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PERFORMANCE EVALUATION OF MASS-TRANSFER COEFFICIENTS FOR CONSTANT-RATE PERIOD OF DRYING DURING TAPE CASTING

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ABSTRACT

Temperature-dependent mass-transfer coefficient is presented for the constant-rate period during non-convective drying of water-based alumina suspension for tape casting. Predicted drying rates based on the temperature-dependent mass-transfer coefficient and constant value of the mass-transfer coefficient are compared with experimental data in a range of ambient temperature from 298K to 328K and a range of relative humidity from 40% to 90%. It is shown that the temperature-dependent mass-transfer coefficient is adequate with maximum error of about 9% in predicted drying rates. The constant mass-transfer coefficient is also adequate, but with errors in predicted drying rates of about 18% and 16% at 40%RH(328K) and 65%RH(328K) respectively, and maximum error of about 9% at all other data points. A model based on drying parameters of the suspension in the constant-rate period is also presented for estimating wet-bulb temperature within the specified ranges of ambient temperature and relative humidity. Model-estimated wet-bulb temperatures are compared with those estimated from a humidity-temperature chart for air-water vapour system at atmospheric pressure and good agreement is obtained.

KEYWORDS: Drying; Suspension; Ceramics; Wet-bulb temperature; Tape casting.

1. INTRODUCTION

Drying of materials at atmospheric pressure is a complex mechanism involving simultaneous heat and mass transfer. The drying rate in the constant-rate period can be characterized by a mass-transfer coefficient or a heat-transfer coefficient (Perry and Green, 1984) as

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

where α is the drying rate per unit area ($\mathrm{kg/m^2s}$); 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 surrounding (i.e. bulk air); h is the heat-transfer coefficient ($\mathrm{kJ/m^2s\,K}$); and E' is taken here as the latent heat of evaporation 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.

The formulation of water-based alumina suspension for tape casting, and a detailed experimental study on non-convective drying kinetics of the suspension in a temperature range from 298K to 328K and a range of relative humidity from 40% to 90%, are presented by Briscoe et al. (1998). Puyate (2003) estimated a constant value of $k = 7.55 \times 10^{-9}\ \mathrm{kg/m^2s\,Pa}$ 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). In reality, the mass-transfer coefficient in the constant-rate period of the suspension may depend upon temperature, but this has not been investigated. Also no model exists at the moment for estimating wet-bulb temperature in the constant-rate period. It is the purpose of this paper to present a temperature-dependent mass-transfer coefficient for the constant-rate period during non-convective drying of water-based alumina suspension for tape casting using the work of Briscoe et al (1998), and to assess the performance of the constant mass-transfer coefficient (Puyate, 2003) and the temperature-dependent mass-transfer coefficient. A model based on drying parameters of the suspension in the constant-rate period is also presented for estimating wet-bulb temperature within the specified ranges of temperature and relative humidity.

2. Temperature-dependent mass-transfer coefficient

For the air-water vapour system considered in the analysis, P_{ws} and P_{wb} are both small compared to atmospheric pressure, P_{atm}, so that P_{wb}/P is approximately equal to the relative humidity expressed as a fraction. The mass-transfer part of eq. (1) may then be expressed as

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$$\alpha = kP_{ws}\left(1 - \frac{RH}{100}\right) \quad (2)$$

where RH is the relative humidity expressed as a percentage. During the constant-rate period, the surface of a wet material behaves like a free liquid surface and the rate of evaporation per unit area from such surface is given by (Davies and Rideal, 1961)

$$\alpha' = B\exp(-E / R_g T) \; (3)$$

where B is a constant independent of temperature and humidity ($\mathrm{kg/m^2s}$), R_g is the universal gas constant (8.314 J/mol K), E is the latent heat of evaporation at a given ambient temperature (J/mol), and the prime indicates that the drying rate is a function of only temperature. Equation (3) is analogous to the expression for the rate of desorption of a species from a surface in which the effect of the partial pressure of the species in the gaseous phase is insignificant and neglected (Morrison, 1990); that is, eq. (3) corresponds approximately to the drying rate of a material in the constant-rate period for dry air. Briscoe et al. (1998) introduced the effect of relative humidity into eq. (3) through empirical modelling and obtained $B = a_n + b_n RH$ which when substituted into eq. (3) gives their model for the drying rate in the constant-rate period during non-convective drying of the suspension as

$$\alpha \approx (a_n + b_n RH)\exp(-E^* / R_g T) \qquad (4)$$

where $a_n = 389.8\,\mathrm{kg/m^2s}$ and $b_n = -3.94\,\mathrm{kg/m^2s\,RH}$ are constants, and $E^* = 41.2\,\mathrm{kJ/mol}$ is the average latent heat of vaporization of the suspension in a temperature range from 298K to 328K

It may be necessary to indicate that the experiments of Briscoe et al. (1998) were carried out at different temperatures (298K, 313K, 328K), with the relative humidity at each temperature varied in succession as 40%, 65%, and 90%. However, since the relationship between B and relative humidity is linear, B can be predicted at any relative humidity outside the range of the experiments. Putting $RH = 0$ for dry air into eq. (2) and equating the resulting expression to eq. (3) indicates that P_{ws} depends upon temperature in an Arrhenius form so that eqs. (2) and (4) are the same in principle. Inspection of eq. (4) reveals that it does not satisfy the zero-drying rate condition at 100% relative humidity with an error of about 1.08% at this relative humidity. On the assumption that eq. (4) is adequate with an average error of about 1.08%, eqs (2) and (4) may be equated to obtain an approximate model for a temperature-dependent mass-transfer coefficient in the constant-rate period during non-convective drying of the suspension as

$$k(T) \approx \frac{a_n}{P}\exp(-E^* / R_g T) (5)$$

where $k(T)$ indicates that the mass-transfer coefficient is a function of temperature. Replacing k in eq. (2) with $k(T)$ gives the drying rate per unit area based on the temperature-dependent mass-transfer coefficient during non-convective drying of the suspension in the constant-rate period as

$$\alpha \approx a_n\left(1 - \frac{RH}{100}\right)\exp(-E^* / R_g T) \, (6)$$

2.1. *Estimation of wet-bulb temperature during suspension drying*

The wet-bulb temperature depends only on the temperature and humidity of the drying medium, and is normally estimated from a humidity-temperature chart for air-water vapour system at atmospheric pressure (Coulson and Richardson, 1977). Puyate (2005) presented a temperature-dependent heat-transfer coefficient, $h(T)$, for the constant-rate period during non-convective drying of the suspension as

$$h(T) = \frac{a_n C_p \rho_m \overline{C}_{As}}{M_w \overline{C}_{ws}^2}\exp(-E^* / R_g T) \, (7)$$

where $C_p = 1.07\,\mathrm{kJ/kg\,K}$ is the specific heat capacity of moist air at the experimental conditions of Briscoe et al. (1998), $\rho_m = 0.55\,\mathrm{kg/m^3}$ is the mean mass density of air and water vapour in the surrounding at the experimental conditions, $\overline{C}_{As} = 35.83\times10^{-3}\,\mathrm{kmol/m^3}$ is the average molar concentration of air at the drying surface for the range of ambient temperature considered in the analysis, $\overline{C}_{ws} = 3.17\times10^{-3}\,\mathrm{kmol/m^3}$ is the average molar concentration of water vapour at the drying surface for the range of ambient temperature considered in the analysis, and M_w is the molar mass of water vapour (18 kg/kmol). The wet-bulb temperature for a range of ambient temperature from 298K to 328K and a range of relative humidity from 40% to 90% may be estimated by replacing h in the heat-transfer part of eq. (1) with $h(T)$ (given by eq. (7)) and equating the resulting expression to eq. (6), to obtain

$$T_{wet} \approx T - 19.64\left(1 - \frac{RH}{100}\right) (8)$$

where $E' = 2289\,\mathrm{kJ/kg}$ for the suspension.

3. RESULTS AND DISCUSSION

In order to use eq. (2) (which is the equivalent of the mass-transfer part of eq. (1)) with the known value of $k = 7.55\times10^{-9}\,\mathrm{kg/m^2s\,Pa}$ for the suspension, in predicting drying rates in the constant-rate period we need to know P_{ws}. Water vapour is assumed to be saturated at the drying surface of the water-based suspension The humidity of saturated water vapour

(H_o) at 100% relative humidity and a given ambient temperature is estimated from a humidity-temperature chart for air-water vapour system at atmospheric pressure (Coulson and Richardson, 1977). The partial pressure of saturated water vapour at the drying surface, P_{ws}, at the given ambient temperature is then calculated from H_o using the relation (Coulson and Richardson, 1977)

$$H_o = \frac{P_{ws} M_w}{(P_{atm} - P_{ws}) M_A} \quad (9)$$

where M_A is the average molar mass of air (29 kg/kmol), and $P_{atm} = 101325\,\text{Pa}$ has been used. Table 1 shows calculated values of P_{ws} at the experimental ambient temperatures of Briscoe et al. (1998).

Table 1 Calculated parameters of water vapour at the drying surface

Temp	H_o (kg/kg)	P_{ws} (Pa)
298K	0.019	3012.79
313K	0.045	6856.58
328K	0.112	15503.28

The diameter of the cylindrical sample holder used in the weight-loss experiments of Briscoe et al. (1998) was 13mm; this gives the surface area of the suspension as $A = 1.33 \times 10^{-4}\,\text{m}^2$. Tables 2–4 show the comparison between predicted drying rates of the suspension in the constant-rate period using eq. (2) with the constant value of k (Puyate, 2003) denoted 'Predicted,' and those of eq. (6) based on $k(T)$ denoted 'Predicted(T),' and the experimental data.

Table 2: Experimental (Briscoe et al., 1998) and predicted drying rates at $RH = 40\%$.

Temp	Drying rate ($\times 10^9$ kg/s)		
	Experiment	Predicted	Predicted(T)
298K	1.7	1.82	1.86
313K	3.8	4.13	4.14
328K	7.9	9.34	8.53

Table 3 Experimental (Briscoe et al., 1998) and predicted drying rates at $RH = 65\%$.

Temp.	Drying rate ($\times 10^9$ kg/s)		
	Experiment	Predicted	Predicted(T)
298K	1.0	1.06	1.09
313K	2.0*	2.41	2.41
328K	4.7	5.45	4.98

Table 4: Experimental (Briscoe et al., 1998) and predicted drying rates at $RH = 90\%$.

Temp.	Drying rate ($\times 10^{10}$ kg/s)		
	Experiment	Predicted	Predicted(T)
298K	3.2	3.03	3.11
313K	4.5*	6.89	6.70
328K	15.4	15.57	14.22

It is shown (Puyate, 2008) that the experimental values marked asterisk in Tables 3 and 4 are incorrect, and therefore not used in assessing the performance of the mass-transfer coefficients in the present analysis. It may be seen from Tables 2–4 that predictions based on the constant mass-transfer coefficient (Puyate, 2003) and the temperature-dependent mass-transfer coefficient are close. The error, E, in a predicted drying rate is calculated as

$$E = \frac{V_{exp} - V_{pred}}{V_{exp}} \quad (10)$$

where V_{exp} is experimental value of the drying rate, and V_{pred} is predicted value of the drying rate. Table 5 shows the percentage errors of the predicted drying rates in Tables 2–4.

Table 5: Calculated percentage errors of predicted drying rates of suspension.

Temp	40%RH		65%RH		90%RH	
	Predicted (%)	Predicted(T) (%)	Predicted (%)	Predicted(T) (%)	Predicted (%)	Predicted(T) (%)
298K	7.06	9.41	6.0	9.0	5.31	2.81
313K	8.68	8.95	ND	ND	ND	ND
328K	18.23	7.97	15.96	5.96	1.10	7.66

Since the asterisked values in Tables 3 and 4 are incorrect, it is inappropriate to calculate the errors in predicted drying rates using the incorrect experimental values as bases, hence the corresponding spaces in Table 5 are marked 'ND' meaning 'Not Determined.'

Table 5 indicates that predictions based on the temperature-dependent mass-transfer coefficient compare well with the experimental data with maximum error of 9.41%. Table 5 also indicates that predictions based on the constant mass-transfer coefficient (Puyate

2003) compare well with the experimental data, but with errors of about 18% and 16% at 40%RH(328K) and 65%RH(328K) respectively, and maximum error of about 9% at all other data points. The numerical values in Tables 2–4 indicate that errors less than or equal to 10% may be neglected, such that the temperature-dependent mass-transfer coefficient may be used for the entire ranges of temperature and relative humidity considered in the analysis, while the constant mass-transfer coefficient is inadequate at 40%RH(328K) and 65%RH(328K) unless rough approximations are required at these data points.

Table 6 shows values of T_{wet} at the experimental conditions estimated from the same humidity-temperature chart (Coulson and Richardson, 1977) for air-water vapour system at atmospheric pressure, while Table 7 shows values of T_{wet} estimated from eq. (8) which may be seen to compare reasonably well with those in Table 6

Table 6: Chart estimated values of T_{wet} at experimental conditions.

T (K)	T_{wet} (K)		
	40%RH	65%RH	90%RH
298	288.50	293.50	297.0
313	301.67	307.0	312.0
328	314.44	321.56	327.0

Table 7: Model estimated values of T_{wet} at experimental conditions.

T (K)	T_{wet} (K)		
	40%RH	65%RH	90%RH
298	286.22	291.13	296.04
313	301.22	306.13	311.04
328	316.22	321.13	326.04

4. CONCLUSION

Temperature-dependent mass-transfer coefficient is presented for the constant-rate period during non-convective drying of water-based alumina suspension for tape casting. It has been shown that the temperature-dependent mass-transfer coefficient may be used for the entire ranges of temperature and relative humidity considered in the analysis with maximum error of about 9% in predicted drying rates. The constant mass-transfer coefficient is also adequate, but with errors in predicted drying rates of about 18% and 16% at 40%RH(328K) and 65%RH(328K) respectively, and maximum error of about 9% at all other data points. Thus, either coefficient may be used to characterize the constant-rate period of drying of the suspension depending on the temperature and relative humidity. The consistency between the estimated wet-bulb temperatures in Tables 6 and 7 indicates that eq. (8) is adequate and may be applied to water-based systems.

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