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ESTIMATION OF CONVECTIVE HEAT AND MASS TRANSFER COEFFICIENTS FOR CONSTANT-RATE DRYING PERIOD DURING TAPE CASTING

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ABSTRACT

Models are presented for estimating the convective heat and mass transfer coefficients in the constant-rate period of drying of water-based alumina suspension for tape casting for a range of flow rate of the drying medium (ambient gas) from $1.25\,\mathrm{cm}^3/\mathrm{s}$ to $3.33\,\mathrm{cm}^3/\mathrm{s}$ and a temperature range from 298K to 328K. The convective mass-transfer coefficient depends only on the gas flow rate, while the convective heat-transfer coefficient is a function of temperature and gas flow rate. Model estimated values of the convective mass-transfer coefficient compare reasonably well with experimental data at ambient temperature and relative humidity of 298K and 65% respectively and different flow rates of the ambient gas, while those of the convective heat-transfer coefficient show significant deviation from the experimental data

KEYWORDS Drying; Ceramics, Convection, Transport coefficients, Tape casting

1. INTRODUCTION

Convective drying of materials at atmospheric pressure is a complex mechanism involving simultaneous heat and mass transfer. The drying rate in the constant-rate period is given as (Perry and Green, 1984)

$$\alpha = k(P_{ws} - P_{wb}) = \frac{h}{E'}(T - T_{wet}) \qquad (1)$$

which is applied here to the constant-rate period of air-drying of water-based alumina suspension for tape casting, where α is the drying rate per unit surface area of the suspension ($\mathrm{kg/m^2s}$), k is the mass-transfer coefficient ($\mathrm{kg/m^2s\,Pa}$); T is the ambient temperature (K); T_{wet} is the wet bulb temperature (K); P_{ws} is the partial pressure of water vapour at the drying surface (Pa), which is taken here as the *saturation vapour pressure* of water at a given ambient temperature. P_{wb} is the partial pressure of water vapour in the bulk air (i e. the surrounding); h is the heat-transfer coefficient ($\mathrm{kJ/m^2s\,K}$); and E' is taken here as the latent heat of evaporation of the suspension at a given ambient temperature (kJ/kg). Equation (1) is valid for convective and non-convective drying processes, and k and h may be defined accordingly. A detailed experimental study on the formulation and drying kinetics of water-based alumina suspension for tape casting is provided in Briscoe et al. (1998) for a range of temperature from 298K to 328K.

Puyate (2003) estimated a constant value of the mass-transfer coefficient for the constant-rate period during non-convective air-drying of the water-based suspension reported in Briscoe at al (1998). Puyate (2005) proposed a temperature-dependent heat-transfer coefficient for the constant-rate period of drying of the suspension under the same conditions as in Puyate (2003). Puyate (2006) presented a modified model that estimates the drying rate per unit surface area of the suspension in the constant-rate period as a function of temperature, relative humidity, and flow rate of the drying medium. It is the purpose of this paper to present models that estimate the convective heat and mass transfer coefficients in the constant-rate period of drying of water-based alumina suspension for tape casting for a range of flow rate of the drying medium (ambient gas) from $1.25\,\mathrm{cm}^3/\mathrm{s}$ to $3.33\,\mathrm{cm}^3/\mathrm{s}$ and a temperature range from 298K to 328K. The advantages of the current models over Sherwood and Nusselt numbers include direct and easy application independence of the models on flow regime and geometry of the flow domain, compact with few parameters, and practical explicit nature

2. Transport coefficients for suspension drying

2.1. Convective heat-transfer coefficient

Puyate (2005) applied Reynolds analogy (developed for convection process) to the constant-rate period of drying for equimolecular counter-diffusion of air and water vapour across the stagnant air-film at the drying surface with bulk flow of the diffusing components, to obtain

$$N_w = \frac{C'_{ws}}{C'_{as}}\frac{\sigma}{\rho_m \upsilon_m} = h_D(C'_{ws} - 0) \qquad (2)$$

where N_w is the total molar flux of water vapour from the drying surface to the surrounding, resulting from normal diffusion of water vapour and its bulk flow away from the surface. $h_D = ((C'_{ws}/C'_{as})\sigma/\rho_m \upsilon_m$ is the mass-transfer coefficient expressed in $\mathrm{kmol/m^2s(kmol/m^3)}$ and is equivalent to k in eq (1). C'_{ws} is the molar concentration of water vapour at the drying surface. C'_{as} is the molar concentration of air at the drying surface. σ is the total shear stress acting on both the water vapour and air at the drying surface. υ_m is the mean velocity of moist air outside the boundary layer and ρ_m is the mean mass density of air and water vapour in the ambient moist air

The drying rate per unit area in the constant-rate period during convective drying of the water-based alumina suspension is given as (Puyate, 2006)

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$$\alpha = (m + nF)\left(1 - \frac{RH}{100}\right)\exp(-E^* / R_g T) \quad (3)$$

where $m = 389.58$ kg/m^{2}s and $n = 124.98$ kg/m^{2}s(cm^3/s) are constants, F is the volumetric flow rate of the drying medium (air) in a range from $1.25\,\text{cm}^3/\text{s}$ to $3.33\,\text{cm}^3/\text{s}$, R_g is the universal gas constant (8.314 J/mol K), RH is the relative humidity expressed as a percentage, T is the ambient temperature (K), and $E^* = 41.2$ kJ/mol is the average latent heat of vaporization of the suspension in a temperature range from 298K to 328K. Putting $RH = 0$ for dry air into eq. (3) and equating the resulting expression (in molar units) to eq. (2) gives the relationship between momentum and mass transfer in the constant-rate period during convective drying of the suspension as

$$\frac{(m + nF)\overline{C}_{As}}{\upsilon_m M_w \overline{C}_{ws}^2}\exp(-E^* / R_g T) = \frac{\sigma}{\rho_m \upsilon_m^2} \quad (4)$$

where M_w is the molar mass of water vapour (18 kg/kmol), and the bar at the top of a variable means average value of the variable within the temperature range $298\text{K} \le T \le 328\text{K}$ (Puyate, 2005).

Reynolds analogy between momentum and heat transfer which also applies to the constant-rate period is given as (Coulson and Richardson, 1977)

$$\frac{h}{C_p \rho_m \upsilon_m} = \frac{\sigma}{\rho_m \upsilon_m^2} \quad (5)$$

which when combined with eq. (4) gives the convective heat-transfer coefficient (h_c) for the constant-rate period of air-drying of the suspension, assuming equimolecular counter-diffusion with bulk flow, as

$$h_c = \frac{(m + nF)C_p \rho_m \overline{C}_{As}}{M_w \overline{C}_{ws}^2}\exp(-E^* / R_g T) \quad (6)$$

where C_p is the specific heat capacity of moist air. It may be necessary to indicate that the temperature-dependent heat-transfer coefficient presented by Puyate (2005) for the constant-rate period during non-convective drying of the suspension corresponds to $F = 0$ in eq. (6), where $\overline{C}_{As} = 35.83 \times 10^{-3}$ kmol/m^3, $\overline{C}_{ws} = 3.17 \times 10^{-3}$ kmol/m^3, $C_p = 1.07$ kJ/kg K, and $\rho_m = 0.55$ kg/m^3.

2.2. *Convective mass-transfer coefficient*

An approximate form of the mass-transfer part of eq. (1) which is valid for convective and non-convective drying processes is given as (Puyate, 2003).

$$\alpha = kP_{ws(ref)}\exp(\hat{E} / R_g T_{ref})\left(1 - \frac{RH}{100}\right)\exp(-\hat{E} / R_g T) \quad (7)$$

where T_{ref} is a reference temperature taken to be 298K, $\hat{E}$ is the average latent heat of evaporation in a temperature range from T_{ref} to T, and $P_{ws(ref)} = 3012.79$ Pa is the saturation vapour pressure of water at T_{ref}. Equating eqs (3) and (7), with $\hat{E} \approx E^*$, gives an estimate of the convective mass-transfer coefficient (k_c) for the constant-rate period of drying of the suspension as

$$k_c = \frac{(m + nF)}{P_{ws(ref)}}\exp(-E^* / R_g T_{ref}) \quad (8)$$

The constant value of the mass-transfer coefficient presented by Puyate (2003) for the constant-rate period during non-convective drying of the suspension corresponds to $F = 0$ in eq. (8).

3. RESULTS AND DISCUSSION

Experimental data on mass-loss of the suspension in the constant-rate period at $T = 298$ K, $RH = 65\%$, and different flow rates of the drying medium are presented in Briscoe et al. (1998) and Puyate (2006). In order to calculate experimental values of h_c using the heat-transfer part of eq. (1), we need to know T_{wet}. The value of T_{wet} corresponding to $T = 298$ K and $RH = 65\%$ is estimated from a humidity-temperature chart (Coulson and Richardson 1977) for air-water vapour system at atmospheric pressure to be $T_{wet} = 293.5$ K. Substituting these values of T, T_{wet}, and $E' = 2289$ kJ/kg for the suspension into the heat-transfer part of eq. (1) gives a relationship between α and h_c, which is used to calculate experimental values of h_c at corresponding experimental values of α for different flow rates of the ambient gas as shown in Table 1 (see Puyate (2006) for details on the determination of α at different flow rates of the ambient gas). Estimated values of h_c using eq (6) are also presented in Table 1

Table 1. Experimental (Briscoe et al., 1998) and estimated values of h_c at $T = 298$ K, $RH = 65\%$, and different flow rates of ambient gas.

F ($\mathrm{cm^3/s}$)	α ($\times 10^5$ $\mathrm{kg/m^2 s}$)	h_c ($\times 10^3$ $\mathrm{kJ/m^2 s\,K}$)	
		Experiment	Estimate
1.25	1.16	5.90	3.82
1.67	1.23	6.26	4.18
2.0	1.37	6.97	4.47
2.5	1.47	7.48	4.91
3.33	1.69	8.60	5.63

It may be seen from Table 1 that the estimated values of h_c are comparable with the experimental values but not very close. Nabhani et al. (2003) obtained similar deviations of estimated values of h_c from experimental data, but at different temperatures and air velocities.

We have obtained from Section 2.2 that $P_{ws} = 3012.79$ Pa at 298K. A corresponding value of $P_{wb} = 1958.31$ Pa at this temperature and $RH = 65\%$ is then calculated using the relation (Coulson and Richardson, 1977)

$$P_{wb} = P_{ws}(RH/100) \quad (9)$$

Substituting the above values of P_{ws} and P_{wb} into the mass-transfer part of eq. (1) gives a relationship between α and k_c which is used to calculate experimental values of the latter at corresponding experimental values of the former for different flow rates of the ambient gas as shown in Table 2. (See Table 1 for values of α at different flow rates of the drying medium). Estimated values of k_c using eq. (8) are also presented in Table 2, from which it may be seen that the estimated values are very close to the experimental values.

Table 2. Experimental (Briscoe et al., 1998) and estimated values of k_c at $T = 298$ K, $RH = 65\%$, and different flow rates of ambient gas.

F ($\mathrm{cm^3/s}$)	k_c ($\times 10^8$ $\mathrm{kg/m^2 s\,Pa}$)	
	Experiment	Estimate
1.25	1.10	1.09
1.67	1.17	1.19
2.0	1.30	1.27
2.5	1.39	1.40
3.33	1.60	1.60

4. CONCLUSION

Models are presented that estimate the convective heat and mass transfer coefficients for the constant-rate period of drying of water-based alumina suspension for tape casting. The results obtained show that estimated values of the convective mass-transfer coefficient compare better with experimental data than those of the convective heat-transfer coefficient. The key parameter in the present analysis is the ambient gas flow rate. The convective mass-transfer coefficient depends only on the gas flow rate, while the convective heat-transfer coefficient is a function of temperature and gas flow rate.

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REFERENCES

Briscoe, B. J., Lo Biundo, G. and Ozkan, N., 1998. Drying kinetics of water-based ceramic suspensions for tape casting, Ceramics International, 24, pp. 347-357

Coulson, J. M. and Richardson, J. F., 1977. Chemical Engineering, Vol. 1 (3rd ed.), Pergamon Press, Oxford

Nabhani, M., Tremblay, C. and Fortin, Y., 2003. Experimental determination of convective heat and mass transfer coefficients during wood drying. Proceedings of the 8th International Conference on IUFRO Wood Drying Transilvania University of Brasov, Romania, pp. 225-230.

Perry, R. H. and Green, D. W., 1984, Perry's Chemical Engineers' Handbook, 6th ed., McGraw-Hill, Lonon

Puyate, Y. T., 2003. Determination of the constant-rate mass-transfer coefficient for drying during tape casting, Journal of Modeling Design and Management of Engineering Systems 2(1) 83-88

Puyate, Y. T., 2005. Performance evaluation of heat-transfer coefficients for constant-rate period of drying during tape casting, Journal of Modeling, Design, and Management of Engineering Systems, 3(1). 25-37

Puyate, Y. T., 2006, Modified model of convective drying of water-based ceramic suspension for tape casting, Global Journal of Engineering Research, 5(1&2), 67-72.