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AN EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER COEFFICIENTS IN A PACKED BED OF SPHERES

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Abstract. This paper present an experimental investigation of the heat and mass coefficients in a packed bed of spheres occupying a heated channel for two-dimensional laminar flows. To verify the analytical model developed and invoke the heat/mass transfer analogy, an experiment is carried out by naphthalene sublimation technique for the case of negligible radiation field. From the effects of the wake, the Sherwood number is maximum around the region where the porous medium is attached. The theoretical results are compatible with the experimental results at small Darcy number.

Keywords. Measurement of mass and heat coefficients, analogy between heat and mass transfer, naphthalene sublimation technique, drying systems and packed bed of spheres.

1. INTRODUCTION.

The production of regional fruit and grains are an important activity in the Amazon, with is based on small and medium producers. The fundamental factor for the storage and marketing of these products is the final moisture content. In case of the pepper, for example, the value of the moisture content level required must be about 13%. The drying process commonly used by many small rural producers in the Amazon region is the natural drying (direct sunlight exposition), with a characteristic high drying time and large area need. This method does not always give good results due to bad weather conditions, leading to losses of product and detriment of its quality.

The use of solar dryers is an interesting alternative to overcome these problems. Many applications of solar drying systems have been reported, but in r our case we should know the heat and mass coefficients. The attractive this dryer is the low cost, especially for the tropical countries due to their good insulation conditions.

The idealized model used in the present experimentally analysis is shown in figure 1, where the two-dimensional medium is assumed to extend to infinity in both directions. One region is a high porosity layer bounded by an impermeable layer on the bottom surface. A free stream region bound the top surface. An imposed flow is specified at the leading edge of the two-region system.

To verify this analytical model developed, an experiment was carried out by the naphthalene sublimation technique for the case of negligible radiation, which has been used by several researchers to obtain mass transport results. Permeability in packed bed of spheres used for experiment was also measured.

By using the analogy between heat and mass transfer, the Sherwood number presented here may be correlated to the Nusselt number, as in the non-porous region if the analogy relations in the porous region are verified from the experimental measurements.

2. THEORETICAL ANALYSIS

The conservation equations of a porous medium, which is regarded as homogeneous and isotropic, were derived in terms of the superficial (Darcian) velocity within the porous medium using a control volume (Lee et al., 1990)

Porous region:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\rho}{\varepsilon^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{dp}{dx}-\frac{\mu}{K}v \tag{2}$$

$$\frac{\rho}{\varepsilon^2}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{dp}{dy}-\frac{\mu}{K}v \tag{3}$$

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_c\nabla^2T-\nabla q_r \tag{4}$$

$$u\frac{\partial C}{\partial x}+\frac{\partial C}{\partial y}=D_e\nabla^2C \tag{5}$$

where: $k_e=\varepsilon k_f+(1-\varepsilon)k_p$

$D_e=\varepsilon D$

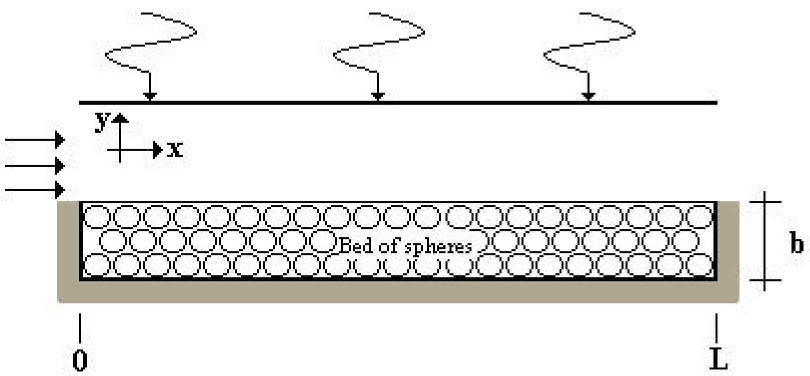

Figure 1. Schematic of the porous medium

2.1 **Heat and Mass Transfer Analogy**

The usual definition of heat transfer coefficient comes form the equation:

$$h=q/(T_w-T_\infty) \tag{6}$$

Compatibly, the mass transfer coefficient is given by:

$$h_m = \dot{m}/(\rho_w - \rho_\infty) \tag{7}$$

Analogy between Eqs. (6) and (7) implies that (T_w – T) and *q* in heat transfer correspond to (ρ_w - ρ) and *m* in mass transfer. In the present study, the naphthalene vapor concentration in the free stream is zero. Then, Eq. (7) reduces to

$$h_m = \dot{m}/\rho_w \tag{8}$$

As the mass transfer system is essentially isothermal, the naphthalene vapor concentration at the wall is constant. This is equivalent to a constant temperature wall boundary condition in heat transfer study.

Local mass transfer from a naphthalene plate can be evaluated from the change surface elevation, which is equivalent to the change in naphthalene thickness. The elevation change or thickness due to sublimation is given by:

$$dy = m.dt / \rho_s \tag{9}$$

where $ñ_s$ is the density of solid naphthalene. Note that dy and *m* are functions of coordinates of the mass transfer active surface. Combining Eqs. (8) and (9) and integrating over the test duration yields.

$$h_m = (\rho_s \Delta y)/(\rho_w \Delta t) \tag{10}$$

The dimensionless mass transfer coefficient, of Sherwood number, is defined by

$$Sh = h_m d / D \tag{11}$$

where *D* is the naphthalene-air diffusion coefficient, which is determined by talking the Schimidt number equal to 2,5 suggested by Sogin; i.e.,

$$Sc = \nu / D \tag{12}$$

since naphthalene concentration in the boundary layer is extremely small, the cinematic viscosity, ν, uses the value of air under the operation conditions. By analogy the Sherwood number can be transformed to its heat transfer counterpart, Nusselt number (Nu), by using the relation:

$$\frac{Nu}{Sh} = \left(\frac{Pr}{Sc}\right)^n \tag{13}$$

where Pr is the Prandtl number and the power index *n*, according to Igarashi (1986), is equal to 1/3.

The local mass transfer coefficients are determined from the measured change of the elevation (Δy) at each of the measurement points, the duration of the experiment (Δt), the density of solid naphthalene ($ñ_s$), and the difference between the naphthalene vapor density at the plate surface ($ñ_w$) and the naphthalene vapor density in the free stream (ñ)

From the Chemical Engineer's Handbook, data for naphthalene are D=0.62x10^{-5}m^{-2}.s^{1}, ñ$_s$=1145kg.m^{-3}, M=128, 16 kg kmol^{-1}. The naphthalene vapor density at the wall is calculated from the vapor pressure-temperature relation for naphthalene in conjunction with the perfect gas law.

$$\rho_w = \frac{p_{nw} M}{\bar{R} T_w} \tag{14}$$

Where: $\log_{10} p_{nw} = 13.564 - T_w^{-1}$, p_{nw} is (N/m^2) and T_w is K.

In Porous region from the conservation equations normalized by use of dimensionless variables and equations (2)-(5) within the porous region, the momentum equation is a function of not only *Re* but also *Da* and ε. The mass and energy equation are a function of the effective Schmidt and Prandtl numbers, respectively. Thus, following the same procedure as above, the Sherwood and Nusselt number are

$$Sh = C_s f_s (Re, Da, \varepsilon) Sc_e^{n_s} \tag{15}$$

$$Nu = C_n f_n (Re, Da, \varepsilon) Pr_e^{n_n} \tag{16}$$

If $C_s = C_n$, $f_s = f_n$ and $n_s = n_n$, equation (13) can be applied for analogy in the region as in the non-porous region

$$Nu = (Pr_e / Sc_e)^n Sh \tag{17}$$

but the relations should be first verified from the experimental measurements.

2.2 **Measurement of Permeability**

Permeability of bed of spheres was calculated in terms of the geometrical parameters, at least the case of simple geometry. For our case the Ergun's equation recommend

$$K = \frac{d_p^2 \varepsilon^3}{\beta (1 - \varepsilon)} \tag{18}$$

Where ε is porosity, d_p is the diameter of sphere and β are shape factors that must be determined empirically, we used β=150 (Bejan and Donald, 1992).

The functional dependence of the porosity on the distance from the boundary can be found from the experimental results of Benenati and Brosilow. These results can be represented by an exponential function of the following form:

$$\varepsilon = \varepsilon_\infty [1 + b.e^{-cy/d_p}] \tag{19}$$

This result neglects the small oscillations of the porosity that are considered as be secondary. The emphasis here is on the decay of the porosity from the external surface, which has the primary effect. The empirical constant *b* and *c* are dependent on the ratio of the bed to particle diameter, *y* is the high porosity. The particle diameter used in the experimental study was 10 mm. These correspond to experimental bed to particle diameter ratios of 6.25. From the results of Benenati and Brosilow the porosity variation as a function of y/d_p is found to be almost identical for these bed to particle diameter ratios. The constants chosen to represent the porosity variation were $b=0.9$ and $c=2$ for 10mm bead.

3. EXPERIMENTAL APPARATUS AND PROCEDURES

The description of the experimental apparatus and its components is shown by figure 2, which is schematic side view of the experimental set-up. As shown there in, air from the laboratory room is draw into the channel formed by nozzle upon fourth part ellipse form, a contraction and the test section with porous medium. Upon traversing the length of the channel, the air exits to an other contraction from which it passes successively to a rotameter, a control valve, a cut-off valve and a blower and is finally ducted to an exhaust system which to the atmosphere at roof of the building.

The experimental apparatus is composed by acrylic and plastic both of which 0,5 cm thick. The entrance test section which is constructed entirely of acrylic is dimensioned as 3 x 15 x 50 cm (height x width x length) and 3 cm of height in porous medium, because we has been three spheres layer of 10 mm diameter glass spheres. Special care was taken in packing the beads to ensure uniformity in the structure of the porous medium. The spheres with naphthalene were poured in packed 5 to 5 cm until all the end bed of spheres for each Reynolds number. After allowing the glass spheres to settle, more of the porous medium was placed in the channel and packed by the weight to top plate. This procedure was repeated until no more glass spheres could be placed into the channel.

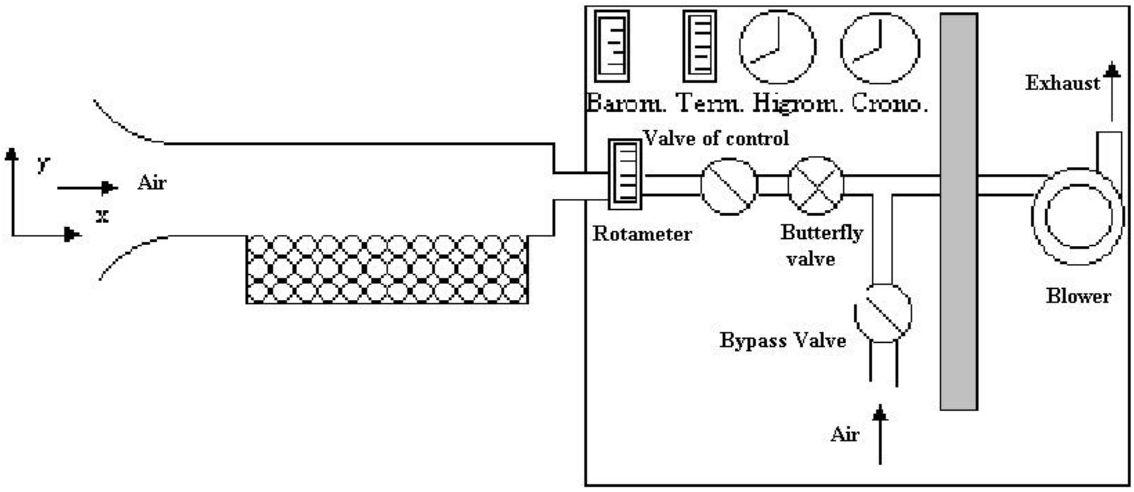

Figure2. Platform Test

Average transfer coefficients were experimentally obtained by application of the naphthalene sublimation technique in accordance with the analogy between heat and mass transfer, with the test performed with nineteen exchangers for Reynolds number in the interval from 200 to 2000. The overall mass transfer was measured with a precision balance cable of discriminating to within 0,0001 grams for specimens having a mass up to 200 grams. For all the experimental runs, each bulk with naphthalene spheres were weighed before and after being exposed to the airflow.

4. RESULTS AND DISCUSSION

As ÄM$_n$ is of sublimated naphthalene mass, the average values of transfer coefficients *h* were determined for each experiment. (Sogin et al., 1958) for to found the average Sherwood number used this equation

$$\overline{Sh} = \frac{\Delta M_n D_e}{t_e A_w \Delta \overline{\rho}_{nb} D_n} \tag{20}$$

were A_w is total area of sublimation, D_e is hydraulic diameter given by 2ab/(a+b), Äñ$_{nb}$ is log-mean concentration difference and D_n (Naphthalene diffusion coefficient) equal 6.27x10^{-6}m^2/s.

Both the local and average Sherwood number results can be correlated to Nusselt number results by employing the analogy between heat and mass transfer.

The bulk concentration results can be converted to bulk temperature results by means of the analogy. This conversion can be performed though the equation

$$1-\theta = (-\rho_{nx}/\rho_{nw})^{(Sc/Pr)^{1-m}} \tag{21}$$

were: $$\theta = \frac{T_{b0} - T_{bx}}{T_{b0} - T_w} \tag{22}$$

θ is the dimensionless bulk temperature analogous to ρ_{nx}/ρ_{nw}

The average Sherwood numbers of the porous media are obtained as

$$\bar{Sh} = \frac{h_m H}{D} = 1{,}68467 \times 10^{-5}.Re_H (H/x)^{0.8}.Sc^{1/3} \tag{23}$$

Figure 3 shows that the experimental Sherwood number is very large near the leading edge of first naphthalene body because of the developing boundary layer. The Sherwood number decreases very sharply from the effects of the porous medium.

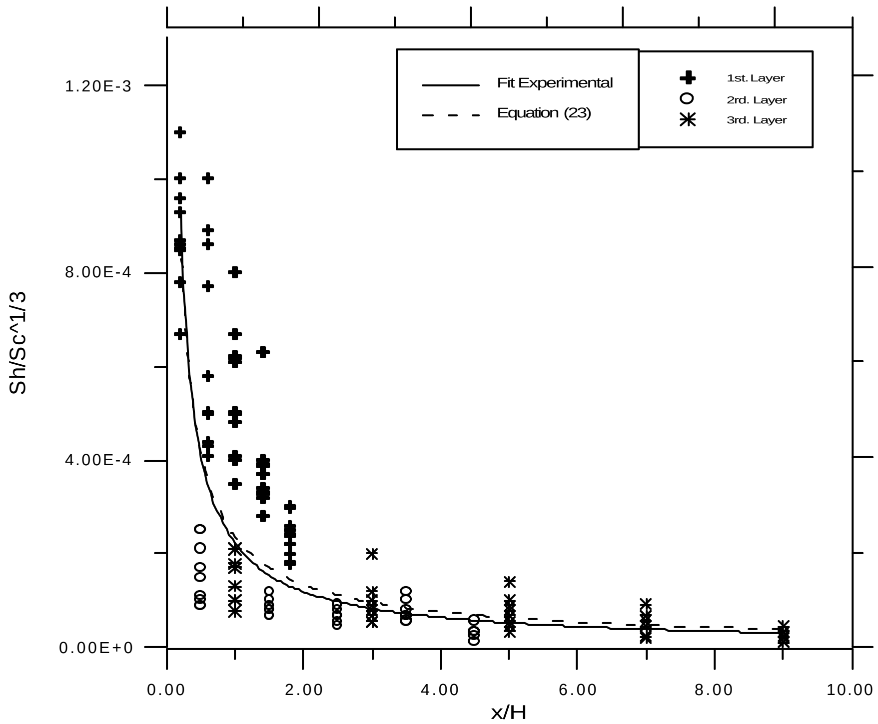

Figure 3. Average Sherwood number

The core friction factors, f, were determined from pressure drop ÄP the pressure drop determined measurements across the test section without heat impute according to

$$f = 2r_h \Delta P / L\mu u^2 \tag{24}$$

Where r_h is the hydraulic radius and μ is the density.

The heat transfer data were transferred to a Stanton number, St, through the relation

$$St = Nu / Re\ Pr \tag{25}$$

Friction factor and heat transfer were transferred to the relation $StPt^{2/3}/f$, as function of Re to evaluated the thermal performance of the exchangers surface.

From the experiment performed by application of the naphthalene sublimation technique, using an adiabatic flat plate and isothermal bed of spheres as boundary conditions. The results are presented as follows:

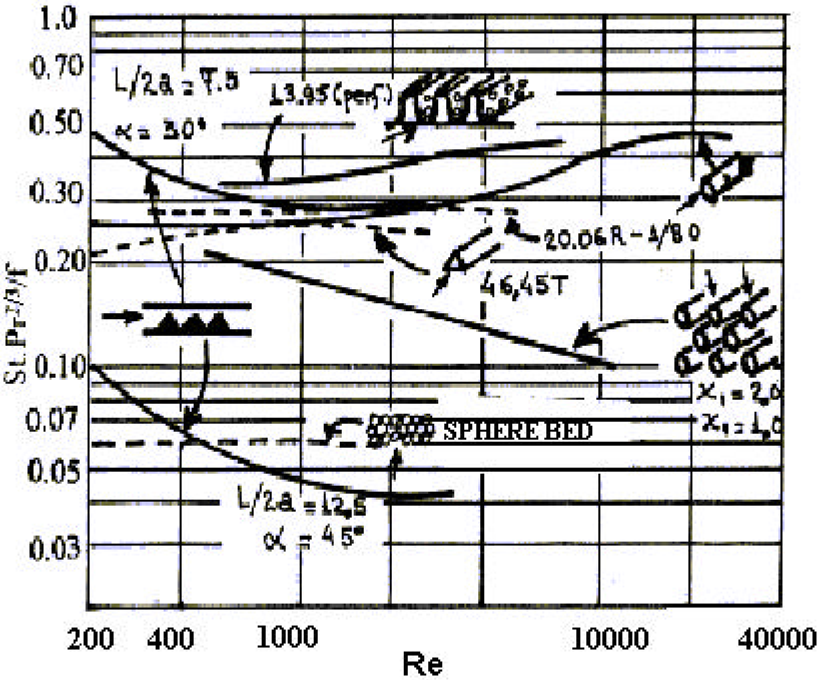

Figure 4 – Core-surfaces characteristics for sphere bed

5. CONCLUSION

The heat transfer coefficient was found experimentally to see the effects the of transfer mass around the porous medium. To verify the analytical model developed, an experiment was carried out using the naphthalene sublimation technique for the negligible radiation fields and a comparison was made between both results in terms of the Sherwood number.

The following conclusions are obtained below.

1) The theoretical results correspond to the experimental results at the smaller Darcy number ($Da=1.2x10^3$), the experimental results are much larger than the theoretical results due to both developing boundary effects and wake effects around the porous medium.

2) If the following relation, $Nu = (Pr_e/Sc_e)^n Sh$, is verified in the porous region form the experimental measurements as in the non-porous region, the mass transfer results presented here may be converted to heat transfer results by employing the heat/mass analogy.

3) The increasing rate of the average heat and mass transfer coefficients due to around of the porous media increase with the Reynolds number of the air flow intensity, which can be correlated with equation (23) or the equation below:

$$h_m = Sh.D/H = 1{,}68467\times10^{-5}\ Re_H\ (H/x)^{0.8}.Sc^{1/3}$$

4) The permeability for the bed of spheres used for experiment was also measured and the Forchheimer equation is applicable in our measurement was 6.9×10^{-4} cm^2.

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