ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XIV [2016] – Fascicule 3 [August]
ISSN: 1584-2665 [print; online]
ISSN: 1584-2673 [CD-Rom; online]
a free-access multidisciplinary publication of the Faculty of Engineering Hunedoara

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MODELLING OF CONVECTIVE HEAT TRANSPORT AROUND POROUS OBJECTS

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ABSTRACT: This paper presents results of experimental and theoretical approach of heat transfer around simple porous bodies during forced convection. The calculated heat transfer coefficients using the measured parameters shows a higher values as the heat transfer coefficients values from the dimensionless Nusselt correlations given in the literature. The reason of this difference was provided by theoretical way using a boundary layer theory. There exist general equations for the heat, mass and momentum transfer on the boundary layer. Numerous experimental and theoretical studies deal with the solution of these equations by analytical or numerical way. An analytical model was proved by this experimental study; and the existence of the non-zero surface velocity is verified during the steady-state period of convection drying.
Keywords: heat transfer, convective drying, porous body, boundary layer, flat plate, sphere

2. INTRODUCTION

The convective drying plays an important role in the industrial production. At convective drying, the fluid flows and contacts the solid surface in a drying unit. A boundary layer appears on the solid surface and its parameters are very important for controlling the process. There exist general equations for the heat, mass and momentum transfer on the boundary layer. Numerous experimental and theoretical studies deal with the solution of these equations by analytical or numerical way. The analytical solutions are difficult; most of the researchers use the empirical and the numerical methods. Ref. [1] reports and summarises useful correlations for the boundary layer conditions of simple shaped bodies.

In the present study, convective heat transfer coefficient at drying of porous bodies under forced conditions is investigated in the steady state period. In this period, the surface of the body is covered by moisture. The existence of a non-zero surface-velocity is considered in the theoretical approach. This non-zero velocity (u_o) has an influence on the heat transport and increases the heat transport coefficient. This theoretical conclusion is verified by the experimental results and illustrated by discrepancies of Nu numbers.

2. MATERIALS AND METHODS

Gypsum and Gypsum-paper plates and spheres were used for the experiments. Psychrometry measuring method of Ref. [1] was adopted for the measuring process.

A horizontal drying channel with a cross section of 0.1 m^2 was applied. The airflow is generated by a fan and heated by an electric device in the inlet pipe of the unit. The air temperature as well as the air velocity was kept on a constant level during each experiment. Experiments were carried out four or five times with the same sized plates in Ref. [2], and sphere shaped specimens in Ref. [3] applying different Re numbers (velocity and temperature of the drying air was changed).

The dried material in the airflow was placed onto a frame standing on a balance. Weight loss of the specimen, inlet air temperature and humidity and air temperature in the drying channel was measured and transmitted to a computer by a data collector in every 2 minutes. Surface temperature of the specimen was measured by thermocouples and forwarded to the computer by the data logger. The air flow rate was measured by an orifice.

Convective heat transfer coefficients in the steady-state period of drying (h_{h+m}) were calculated using the measured data. In this very part of the drying process, the temperature of the dried material is constant (approximately the wet bulb temperature) and the heat flux coming from the gas (j_q) covers the evaporation (j_m) of the liquid from the thin wetted surface layer:

$$j_q = h(T_G - T_F) \quad \text{and} \quad j_q = j_w + j_m \tag{1,2}$$

where

$$j_w = \frac{m_s \cdot c}{A}\frac{dT}{dt} = 0 \tag{3}$$

$$j_m = -\frac{1}{A}\frac{dm}{dt} = -\frac{m_s}{A}\frac{dX}{dt} \cdot r_{LV} \tag{4}$$

the heat transfer coefficient without the warming of the material:

$$h_{h+m} = \frac{-\frac{m_s}{A}\frac{dX}{dt} r_{LV}}{(T_G - T_F)} \tag{5}$$

The heat transfer coefficients predicted by Nusselt correlations (h_h) in the literature assumed to be the coefficients of heat transfer only without the existence of wet surface. Ref. [3] published results of this phenomena at flat plate; Ref. [5] found similar achievements for cylinders and this study with Ref [4] for spherical bodies, see Figure 1.

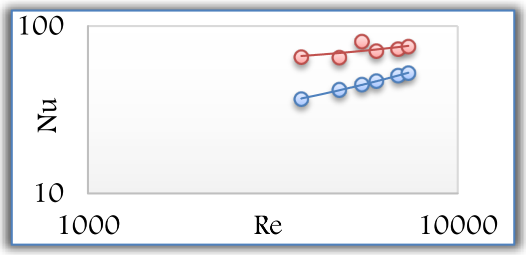

Figure 1. Nusselt numbers vs. Reynolds number for single spheres in drying; Varga-Simon E, Örvös M (2014)

The coupled heat and mass transfer was studied by several researchers and suggested to improve the basic Nu-correlations by introducing the Gukhman number; Ref.[6],[7],[8]. Although this dimensionless Gu-number gave good agreement between the experimental (h_{h+m}) and the calculated (h_h) heat transfer coefficients but it has less consideration. However, heat transfer coefficient calculated from Nusselt correlations may be inaccurate particularly when the moisture transfer rates are high. In this experimental study, the reason of the discrepancy of the experimental and calculated heat transfer coefficient was supposed to originate in the boundary layer conditions. Based on Ref. [9] and [4], a non-zero velocity (u_o>0) was assumed to be on the wetted drying surface. Using the approximate method for the balance equation of the boundary layer, the thickness ratio can be written as:

$$\frac{\delta_u^*}{\delta_u} = \sqrt{1 - \frac{u_0}{U_\infty} + \frac{C_2 \cdot u_0}{C_1 \cdot U_\infty}} \tag{6}$$

If

$$K := \frac{C_2}{C_1} \quad \text{and} \quad P := \frac{u_0}{U_\infty} \tag{7,8}$$

(6) turns to:

$$\delta_u = \delta_u^* \cdot \frac{1}{\sqrt{1 + (K-1)P}} \tag{9}$$

Supposing P≥0, the boundary layer on the surface will be thinner $\delta_u \le \delta_u^*$ when a non-zero velocity (u_o>0) exists. Meantime, the shear-stress can be written as in Ref. [9]:

$$\frac{\tau_0}{\tau_0^*} = \sqrt{(1-P)^3 + KP(1-P)^2} \tag{10}$$

If u_o increases, the hydrodynamic resistance decreases due to the sear-stress.

For the thermal boundary layer conditions Ref. [9] indicate theoretical solution for the difference in case of flat plates, see (11). Under the same drying circumstances the j_q/j_q^* gives (12):

$$\frac{\delta_T^*}{\delta_T} = \sqrt{1-(1+L)P} \tag{11}$$

$$\bar{j} = \frac{j_q}{j_q^*} = \frac{h_{h+m}}{h_h} = \sqrt{1+(L-1)P} \tag{12}$$

where * shows zero surface velocity condition, without* has the meaning of wetted surface condition with non-zero velocity and

$$L := \frac{C_2}{H(\Delta)} \quad \text{and} \quad \Delta = \Pr^{-\frac{1}{3}} \tag{13,14}$$

3. RESULTS

Some of our experimental results are given in Table 1. The heat transfer coefficients h_{h+m} were determined using the experimental data and (5). The values of h_h was derived from the Nusselt correlation for flat plate from Refs.[10],[11],[12], [13]. As Table 1 shows, there are relevant discrepancies between h_h and h_{h+m} at each of the plates. This phenomenon exists even for single sphere body where h_h came from Nusselt numbers proposed by Refs. [12],[13].

Table 1. Values of the heat transfer coefficient obtained from measurements (h_{h+m}) and from Nu correlations (h_h)

Body	Typical size [mm]	Gas temperature [°C]	U_∞:Gas mean velocity [m/s]	h_{h+m} [W/m²/K]	h_h [W/m²/K]
Gypsum-1-plate	100	77.5	2.33	31	17.98
Gypsum-mix plate	100	81	1.96	26.74	16.56
Gypsum-2-plate	100	72.6	2.286	32	20
Gypsum-sphere	∅38	61	3.55	59.38	38.19

Adopting (12), the change of the P and the surface velocity was studied based on the thermal boundary layer theory in case of flat plates. For the calculations, the values of C1, C2, H, Δ was taken from the Ref. [1] and [14], as follows:

Based on the fourth polynomial approach C1:= 37/315 and C2:=3/10. In the range of the temperature of the drying air, the Prandtl number has the constant value of 0.71. By this way and using (14), Δ=1.12. The H has the value of 0.1176 in function of Δ=1.12. The definition of L gave the constant number of 2.551, see (13). To demonstrate the influence of P on the velocity, the u_o was defined from (8). Since P is function of the range of h_h/h_{h+m}, the effect of the changing P and u on the heat transfer coefficients was illustrated. Results of the calculations in Table 2, Figure 2, Figure 3 and Figure 4 are represented.

Table 2. : Calculated uo and h in function of P on the basis of (12)

Changing:	P	gypsum-1 u_o [m/s]	gypsum-1 h [W/m²/K]	gypsum-2 u_o [m/s]	gypsum-2 h [W/m²/K]	gypsum -mix u_o [m/s]	gypsum -mix h [W/m²/K]
U_∞ and h_{h+m}	1	2.29	31.94	2.33	28.71	1.96	26.44
	0.9	2.06	30.95	2.10	27.83	1.76	25.63
	0.8	1.83	29.93	1.86	26.91	1.57	24.78
	0.63	1.44	28.12	1.47	25.28	1.23	23.28
	0.6	1.37	27.78	1.40	24.98	1.18	23.01
	0.5	1.15	26.65	1.17	23.95	0.98	22.06
	0.4	0.92	25.46	0.93	22.88	0.78	21.08
	0.3	0.69	24.21	0.70	21.76	0.59	20.04
	0.2	0.46	22.89	0.47	20.58	0.39	18.95
	0.1	0.23	21.49	0.23	19.32	0.20	17.80
u_o and h_h	0	0.00	20.00	0.00	17.98	0.00	16.56

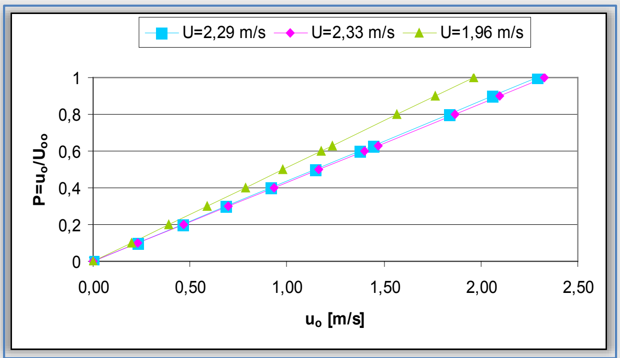

Figure 2. Correlation of P as a function of u_o in case of gypsum-1, gypsum-2 and gypsum-mix

If the value of P increases from zero, the value of the boundary velocities increases similarly. Exceeding the value of P until 1, u_o turns into the value of velocity of the bulk flow (U_∞), see Table 2 and Figure 2, Figure 3 and Figure 4 represent the effect of the changes in P and u_o on the heat transfer coefficients. As u_o increases, the heat transfer coefficient enhances from h_h to h_{h+m}.

The drying surface is assumed to be dry in case of u_o=0, P=0 and marks the heat transfer coefficient as h_h. In case of a wetted drying surface there exists a non-zero velocity on the surface and 0<P<1 which has an improvement on the heat transfer coefficient.

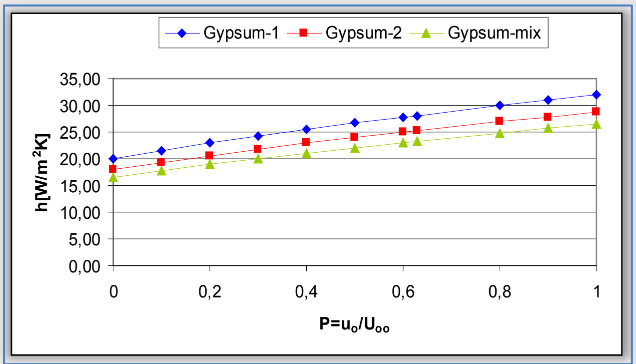

Figure 3. Correlation of heat transfer coefficients as a function of P

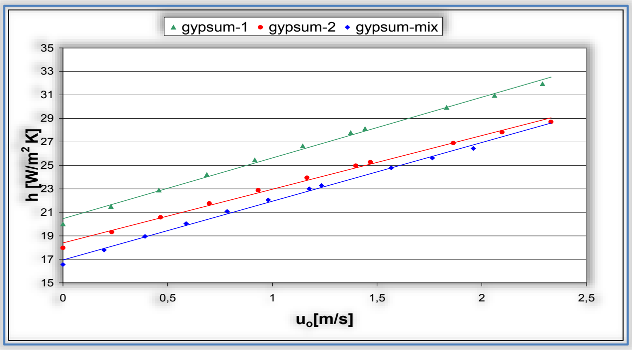

Figure 4. Effects of non-zero velocities on heat transfer coefficients

4. CONCLUSION

Existence of a non-zero velocity on the wetted surface has an influence on the velocity boundary layer and the thermal boundary layer profile and consequently on the mass transfer in the boundary layer. The psychrometry method is suitable for experimental determination of the heat transfer coefficients across simple shaped capillary porous specimens at convective drying. Several experimental measurements demonstrate that the measured heat transfer coefficients are significantly larger than the heat transfer coefficients predicted by Nusselt numbers in the literature. By adaptation of the boundary layer analysis of Refs. [4, 9], the divergence of the heat transfer coefficients has its explanation. Applying (12) for our experimental data, the surface velocity were changed from zero to the bulk flow velocity $0<u_o< U_\infty$. Results clearly show that the value of the convective heat transfer coefficient rises from h_h to h_{h+m} (Figure 3 and Table 2) The values of u and h obtained from (12) demonstrate a very good agreement with the experimental data. The analytical model in Refs. [4] and [9] was proved by this experimental study. The existence of the non-zero surface velocity is verified during the steady-state period of convection drying.

Nomenclature

A surface [m^2]
C_1, constant
C_2 constant
c_p specific heat of the air [$Jkg^{-1}K^{-1}$]
h heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
H constant
j_q heat flux [$W\ m^{-2}$]
j_m mass flux [$kg\ m^{-2}\ K^{-1}$]
K defined in (7)
L constant, def. (13)

m mass [kg]
P defined in (8)
r specific heat of evaporation [Jkg^{-1}]
T: temperature [K]
t time[s]
X moisture content [kg/kg]
U,u: velocity [m/s]

Dimensionless groups
Nu Nusselt number
Re Reynolds number
Pr Prandtl number

Subscripts
0 surface condition
F surface
∞ main stream condition
G gas, air condition
T refer to temperature
* refer to $u_o=0$ condition

Greek symbols
τ skin friction
Δ constant (1,12)
δ_u, δ_T: the thickness of momentum and thermal boundary layers in the air

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