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 m² 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 ($q_g$) covers the evaporation ($m_j$) of the liquid from the thin wetted surface layer:

$$j_q = h(T_G - T_F) \quad \text{and} \quad j_q = j_u + j_m$$

where

$$j_u = \frac{m_x}{A} \cdot \frac{dT}{dt} = 0 \quad (3) \quad j_m = -\frac{1}{A} \frac{dm}{dt} = -\frac{m_x}{A} \frac{dX}{dt} \cdot r_{LV} \quad (4)$$

the heat transfer coefficient without the warming of the material:

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

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.

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:

$$\frac{\delta_\nu^*}{\delta_\nu} = \sqrt{1 - \frac{u_o}{U_\infty} + \frac{C_2 \cdot u_o}{C_1 \cdot U_\infty}}$$

If

$$K = \frac{C_2}{C_1} \quad \text{and} \quad p = \frac{u_o}{U_\infty} \quad (7,8)$$

(6) turns to:

$$\delta_u = \delta_\nu^* \cdot \frac{1}{\sqrt{1 + (K-1)p}} \quad (9)$$

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

$$\tau_u = \sqrt{(1 - P)^3 + KP(1 - P)^2} \quad (10)$$

If $u_o$ increases, the hydrodynamic resistance decreases due to the shear-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):

$$\frac{\delta_q^*}{\delta_q} = \sqrt{1 - (1 + L)P} \quad (11) \quad \bar{j} = \frac{j_q}{j_q^*} = \frac{h_{h+m}}{h_h} = \sqrt{1 + (L-1)P} \quad (12)$$

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

$$L = \frac{C_2}{H(\Delta)} \quad \text{and} \quad \Delta = Pr \frac{1}{\tau} \quad (13,14)$$

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

<table>
<thead>
<tr>
<th>Body</th>
<th>Typical size [mm]</th>
<th>Gas temperature [°C]</th>
<th>$U_{∞}$: Gas mean velocity [m/s]</th>
<th>$h_{h+m}$ [W/m²/K]</th>
<th>$h_{h}$ [W/m²/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum-1-plate</td>
<td>100</td>
<td>77.5</td>
<td>2.33</td>
<td>31</td>
<td>17.98</td>
</tr>
<tr>
<td>Gypsum-mix plate</td>
<td>100</td>
<td>81</td>
<td>1.96</td>
<td>26.74</td>
<td>16.56</td>
</tr>
<tr>
<td>Gypsum-2-plate</td>
<td>100</td>
<td>72.6</td>
<td>2.286</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>Gypsum-sphere</td>
<td>123</td>
<td>61</td>
<td>3.55</td>
<td>39.38</td>
<td>38.19</td>
</tr>
</tbody>
</table>

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 $C_1$, $C_2$, $H$, $Δ$ was taken from the Ref. [1] and [14], as follows:

Based on the fourth polynomial approach $C_1$ := 37/315 and $C_2$ := 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.

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.
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 \(h_0\) to \(h_{0+n}\) (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 \([\text{m}^2]\)
- \(C_1, C_2\): constant
- \(c_p\): specific heat of the air \([\text{J/kg} \cdot \text{K}]\)
- \(h\): heat transfer coefficient \([\text{W/m}^2 \cdot \text{K}]\)
- \(H\): constant
- \(j_q\): heat flux \([\text{W/m}^2]\)
- \(j_m\): mass flux \([\text{kg/m}^2 \cdot \text{K}]\)
- \(K\): defined in (7)
- \(L\): constant, def. (13)
- \(m\): mass \([\text{kg}]\)
- \(P\): defined in (8)
- \(r\): specific heat of evaporation \([\text{J/kg}]\)
- \(\xi\): constant
- \(\delta\): the thickness of momentum and thermal boundary layers in the air

Dimensionless groups

- \(Nu\): Nusselt number
- \(Re\): Reynolds number
- \(Pr\): Prandtl number

Subscripts

- \(0\): surface condition
- \(F\): surface
- \(\infty\): main stream condition
- \(G\): gas, air condition
- \(T\): refer to temperature
- \(*\): refer to \(u_o=0\) condition

Greek symbols

- \(\tau\): skin friction
- \(\Delta\): constant

References