponent of the Gukhman number the Eq. (15) was resulted.

$$Nu_{Cor} = Nu_{Iit} \cdot Gu^{-0,69} \tag{15}$$

Every predicted value of the Eq. (15) is closer to the experimental values than those calculated from Eqs. (7) and (8), see Figs. 5 and 6.

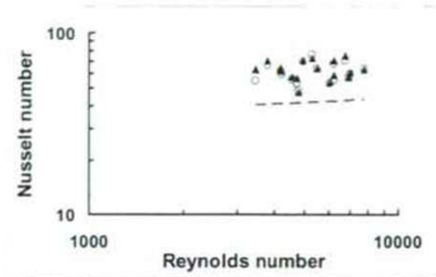


*Figure 5. Nusselt numbers as a function of Reynolds number for single spheres in drying:*
*▲-experimental values used Eq. (6); ○-$Nu_{Cor}$=f(Re, Pr, Gu) with Eq. (15).;*
*dashed line means $Nu_{lit,1}$ derived from Eq. (7).*

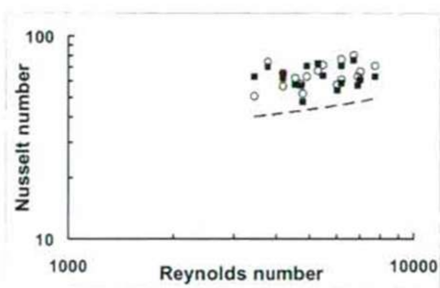


*Figure 6. Nusselt numbers as a function of Reynolds number for sphere-like drops:*
*▲-experimental values used Eq. (6); ○-$Nu_{Cor}$=f(Re, Pr, Gu) with Eq. (15).;*
*dashed line means $Nu_{lit,2}$ derived from Eq. (8).*

The deviations of the corrected Nusselt numbers from the experimental Nusselt values are given in Fig. 7. Deviation was defined as follows:

$$Deviation = \frac{|Nu - Nu_{Cor}|}{Nu_m} \qquad (16)$$

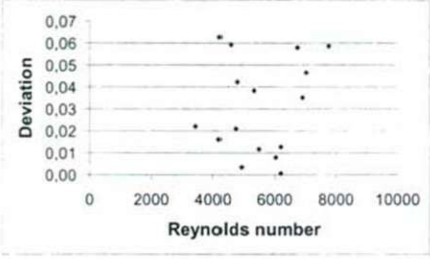


*Figure 7. The deviation of the corrected Nusselt numbers from the experimental values*

In the case of mass transfer, there is no significant difference between the experimental data given and the calculated ones based on the literature.

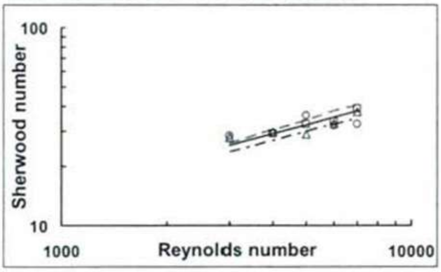


*Figure 8. Sherwood numbers as a function of Reynolds number for spheres in drying:*

*○□Δ-experimental values used equation 11;*

*- - -/- - - -/—: lines using Eqs. (12)/ (13)/ (14)*

The Sherwood numbers defined from the experimental values are below the Sherwood numbers predicted from the literature in Fig. 8. This similarity of the Sherwood numbers could thank to the continuously evaporation in the constant rate period. The Eqs. (12-14) predicted Sherwood numbers only for mass transfer without any influence of heat transfer. Therefore the experimental data seem to support the accuracy of the equations taken from the literature in case of the spheres in the given Reynolds range.

## 4. CONCLUSIONS

The heat and mass transfer coefficients analysed at convective drying by correction method across single gypsum and gypsum-paper spheres. The measured heat transfer coefficient is larger in the same Reynolds range than the coefficient predicted for heat transfer only. Introducing the Gukhman number, the Eq. (15) gives more accurate Nusselt number to predict the heat transfer coefficient for the coupled heat and mass transfer.

## Nomenclature

| | |
|---|---|
| $D_{sp}$ | diameter of the sphere [m] |
| $D$ | water diffusivity in air [$m^2 s^{-1}$] |
| $A_{sp}$ | surface of the sphere [$m^2$] |
| $m$ | weight of the sphere [kg] |
| $T$ | temperature [K] |
| $T_{sp}$ | inner temperature of the sphere |
| $L_{vap}$ | latent heat of evaporation [$J kg^{-1}$] |
| $Y$ | moisture fraction [$kg kg^{-1}$] |
| $h$ | heat transfer coefficient [$W m^{-2} K^{-1}$] |
| $k'$ | mass transfer coefficient [$m s^{-1}$] |
| $v$ | air velocity [$m s^{-1}$] |

Greek symbols

| | |
|---|---|
| $\phi_m$ | moisture flux [$kg m^{-2} s^{-1}$] |
| $\phi_h$ | heat flux [$W m^{-2}$] |
| $\eta$ | dynamic viscosity [$kg m^{-1} s^{-1}$] |
| $\lambda$ | thermal conductivity [$W m^{-1} K^{-1}$] |
| $\rho$ | density [$kg m^{-3}$] |
| $\nu$ | kinematic viscosity [$m^2 s^{-1}$] |

Dimensionless groups

| | |
|---|---|
| Nusselt number | $hD_{sp}/\lambda$ |
| Sherwood number | $k'D_{sp}/D$ |
| Reynolds number | $vD_{sp}/\nu$ |
| Schmidt number | $\nu/D$ |
| Prandtl number | $\nu/a$ |

Subscripts

| | |
|---|---|
| s | surface condition |
| G; $\infty$ | free stream condition of the drying air |
| lit | taken from the literature |
| wb | wet bulb condition |

## REFERENCES


1. Kondjoyan, J.D. Daudin: Determination of transfer coefficients by psychrometry. Int. J. of Heat and Mass Transfer, Vol. 36(7), pp. 1807-1818. (1993).
2. V. Luikov: Heat and mass transfer in capillary-porous bodies. Adv. Heat Transfer Vol. 1., pp. 123-184. (1964).
3. A.E. Delago, Da-Wen Sun: Heat and mass transfer models for predicting freezing processes-a review. J. of Food Eng. , Vol. 47. pp. 157-174. (2001).
4. E. Simon: Investigation of heat transfer phenomenon in green peas at fluid bed drying and tray drying. Analecta Technica Szegedinensia-Review of Faculty of Engineering; pp. 80-88. (2007).
5. F. P. Inncoropera, D. P. De Witt: Fundamentals of heat and mass transfer. John Wiley & Sons Inc., New York, pp. 339-340. (1985).
6. Stommen, O. Alves-Filho, T. M. Eikevik, I. C. Claussen: Physical Properties in Drying of Food Products with Combined Sublimation and Evaporation. Chinese J. Chem. Eng., Vol. 12 (6); pp. 814-817. (2004).
7. K. Torii, M. Isobe, N. Miura, T. Horikoshi: Free stream turbulence effect on heat transfer from spheres. Bull. J. S. M. E. Vol. 24. pp. 131-137 (1981).
8. M. Örvös, E. Simon: Study of Parameters at Drying Foods in Spray Dryer, The 4th International Conference Integrated Systems for Agri-Food Production SIPA'05., Romania-Temesvár, (2005).
9. O. Jonassen, I. Stommen: Performance test of a new 2-stage counter-current heat pump fluidized bed dryer. Doctoral thesis- Heat transfer to immersed horizontal tubes in gas fluidized bed dryers. NTNU, Trondheim (1999)
10. P.D. Lebedev: Heat and mass transfer between moist solids and air. Int. J. Heat Mass Transfer, Vol. 1., pp. 302-305. (1961).

11. R. B. Keey: Drying: Principles and Practice. pp.152. Pergamon, New York, (1972).
12. SSU-Hsueh Sun, T. R. Marrero: Experimental study of simultaneous heat and mass transfer around single short porous cylinders during convection drying by a psychrometry method. Int. J. Heat Mass Transfer, Vol. 39 (17), pp. 3559-3565. (1996).