

HEAT AND MASS TRANSFER PHENOMENON AROUND SPHERES

¹Erika SIMON;² Mária ÖRVÖS

¹ UNIVERSITY OF SZEGED, FACULTY OF ENGINEERING, DEPARTMENT OF MECHANICAL AND PROCESS ENGINEERING, HUNGARY

² BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS, FACULTY OF MECHANICAL ENGINEERING, DEPARTMENT OF PROCESS ENGINEERING,

ABSTRACT:

In this paper, the heat and mass transfer was studied in case of spherical porous material. The model spheres 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.

KEYWORDS:

drying, heat transfer, mass transfer, sphere

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.

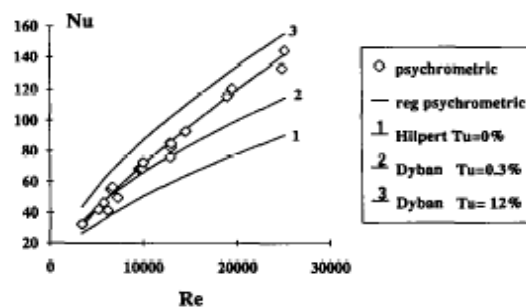


Figure 1. THE EFFECT OF TURBULENCE ON HEAT TRANSFER NU AT CYLINDER [2]

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. [1,3]. The transfer coefficient increases according to the free stream turbulence level either in the laminar boundary layer or in the turbulent boundary layer. [2]

Others found that the measured heat transfer coefficient is twice larger than the coefficient predicted for heat transfer only. [7,8] See Figure 2 and 3.

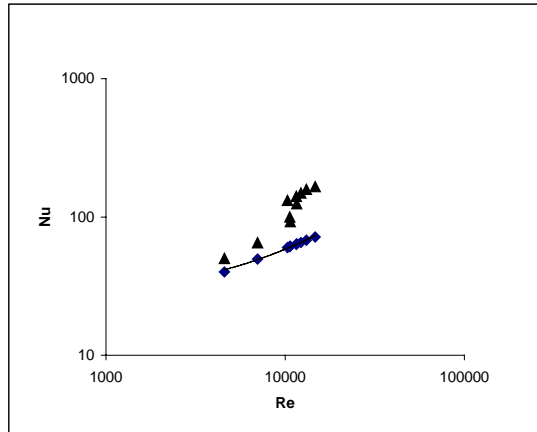


Figure 2. NU NUMBERS DERIVED FROM EXPERIMENT (▲) AND CALCULATED FROM LITERATURE (◆) FOR PLATES [7]

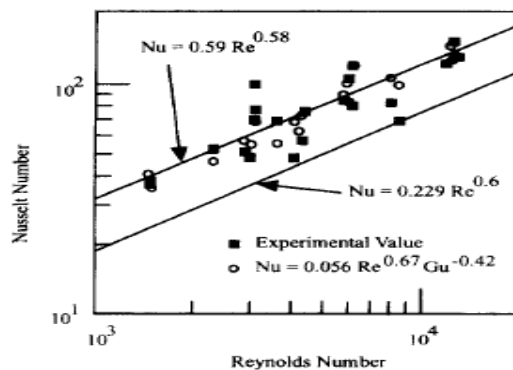


Figure 3. Nu NUMBERS DERIVED FROM EXPERIMENT ($Nu=0,59Re^{0,58}$) AND CALCULATED FROM LITERATURE ($Nu=0,229Re^{0,6}$) AND A CORRECTED Nu FOR CYLINDER [8]

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

2. METHODS AND MATERIAL

a. Apparatus and drying conditions

The experimental way used in this study adopted from [3]. A horizontal drying chamber was made for this study. The cross-section of the chamber was $0,1 \text{ m}^2$. 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.

b. 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.

c. 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:

$$\phi_h = \phi_m \cdot L_{vap} \quad (1)$$

Where:

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

$$\phi_m = k' \cdot \rho_G \cdot (Y_s - Y_G) \quad (3)$$

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

$$\phi_m = \frac{1}{A_{sp}} \cdot \frac{dm}{dt} \quad (4)$$

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

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

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

$$Nu = \frac{h \cdot D_{sp}}{\lambda_G} \quad (6)$$

There are Nusselt numbers proposed by [5] and [9] with which the heat transfers could be described around a single sphere.

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

A special case of convection heat transfer from spheres relates to the heat transport from freely falling drops. The equation (8) is suggested by [5].

$$Nu_{lit,2} = 2 + 0,6 \cdot Re^{0,5} \cdot Pr^{0,33} \quad (8)$$

Introducing a dimensionless group, the Equation (7) and (8) can be improved. The Gukhman number, see equation (9), is published by [4].

$$Gu = \frac{T_{G\infty} - T_{wb}}{T_{G\infty}} \quad (9)$$

The suggested dimensionless Nu-relation:

$$Nu_{Cor} = Nu_{lit} \cdot Gu^n \quad (10)$$

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

The Sherwood number was calculated by:

$$Sh = \frac{k' \cdot D_{sp}}{D} \quad (11)$$

There are Sherwood numbers proposed by [5] and [6] with which the mass transfers could be described around a sphere. Equation (12) describes the mass transfer around a single porous sphere:

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

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

$$Sh = 2 + 0,6 \cdot Re^{0,5} \cdot Sc^{0,33} \quad (13)$$

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

$$Sh = 2 + 0,55 \cdot Re^{0,5} \cdot Pr^{0,33} \quad (14)$$

3. RESULTS AND DISCUSSION

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 figure 4, marked with \blacklozenge -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 \square \diamond -marked lines on the figure 4.

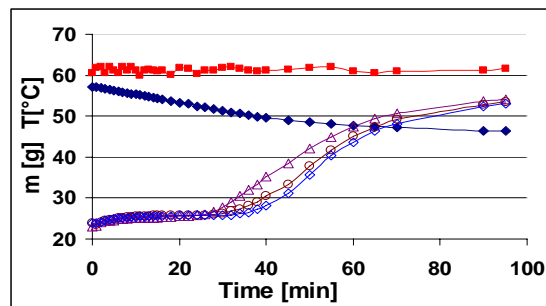


Figure 4. DRYING PARAMETERS OF THE SPHERE (diameter 41 mm, \blacksquare air temperature 60°C; air velocity 2,39 ms^{-1}): \blacklozenge m-weight loss; Δ \square \diamond : T_s -inside temperature of the sphere

The calculated Nusselt numbers are significantly higher than the Nusselt numbers derived from the equations predicted the literature. The Nusselt numbers derived from literature took into consideration the heat transfer only. The calculated Nusselt numbers denote the simultaneous heat and mass transfer. Introducing the dimensionless Gukhman number, suggested by [4], the corrected Nusselt number taken from the literature can be improved, see equation (9). After determination the exponent of the Gukhman number the equation (15) was resulted.

$$Nu_{Cor} = Nu_{lit} \cdot Gu^{-0,69} \quad (15)$$

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

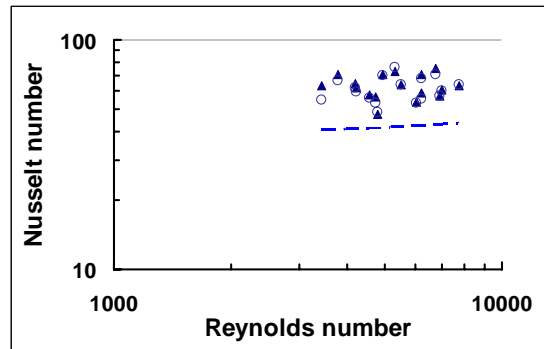


Figure 5. NUSSELT NUMBERS AS A FUNCTION OF REYNOLDS NUMBER FOR SINGLE SPHERES IN DRYING: ▲-experimental values used equation (6); □- $Nu_{Cor}=f(Re, Pr, Gu)$ with equation (15).; dashed line means $Nu_{lit,1}$ derived from equation (7).

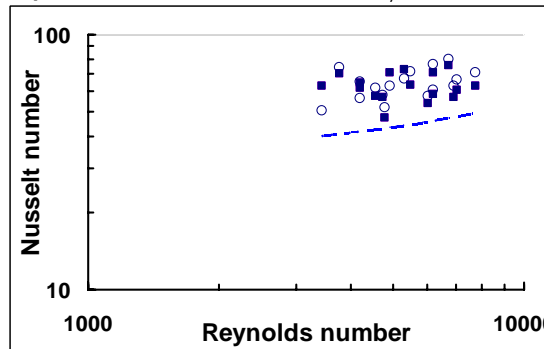


Figure 6. NUSSELT NUMBERS AS A FUNCTION OF REYNOLDS NUMBER FOR SPHERE-LIKE DROPS: ▲-experimental values used equation (6); □- $Nu_{Cor}=f(Re, Pr, Gu)$ with equation (15).; dashed line means $Nu_{lit,2}$ derived from equation (8).

The divergences of the corrected Nusselt numbers from the experimental Nusselt values are given in figure 7. Divergence was defined as follows:

$$\text{Divergence} = \frac{|Nu - Nu_{Cor}|}{Nu_m} \quad (16)$$

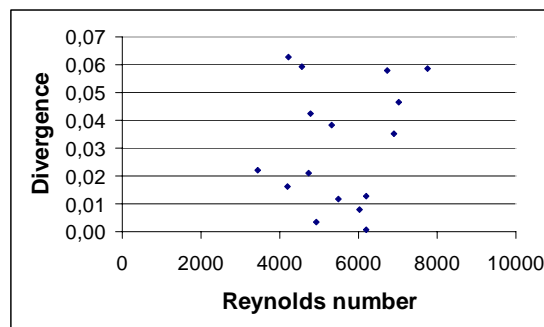


Figure 7. THE DIVERGENCE OF THE CORRECTED NUSSELT NUMBERS FROM THE EXPERIMENTAL VALUES

There is no significant difference between the experimental data and from literature calculated data of mass transfer.

The Sherwood numbers defined from the experimental values are under the Sherwood numbers predicted from the literature in figure 8. This similarity of the Sherwood numbers could thank to the continuously evaporation in the constant rate period. The equations (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.

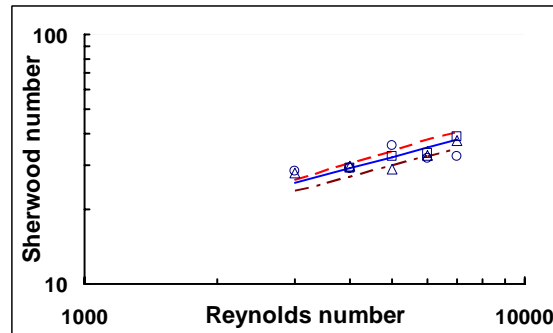


Figure 8. SHERWOOD NUMBERS AS A FUNCTION OF REYNOLDS NUMBER FOR SPHERES IN DRYING:

□□△-experimental values used equation 11;

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

3. CONCLUSION

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 equation (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]	λ	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
D	water diffusivity in air [$m^2\ s^{-1}$]	ρ	density [$kg\ m^{-3}$]
A_{sp}	surface of the sphere [m^2]	ν	kinematic viscosity [$m^2\ s^{-1}$]
m	weight of the sphere [kg]	Dimensionless groups	
T	temperature [K]	Nusselt number	hD_{sp}/λ
T_{sp}	inner temperature of the sphere	Sherwood number	$k'D_{sp}/D$
L_{vap}	latent heat of evaporation [$J\ kg^{-1}$]	Reynolds number	$\nu D_{sp}/\nu$
Y	moisture fraction [$kg\ kg^{-1}$]	Schmidt number	ν/D
h	heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]	Prandtl number	ν/a
k'	mass transfer coefficient [$m\ s^{-1}$]	Subscripts	
ν	air velocity [$m\ s^{-1}$]	s	surface condition
Greek symbols		$G; \infty$	free stream condition of the drying air
ϕ_m	moisture flux [$kg\ m^{-2}\ s^{-1}$]	lit	taken from the literature
ϕ_h	heat flux [$W\ m^{-2}$]	wb	wet bulb condition
η	dynamic viscosity [$kg\ m^{-1}\ s^{-1}$]		

REFERENCES

- [1.] A. Kondjoyan, F. Péneau, H-C. Boisson, 2002.: Effect of high free stream turbulence on heat transfer between plates and air flows (Review). *Int. J. Therm. Sci.* Vol 41. pp. 1-6.
- [2.] A. Kondjoyan, J.D. Daudin, 1993: Determination of transfer coefficients by psychrometry. *Int. J. Heat Mass Transfer* Vol. 36. (7) pp. 1807-1818.
- [3.] A. Kondjoyan, J.D. Daudin, 1995: Effects of free stream turbulence intensity on heat and mass transfer at the surface of circular and an elliptical cylinder, axis ratio 4. *Int. J. Heat Mass Transfer* vol. 38. (10) pp. 1735-1749.
- [4.] A.V. Luikov 1964.: Heat and mass transfer in capillary-porous bodies. *Adv. Heat Transfer*. Vol. 1. pp. 123-184.
- [5.] Frank P Inncoropera, David P De Witt 1985. *Fundamentals of heat and mass transfer*. John Wiley & Sons Inc., New York, pp. 339-340.
- [6.] S. Szentgyörgyi, K. Molnár, M. Parti 1986. *Transzportfolyamatok Tankönyvkiadó, Budapest*, pp. 343.
- [7.] S. Szentgyörgyi, L. Tömösy, O. Molnár, (2000): Convection Heat Transfer Coefficients at Convective Drying of Porous Materials, *Drying Technology* 18(6), 1287-1304.
- [8.] SSU-Hsueh Sun, Thomas R. Marrero 1996: 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.
- [9.] T. Környey: *Hőátvitel. Pp V-10, Műegyetemi Kiadó, 1999.*