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Experimental study of simultaneous heat and moisture transfer around single short porous cylinders during convection drying by a psychrometry method

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Abstract—This paper presents results of theoretical and experimental studies on heat and moisture transfer around single short porous cylinders during forced convective drying. Air was passed across saturated coal logs, varying air humidity, temperature and velocity, as well as log aspect ratio and diameter. After considering the transport coupling effects, experimental results from loss of moisture and surface temperature indicate that calculated heat transfer coefficients are twice coefficients for systems with only heat transfer. The coupled heat and mass transfer results are correlated in terms of the dimensionless Nusselt and Sherwood numbers, $Nu = 0.056\,Re^{0.65}\,Gu^{-0.43}$ and $Sh = 0.047\,Re^{0.67}\,Gu^{-0.42}$, where Re is the Reynolds number and Gu the Gukhman number. The surface temperatures during drying were well estimated using a modified energy balance formula. The new correlation is useful to predict the initial drying rates for short cylinders with an aspect ratio from 1.2 to 2.0. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

Drying solids by forced convection is widely used in the manufacturing and process industries. In analyses of systems for drying solids, convective transfer coefficients are important parameters for the prediction of drying rates and temperatures. Large cylindrical solids containing moisture dry by the coupling of heat and mass transfer. A large portion of water can be removed from a solid during convection controlled periods. Under convection control, the drying rate is fast and predicted by convective transfer coefficients.

However, the coupled effects of moisture transfer on heat transfer still need to be better understood, especially for short cylindrical objects. Although many studies have been done on the heat transfer across an infinite cylinder, in the case of drying of a more realistic object, like a short cylinder, meagre information is available. For short cylinder drying, experimental studies of convective transfer coefficients are needed.

In this study, convective transfer coefficients across single short cylinders are investigated by experiments adapted from a psychrometry method [1]. The measured heat and moisture transfer coefficients are correlated by dimensionless equations, such that the results can be applied to cylinders of different sizes and at different conditions. The dimensionless equations obtained will be used to simulate the coupled, unsteady state heat and moisture transfer of different sized cylinders.

2. THEORETICAL ANALYSIS

For drying processes, traditionally, the convective heat transfer coefficient has been assumed to be the same as the coefficient of heat transfer only. This estimation is very convenient because the needed heat transfer coefficients are usually available, but may be inaccurate, especially when moisture transfer rates are high.

$$Nu = 0.229Re^{0.6} \quad 1.0\times10^{3} < Re < 2.0\times10^{5} \quad (1)$$

$$Nu = 0.123Re^{0.651} + 0.00416\left(\frac{l}{d}\right)^{-0.85} Re^{0.792}$$

$$7.0\times10^{3} \leqslant Re \leqslant 2.3\times10^{5}$$

$$1.0 \leqslant \frac{l}{d} \leqslant 7.0. \quad (2)$$

Equations (1) and (2) are two heat transfer correlations, which will be discussed later in this article. On the basis of literature review, equation (1) was suggested by Zukauskas and Ziugzda [2] for the case of forced convective air flow across an infinitely long cylinder. The convective heat transfer coefficient is correlated in terms of the Nusselt number as a function of Reynolds number. The parameters in equation (1) are dependent on the range of Reynolds number. Quarmby and Al-Fakhri [3] proposed equation (2)

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NOMENCLATURE

A	fitting constant
C_p	specific heat [J kg^{-1} K^{-1}]
d	diameter of cylinder [m]
D	diffusivity of water in air [m^2 s^{-1}]
h	convective heat transfer coefficient [W m^{-2} K^{-1}]
h_m	convective moisture tansfer coefficient [m s^{-1}]
k	thermal conductivity [J s^{-1} m^{-1} K^{-1}]
l	length of cylinder [m]
L_{vap}	latent heat of evaporation [J kg^{-1}]
m_f	moisture concentration at film [kg m^{-3}]
n'	fitting parameter
n	fitting parameter
q_m	moisture flux [kg m^{-2} h^{-1}]
$R.H.$	relative humidity [%]
T_{bp}	boiling point temperature [K]
T_f	film temperature [°C]
T_s	coal log surface temperature [°C]
T_w	wet bulb temperature [°C]
T_∞	ambient air temperature [°C]
V	air velocity [m s^{-1}]
W	weight of coal log [kg]
y_s	moisture mole fraction near the surface
y_∞	moisture mole fraction in the ambient air.

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
ε	partial moisture coverage parameter
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}].

Dimensionless groups

$Gu = (T_\infty - T_w)/T_{bp}$ Gukhman number

$Nu = hd/k$ Nusselt number

$Pr = \nu/\alpha$ Prandtl number

$Re = dV/\nu$ Reynolds number

$Sh = h_m d/D$ $Sc = \nu/D$ Schmidt number.

for the case of heat transfer across a short cylinder. The effects of aspect ratio, defined as length-to-diameter, are taken into account in equation (2).

By applying Chilton–Colburn analogy, the convective moisture transfer coefficient can be estimated from the heat transfer coefficient, see equation (3).

Validation of Chilton–Colburn analogy on various conditions has been confirmed by Kondjoyan and Daudin [1] and Nomura and Farrell [4]. This analogy is well known and widely used in analyses of coupled heat and mass transfer.

$$\frac{h}{h_m} = \rho C_p \left(\frac{Sc}{Pr}\right)^{2/3}. \quad (3)$$

After taking the coupling effects of moisture transfer on heat transfer into account, more accurate predictions can be expected by introducing other factors such as air temperature and humidity. Lebedev [5], Keey [6] and Luikov [7] have suggested that equation (1) is improved by introducing the dimensionless group, the Gukhman number, see equations (4) and (5). The Gukhman number represents the maximum thermal driving force. By introducing Gukhman number, for a infinite long cylinder, equation (1) becomes equation (5). For short cylinders, at present, the Nusselt number has not been correlated as a function of the Reynolds and Gukhman numbers.

$$Gu \equiv \frac{T_\infty - T_w}{T_{bp}} \quad (4)$$

$$Nu = ARe^n Gu^{n'}. \quad (5)$$

The method used in this study is mainly adapted from the psychrometry method proposed by Kondjoyan and Daudin [1]. Two advantages of this method are beneficial to this study. First, the necessary equipment is simple; only a balance and a wind tunnel are needed. Second, the method can be used for objects of complex geometry; no additional equipment is needed for the study of short cylinders.

According to the psychrometry, the moisture flux across a short cylinder can be estimated by the second-order derivative formula, see equation (6), from the weight changes during constant rate period. In equation (6), q_m is the moisture flux; $W(t_{n-1})$ is the weight of a porous cylinder at the $n-1$th sampling time; $W(t_{n+1})$ is the weight at the $n+1$th sampling time; Δt is the interval between sampling time. Area, defined as equation (7), is the exposed cylinder surface for drying which includes the ends and circumferential area.

$$q_m = \frac{W(t_{n-1}) - W(t_{n+1})}{2 \cdot \text{Area} \cdot \Delta t} \quad (6)$$

$$\text{Area} \equiv 2 \cdot \frac{\pi a^2}{4} + \pi d l. \quad (7)$$

Using this definition for the moisture flux, the convective transfer coefficients are calculated by equations (8) and (9). Equation (9) is the rate equation of mass transfer for high transfer rates. Equation (9) will approach equation (10) for low mass transfer rates. To obtain more consistent results, the physical properties in equations (8)–(10) are calculated at the film temperature, which is defined by equation (11). Here h is the average convective heat transfer coefficient, h_m is the average convective moisture transfer coefficient; m_f is the moisture concentration at film temperature; y_s the gas phase mole fraction of moisture near the surface; the mole fraction of moisture in the ambient air.

$$h = \frac{q_m \cdot L_{vap}}{T_\infty - T_s} \tag{8}$$

$$h_m = \frac{q_m}{m_f} \frac{1-y_s}{y_s - y_\infty} \tag{9}$$

$$h_m = \frac{q_m}{m_f \cdot (y_s - y_\infty)} \tag{10}$$

$$T_f = \frac{T_\infty + T_s}{2}. \tag{11}$$

The drying surface will reach a pseudo-steady-state condition in the constant rate period. The psychrometry method [1] is based on the material and energy balance during a pseudo-steady state, or the so-called constant rate period. Equations (8)–(10) are only valid during that constant rate period. In this study, the constant rate period is estimated from experimental data.

The average surface temperature can be theoretically predicted; Bird *et al.* [8] proposed a simple method to estimate the surface temperature as the wet and dry bulb psychrometry, see equation (12). This analysis assumed that all the exposed surface is covered by water. In the case of a drying porous media, equation (13) will give more accurate predictions by introducing the ratio of surface covered by water. Here ε represents the ratio of the surface covered by water to the total surface. In this study, the value of ε is determined by experimental data.

$$\frac{C_p}{L_{vap}} \cdot \left(\frac{Sc}{Pr}\right)^{2/3} \cdot (T_\infty - T_s) = \frac{y_s - y_\infty}{1-y_s} \tag{12}$$

$$\frac{C_p}{L_{vap}} \cdot \left(\frac{Sc}{Pr}\right)^{2/3} \cdot (T_\infty - T_s) = \frac{y_s - y_\infty}{1-y_s} \cdot \varepsilon. \tag{13}$$

3. EXPERIMENTS

Experiments were conducted to measure the forced convective heat and moisture transfer coefficients around single short cylinders during convective drying. As described in the theoretical approach, the forced convective heat and moisture transfer coefficients are calculated from the average surface temperature and the drying rate during the constant rate period of convection drying. The experiment details are discussed below.

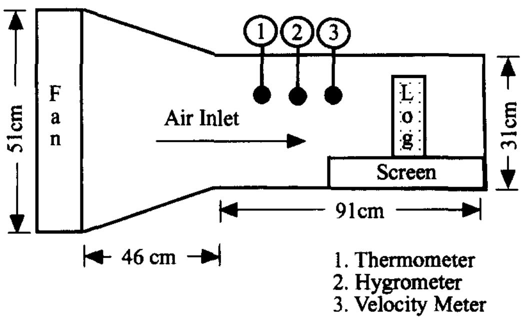

Fig. 1. Wind tunnel for coal log drying experiments.

Materials

Coal logs are used as the short cylinders and are made as briefly described below. Bituminous coal from the Mettiki mine, Maryland, is ground and passed through a 20 mesh screen. The coal is mixed with water to about 30 wt%, and this mixture is stored in a water-tight sealed container for more than 24 h. The mixture of coal and water is fed into a compaction mold and compacted into a coal log at room temperature. The peak loading during the compacting process is about 667 atm for 5 min. The compaction procedure takes about 15 min. After compaction, the coal logs are ejected from the mold and cured in air for 2 h, then stored in water. Before convective drying tests are initiated, the coal logs are immersed in a water chamber at 35 atm pressure for 1 h and stored in water at atmospheric pressure. The porosity of these coal logs, estimated by the amount of water absorbed, is about 0.15. The specific gravity of coal log is about 1.3, when saturated with water. The aspect ratios are controlled from 1.2 to 2.0. Three compaction molds with diameters 22, 33 and 45 mm are used to make logs of different sizes. The length of the coal logs is controlled by adjusting the amount of coal which is fed into a compaction mold.

Apparatus

A small wind tunnel is constructed for this study, see Fig. 1. This wind tunnel is operated with a fan at its inlet. The area of cross-section is reduced from 0.26 m^2 (inlet) to 0.09 m^2 (working section and outlet) to increase the maximum air velocity. The total length of this wind tunnel is 1.52 m. The air velocity, air temperature and relative humidity through the working section are measured by a portable air velocity meter with a multi-function probe, VELOCICALC PLUS (TSI Model 8360). The velocity variation inside the central square, at least 75 mm away from the wall of the wind tunnel, is less than 10%. Coal logs are dried on a metal screen, 75 mm high in the working area. The metal screen has holes about 1 cm^2, such that evaporation occurs from all coal log surfaces.

Experimental procedure

Before starting the experiments, the fan in the wind tunnel is turned on for 10 min until the system becomes stable. The coal log is taken out of the water and the surface water wiped off with a paper towel; inevitably some water is still left on the surface. As a result, the weight loss in the first measurement is unusually higher than that of the rest in the constant rate period. Then, measure the coal log weight. Put the coal log into the wind tunnel. Take the coal log out of the wind tunnel and measure its weight, then put it back every 3 min in the first half hour. Record the weight and surface temperature changes against time. Estimate when the drying rate becomes constant and calculate the average surface temperature and the drying rate during constant rate drying period.

4. RESULTS AND DISCUSSION

Drying rates during constant rate drying

The constant rate is period is easily observed from the coal log weight change during convective drying, see Fig. 2. The coal log overall weight, including dry coal and moisture, decreases proportional to drying time within the initial 2 h. From the experimental data, the constant rate drying periods were estimated. For 45 mm diameter logs, the average constant rate period is 2 h; for 33 mm logs, 30 min, and for 22 mm logs, 20 min. The bigger the coal log diameter, the longer the constant rate period lasts. For the rest of this study, based on these drying data, constant rate drying periods for logs of three diameters and convective transfer coefficients are calculated by equations (8) and (9).

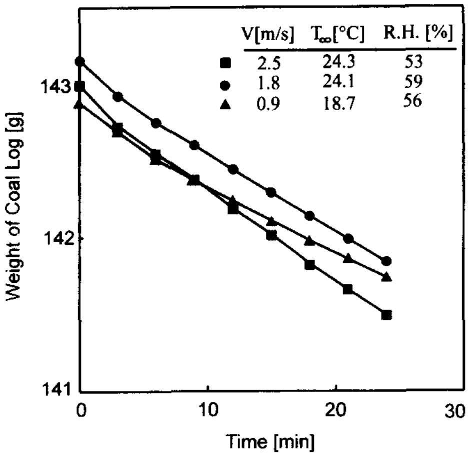

Fig. 3. Coal log weight change during the constant rate period for various convective conditions in air (Mettiki coal): log length 68.5 mm, diameter 45.3 mm.

The effects of convective conditions on drying the same coal log are illustrated in Figs. 3 and 4. Figure 3 shows the weight change of the same coal log dried under three different convective conditions. The initial weight of the same log is slightly different in each drying test, because when the saturated coal log is taken out of water and dried by a paper towel different amounts of surface water are left. As a result, the initial weights of the same log in three series are slightly different. The different initial weights have negligible effects on constant drying rates. In fact, the amount of water contained in saturated coal logs is about 30% of the total weight. In Fig. 3, the differences in the initial weight among three series are less than 1% of the total weight. The total amount of water loss during the first 20 min in drying is about 1% of the total weight. The moisture content near the surface is still very close to saturation. The drying rate during constant rate period is not significantly affected by initial moisture content.

The drying rate can be estimated by equation (6), in terms of moisture flux from the weight change data. Figure 4 shows the moisture fluxes of water calculated from the data in Fig. 3. Initially, the moisture fluxes are higher and gradually become constant. The first two moisture fluxes in each series are usually much higher than the rest, due to the transition periods caused by suddenly taking the coal log out of the wind

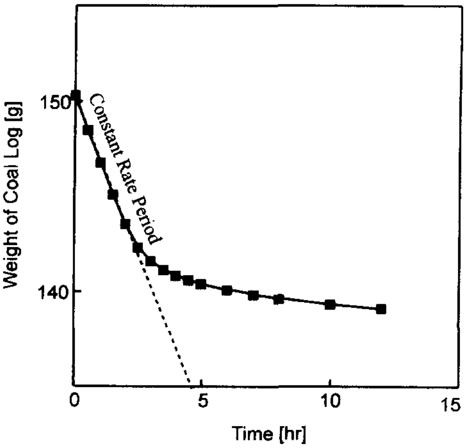

Fig. 2. Coal log weight change during convective drying (Mettiki coal): log length 73 mm, diameter 45 mm, air temperature 27.8°C, relative humidity 58%, air velocity 2.1 m s^{-1}.

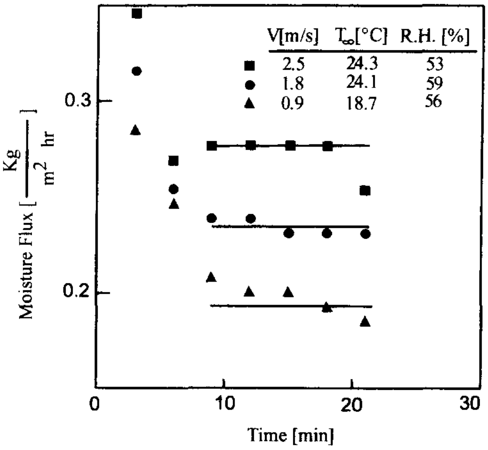

Fig. 4. Coal log moisture flux as a function of time for various convective drying conditions in air (Mettiki coal): log length 68.5 mm, diameter 45.3 mm.

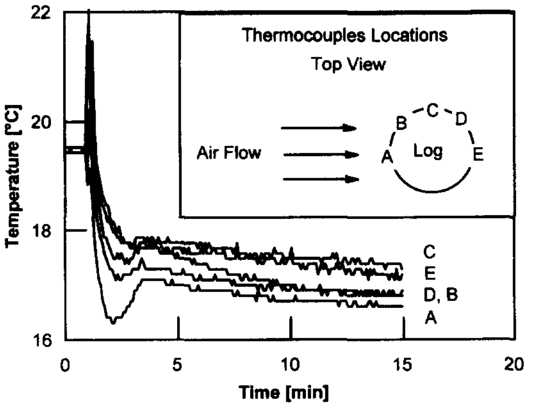

Fig. 5. Coal log surface temperature measured at different angular locations as a function of time (Mettiki coal): log length 68.5 mm, diameter, 45.3 mm, air temperature 21.4°C, relative humidity 39.6%, air velocity 1.15 m s^{-1}.

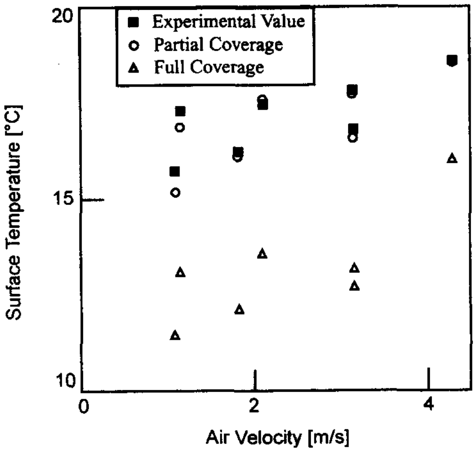

Fig. 6. Prediction of coal log surface temperature, for drying conditions see Table 1.

tunnel and drying in air. After the first two fluxes, the drying rates gradually reach a constant. In order to get a more consistent drying rate, the data before reaching the constant rates period are always discarded.

Surface temperature during constant rate drying

The constant rate drying period observed from the surface temperature is consistent with the results obtained from the weight change data, see Fig. 5. This figure shows the log surface temperature changes during the constant rate of period of forced convective drying. The temperatures are measured by thermocouples at five different angular locations. All the surface temperatures are equal to the temperature of water when the coal logs are still immersed in water. As soon as the coal log is taken out of water and dried by paper towel, the surface temperatures suddenly increase due to the contact of the dry paper towel whose temperature is assumed higher than water temperature, close to room temperature, then immediately drop quickly due to the evaporation of water at the surface. As the surface temperature decreases, the amount of heat consumed also decreases because of the decreasing drying rate, see Fig. 5. The surface temperature gradually stabilizes, but continues to decrease at a very slow rate. This means that the log surface has reached pseudo-state-steady conditions As drying continues and most water has evaporated, the surface temperature will start to increase and return to the air temperature. Temperature data indicates that the surface temperature reaches a constant value approximately 3 min after drying is initiated, which is consistent with the weight changes data in Fig. 4.

Surface temperature observations confirm that equation (13) makes more accurate predictions than equation (12), see Table 1 and Fig. 6. The coal log drying conditions are listed in Table 1. Figure 6 shows the average surface temperature during the constant rate period of forced convection drying. The average value of the surface temperatures measured by five thermocouples during the constant rate period is taken as the average surface temperature of a coal log in equation (8), required to calculate the convection transfer coefficients. The coal log surface is only partially covered by water instead of fully covered; portions of the surface area are occupied by a coal structure which makes no contribution to water vaporization during drying. Also, equation (13) is more accurate at high Reynolds numbers. In the case of high air velocity, the radial heat transfer is negligible. However, the radial heat transfer is not neg-

Table 1. The coal log surface temperature under various convective drying conditions

Air velocity [m s^{-1}]	Air temperature [°C]	Relative humidity [%]	Measured temperature [°C]	Errors [°C]	
				Predicted[A]	Predicted[B]
4.29	22.0	0.55	18.64	2.59	0.01
3.15	21.2	0.38	16.83	4.10	0.20
3.15	23.8	0.27	17.90	4.67	0.10
2.10	22.7	0.37	17.53	3.92	−0.17
1.83	20.7	0.37	16.25	4.11	0.13
1.15	21.4	0.40	17.33	4.20	0.42
1.08	19.5	0.38	15.77	4.33	0.52

[A] Equation (12), Bird *et al.* [8].
[B] Equation (13).

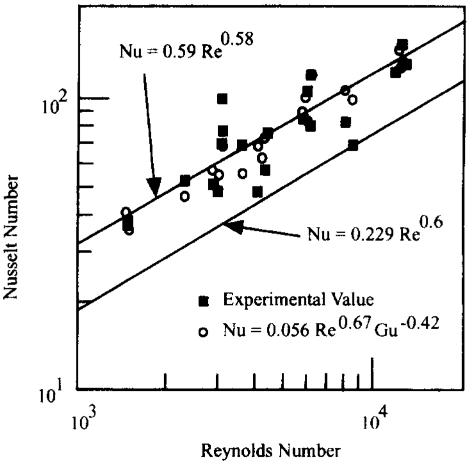

Fig. 7. Correlation of Nusselt number as a function of Reynolds number for coal log drying experiments.

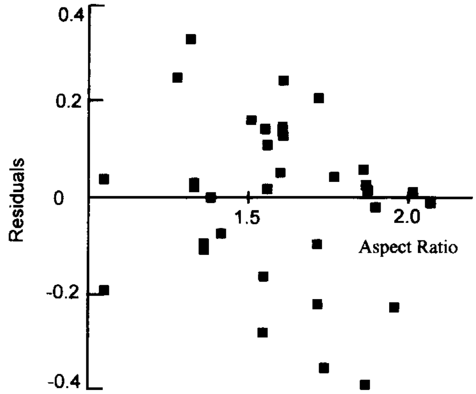

Fig. 9. Residual of Nusselt number linear regression as a function of coal log aspect ratio.

ligible at low air velocities. As a result, surface temperatures are slightly underestimated by equation (13) due the effects of thermal radiation.

Dimensional analysis

The calculated Nusselt number of convective drying is significantly higher than that of heat transfer only. Figures 7 and 8 show the Nusselt and Sherwood numbers of 35 experiments as functions of Reynolds number. The correlation obtained in this study, see equation (14), predicted a higher Nusselt number than both of the correlations of heat transfer only, see equations (1) and (2). The Nusselt number obtained by this study, which is for simultaneous heat and moisture transfer, is significantly higher than the Nusselt number predicted by Zukauskas and Ziugzda [2], which is considered for heat transfer only. Higher heat transfer rates are caused by phase change and shorter aspect ratios.

$$Nu = 0.59 \cdot Re^{0.58}. \tag{14}$$

Gukhman number can improve the dimensionless equation, equation (14), by introducing the effects of humidity. The Nusselt and Sherwood numbers also correlate in the form of equation (5), see equations (15) and (16). In Fig. 7, every predicted value of equation (15) is closer to the experimental value than the predictions by equation (14).

$$Nu = 0.056 \cdot Re^{0.65} \cdot Gu^{-0.43} \tag{15}$$

$$Sh = 0.047 \cdot Re^{0.67} \cdot Gu^{-0.42}. \tag{16}$$

The experimental data in this study show that the effect of aspect ratio on convective transfer coefficients are not significant. Figure 9 shows the residual of fitting equation (15), defined as equation (17), vs aspect ratio. No significant pattern exists.

$$\text{Residual} \equiv \ln\left(\frac{Nu_{\text{Experiment}}}{Nu_{\text{Prediction}}}\right). \tag{17}$$

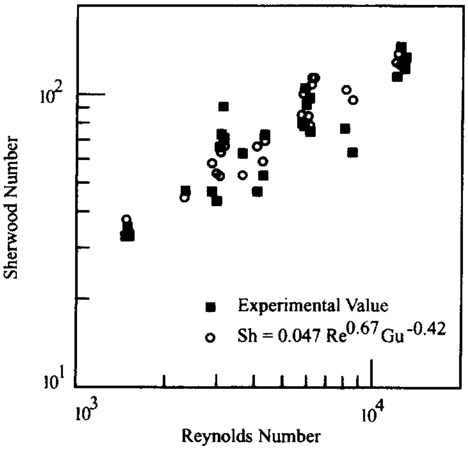

Fig. 8. Correlation of Sherwood number as a function of Reynolds number for coal log drying experiments.

5. CONCLUSIONS

With simple equipment, the psychrometry method works well in determining the convective heat and moisture transfer coefficients across single coal logs. For the same Reynolds number range, the measured heat transfer coefficient is twice larger than the coefficient predicted for heat transfer only, based on the experiments of drying water saturated short logs. Equation (15) gives more accurate predictions for the heat transfer coefficient than equation (14) by introducing the Gukhman number. To obtain the mass transfer coefficients, in terms of the Sherwood number, equation (16) is suggested. More accurate Nusselt and Sherwood numbers can be calculated using corrected surface temperatures. By introducing a correction factor on the ratio of surface covered by water, more accurate surface temperatures are calculated.

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REFERENCES

1. A. Kondjoyan and J. D. Daudin, Determination of transfer coefficients by psychrometry, *Int. J. Heat Mass Transfer* **36,** 1807–1818 (1993).
2. A. Zukauskas and J. Ziugzda, *Heat Transfer of a Cylinder in Crossflow*, p. 137. Hemisphere, New York (1985).
3. A. Quarmby and A. A. M. Al-Fakhri, Effect of finite length on forced convective heat transfer from cylinders, *Int. J. Heat Mass Transfer* **23,** 463–469 (1980).
4. K. Nomura and P. V. Farrell, Heat and mass transfer coefficients for porous horizontal cylinders, *AIChE J.* **31,** 1217–1219 (1985).
5. P. D. Lebedev, Heat and mass transfer between moist solids and air, *Int. J. Heat Mass Transfer* **1,** 302–305 (1961).
6. R. B. Keey, *Drying: Princples and Practice*, p. 152. Pergamon, New York (1972).
7. A. V. Luikov, Heat and mass transfer in capillary-porous bodies, *Adv. Heat Transfer* **1,** 123–184 (1964).
8. R. B. Bird, W. E. Stewart and E. N. Lightfoot, *Transport Phenomena*, p. 651. Wiley, New York (1960).