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APPENDIX A

OVERALL MASS AND ENERGY BALANCE

Overall mass and energy balance have been taken to double-check the reliability of the published data. The equations are as follows:

A.1. Overall balance of water at steady state

$$\begin{Bmatrix}\text{Rate of}\\ \text{water vapor}\\ \text{in with air}\end{Bmatrix}+\begin{Bmatrix}\text{Rate of}\\ \text{moisture}\\ \text{in with solid}\end{Bmatrix}=\begin{Bmatrix}\text{Rate of}\\ \text{water vapor}\\ \text{out with air}\end{Bmatrix}+\begin{Bmatrix}\text{Rate of}\\ \text{moisture out}\\ \text{with solid}\end{Bmatrix}$$

$$G_a H_{in} + G_s W_{in} = G_a H_{out} + G_s W_{out}$$

$$G_s (W_{in} - W_{out}) = G_a (H_{out} - H_{in}) \qquad \text{(A.1)}$$

A.2. Overall energy balance at steady state

$$\begin{Bmatrix}\text{Rate of thermal}\\ \text{energy in}\\ \text{with air}\end{Bmatrix}+\begin{Bmatrix}\text{Rate of thermal}\\ \text{energy in}\\ \text{with solid}\end{Bmatrix}=\begin{Bmatrix}\text{Rate of thermal}\\ \text{energy out}\\ \text{with air}\end{Bmatrix}+\begin{Bmatrix}\text{Rate of thermal}\\ \text{energy out}\\ \text{with solid}\end{Bmatrix}$$

$$G_a i_{a,in} + G_s i_{s,in} = G_a i_{a.out} + G_s i_{s.out} \qquad \text{(A.2)}$$

where $$i_a = (C_a + C_v H) T_a + \lambda_0 H \qquad \text{(A.3)}$$

and $$i_s = (C_s + C_w W) T_s \qquad \text{(A.4)}$$

APPENDIX B

CORRELATIONS OF AIR PROPERTIES

The correlations for psychrometric data, such as the correlations for water vapor pressure with temperature, saturated humidity with total pressure and temperature, humid volume of air with humidity and temperature and latent heat of vaporization with temperature, used in the present model are those proposed by the American Society of Agricultural Engineers (ASAE, 1994). All these correlations have been checked to confirm that they yield results that agree closely with the air properties in the humidity chart of R. Toei (1986).

B.1 Correlation for vapor pressure of water

$$\ln\left(\frac{P_{sat}}{2.21*10^{7}}\right)=\frac{-2.74*10^{4}+97.541T-0.146T^{2}+1.256*10^{-4}T^{3}-4.85*10^{-8}T^{4}}{4.349-3.938*10^{-3}T}$$

$$\text{for} \quad 273.16\,\text{K} \le T \le 533.16\,\text{K} \qquad \text{(B.1)}$$

B.2 Correlation for saturated humidity of air

$$H_{sat} = \frac{0.6219P_{sat}}{P_{atm}-P_{sat}} \qquad \text{for} \quad P_{sat} < P_{atm} \qquad \text{(B.2)}$$

B.3 Correlation for humid volume

$$V_H = (0.772 + 1.24H)\frac{T_a}{273.16} \tag{B.3.1}$$

Then, the density of humid air is given by

$$\rho_a = \frac{(1+H)}{V_H} \tag{B.3.2}$$

B.4 Correlation for latent heat of vaporization at temperature T_a

For $273.16\,K \le T_a \le 338.72\,K$

$$\lambda = \frac{2.503 * 10^6 - 2.386 * 10^3 (T_a - 273.16)}{4.19 * 10^3} \tag{B.4.1}$$

For $338.72\,K \le T_a \le 533.16\,K$

$$\lambda = \frac{\sqrt{7.329 * 10^{12} - 1.6 T_a^2}}{4.19 * 10^3} \tag{B.4.2}$$

B.5 Correlation for water vapor diffusivity in air

For pressure up to about 10 atm, the diffusion coefficient for a binary mixture may be estimated from the Fuller, Schettler, and Giddings relation (Perry, 1984). The relation for the water vapor-air system is in the following form.

$$D_{AB} = \frac{10^{-7} T^{1.75} \sqrt{(M_a + M_w) / M_a M_w}}{P[(\Sigma \upsilon)_a^{1/3} + (\Sigma \upsilon)_w^{1/3}} \tag{B.5}$$

where P is in atmospheres. M_a and M_w are the molecular weights of air and water, respectively. The atomic diffusion volumes, $\sum \upsilon$, of air and water are 20.1 and 12.7, respectively. Generally, this equation is reported to predict D_{AB} within 5 to 10 percent.

B.6 Correlation for drag coefficient of a sphere

The drag coefficient, C_D, is dependent on Reynolds number. The correlation for drag coefficient used in the present model ranges from Stoke's law, through Allen's law to Newton's law, as shown in equation (B.6).

$$
\begin{aligned}
C_D &= \frac{24}{Re} \quad Re \leq 5 \quad \text{(Stoke's law)} \\
&= \frac{10}{\sqrt{Re}} \quad 5 < Re < 500 \quad \text{(Allen's law)} \\
&= 0.44 \quad Re \geq 500 \quad \text{(Newton's law)}
\end{aligned}
\tag{B.6}
$$

The correlations for specific heat, thermal conductivity and viscosity of air are obtained by curve-fitting published data over the range of conditions generally used in drying. These data are published in Perry's chemical engineering handbook (Perry, 1984). A comparison between the values predicted by these empirical correlations and those given in the handbook have also been carried out.

B.7 Correlation for specific heat of air

$$C_a = 8.91*10^{-8}T_a^2 - 4.13*10^{-5}T_a + 0.24454 \qquad (B.7)$$

Figure B.7 reveals the comparison between the specific heat of air as predicted by the above correlation and that obtained from the handbook.

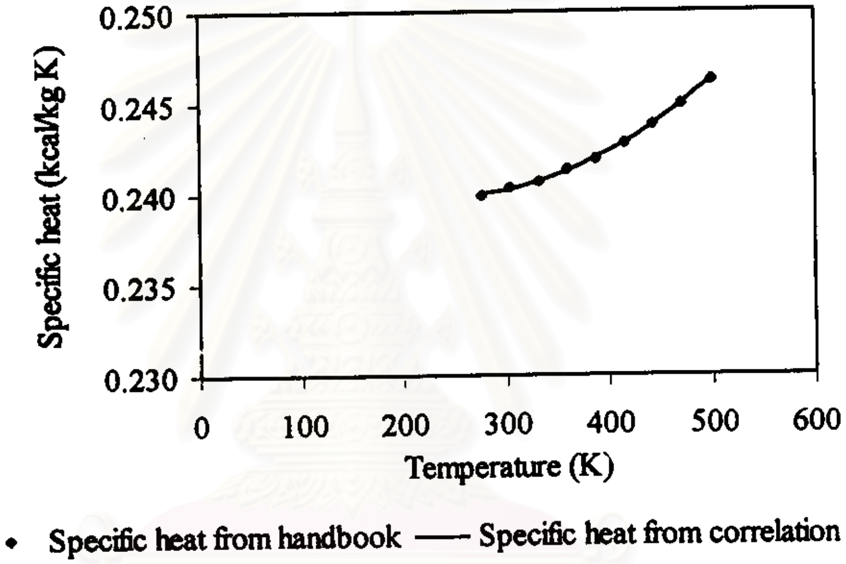

Figure B.7 Comparison between the predicted specific heat of air and that obtained from the handbook

B.8 Correlation for thermal conductivity of air

$$k_a = 1.72*10^{-8}T_a + 1.19*10^{-6} \qquad (B.8)$$

Figure B.8 reveals the comparison between the thermal conductivity of air as predicted by the above correlation and that obtained from the handbook.

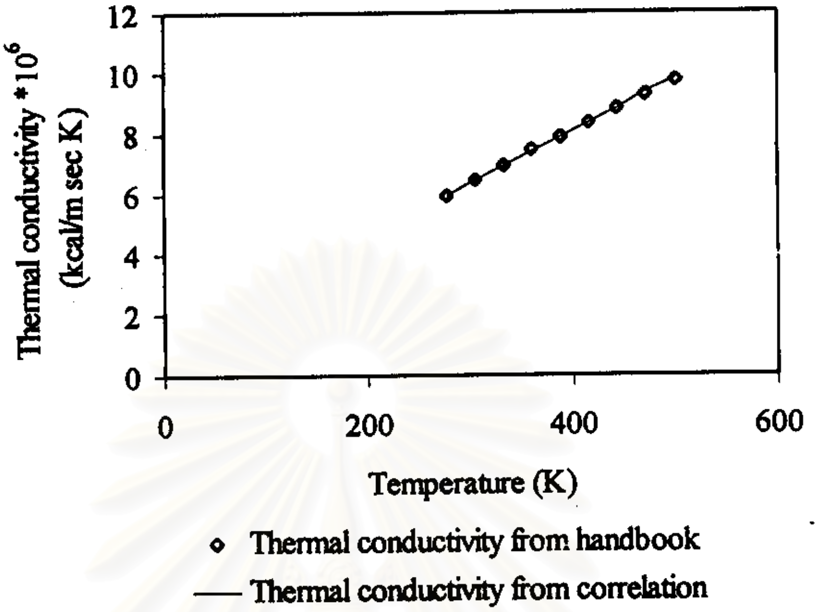

Figure B.8 Comparison between the predicted thermal conductivity of air and that obtained from the handbook

B.9 Correlation for viscosity of air

$$\mu_a = 4.489 * 10^{-5} \exp[269.25/T_a] \qquad (B.9)$$

Figure B.9 reveals the comparison between the viscosity of air predicted by the above correlation and that obtained from the handbook.

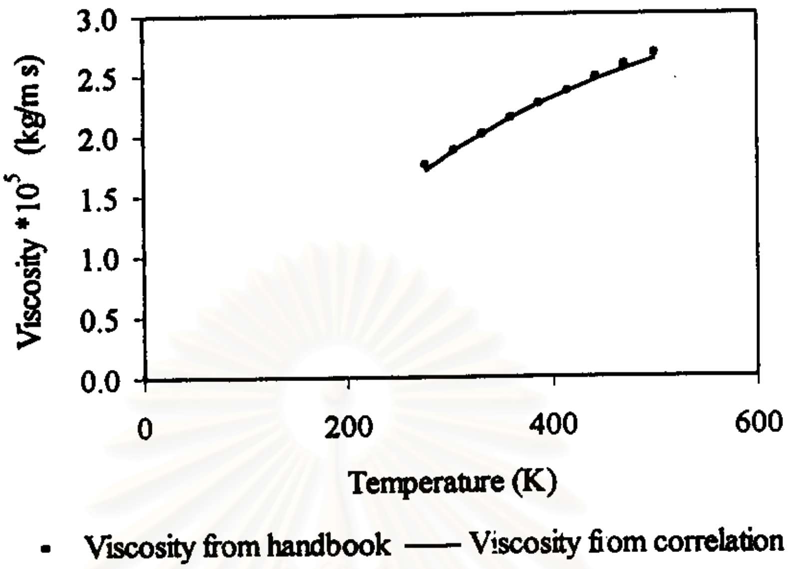

Figure B.9 Comparison between the predicted viscosity of air and that obtained from the handbook

APPENDIX C

EXAMPLE OF THE OVERALL MASS AND ENERGY BALANCES

The operating data on pneumatic conveying drying of ilmenite in Table 6.1 are used in the present example of calculating the overall mass and energy balances. From the overall balance of water, equation (A.1), the outlet humidity of air can be calculated from the following equation.

$$H_{out} \quad = \quad H_{in} + \frac{G_s}{G_a}(W_{in} - W_{out})$$

Thus, the outlet humidity of air is

$$H_{out} \quad = \quad 0.015 + \frac{4000}{3620}(0.064 - 0.001) \quad = \quad 0.0846 \qquad \text{kg/kg dry air.}$$

The specific heat of air can be estimated from equation (B.6). Similarly, the specific enthalpy per unit mass of air and flour at the inlet and outlet conditions can be calculated by using equations (A.3) and (A.4), respectively.

Inlet condition (T_a = 573 K, H = 0.015 kg/kg dry air):

$$C_a \quad = \quad 8.91 * 10^{-8}(573)^2 - 4.13 * 10^{-5}(573) + 0.24454 \quad = \quad 0.25 \qquad \text{kcal/kg K}$$

$$i_a \quad = \quad (0.25 + 0.4512 * 0.015)(573 - 273) + (597.26 * 0.015) \quad = \quad 86 \qquad \text{kcal/kg}$$

$$i_s \quad = \quad (0.157 + 1.0024 * 0.064)(298 - 273) \quad = \quad 5.53 \qquad \text{kcal/kg}$$

Outlet condition (T_a = 353 K, H = 0.0846 kg/kg dry air):

$$C_a \quad = \quad 8.91 * 10^{-8}(353)^2 - 4.13 * 10^{-5}(353) + 0.24454 \quad = \quad 0.241 \qquad \text{kcal/kg K}$$

$$i_a \quad = \quad (0.241 + 0.4512 * 0.0846)(353 - 273) + (597.26 * 0.0846) \quad = \quad 72.86 \text{ kcal/kg}$$

$$i_s = (0.157 + 1.0024 * 0.001)(353 - 273) = 12.64 \qquad \text{kcal/kg}$$

The rate of thermal energy input to the dryer, which equals the left side of equation (A.2), is as follows:

$$G_a i_a + G_s i_s = (3620 * 86) + (4000 * 5.53)$$

$$= 3.33 * 10^5 \qquad \text{kcal/hr}$$

The rate of thermal energy output from the dryer, which equals the right side of equation (A.2), is as follows:

$$G_a i_a + G_s i_s = (3620 * 72.86) + (4000 * 12.64)$$

$$= 3.14 * 10^5 \qquad \text{kcal/hr}$$

Thus the relative error of the overall energy balance is

$$\%\ \text{error} = \frac{3.14 * 10^5 - 3.33 * 10^5}{3.33 * 10^5} * 100$$

$$= -5.70 \quad \%$$

APPENDIX D

EXAMPLE OF THE POSITIVE ROOTS

The first ten positive roots of equation (4.20) are revealed in Tables D.1 to D.5. The parameters B and M are varied in the ranges of 1000-100000 and 0.1-5, respectively.

Table D.1 Positive roots of equation (4.2), ξ_n, when M = 0.1 and $1 \leq n \leq 10$

B	ξ_1	ξ_2	ξ_3	ξ_4	ξ_5	ξ_6	ξ_7	ξ_8	ξ_9	ξ_{10}
1000	4.1319	7.1448	10.1518	13.1808	16.2373	19.3022	22.3857	25.4799	28.5820	31.6902
5000	4.1323	7.1463	10.1554	13.1870	16.2412	19.3137	22.4001	25.4970	28.6019	31.7128
10000	4.1323	7.1465	10.1558	13.1877	16.2423	19.3150	22.4020	25.4991	28.6044	31.7157
50000	4.1323	7.1467	10.1562	13.1883	16.2430	19.3162	22.4033	25.5008	28.6063	31.7180
100000	4.1323	7.1467	10.1562	13.1883	16.2432	19.3164	22.4035	25.5010	28.6065	31.7182

Table D.2 Positive roots of equation (4.2), ξ_n, when M = 0.5 and $1 \leq n \leq 10$

B	ξ_1	ξ_2	ξ_3	ξ_4	ξ_5	ξ_6	ξ_7	ξ_8	ξ_9	ξ_{10}
1000	3.5888	6.5611	9.6168	12.7084	15.8174	18.9356	22.0595	25.1867	28.3166	31.4480
5000	3.5906	6.5653	9.6237	12.7181	15.8296	18.9505	22.0768	25.2067	28.3390	31.4730
10000	3.5908	6.5659	9.6245	12.7193	15.8312	18.9522	22.0789	25.2092	28.3417	31.4760
50000	3.5908	6.5663	9.6253	12.7202	15.8323	18.9538	22.0806	25.2111	28.3440	31.4785
100000	3.5910	6.5663	9.6254	12.7202	15.8325	18.9540	22.0810	25.2115	28.3444	31.4789

Table D.3 Positive roots of equation (4.2), ξ_n, when M = 1 and $1 \le n \le 10$

B	ξ_1	ξ_2	ξ_3	ξ_4	ξ_5	ξ_6	ξ_7	ξ_8	ξ_9	ξ_{10}
1000	3.4030	6.4279	9.5190	12.6324	15.7554	18.8836	22.0144	25.1474	28.2813	31.4164
5000	3.4052	6.4327	9.5263	12.6424	15.7679	18.8985	22.0321	25.1674	28.3040	31.4413
10000	3.4053	6.4332	9.5273	12.6435	15.7694	18.9005	22.0342	25.1698	28.3068	31.4446
50000	3.4055	6.4336	9.5280	12.6445	15.7708	18.9018	22.0359	25.1720	28.3089	31.4471
100000	3.4055	6.4338	9.5280	12.6447	15.7710	18.9020	22.0361	25.1721	28.3093	31.4473

Table D.4 Positive roots of equation (4.2), ξ_n, when M = 5 and $1 \le n \le 10$

B	ξ_1	ξ_2	ξ_3	ξ_4	ξ_5	ξ_6	ξ_7	ξ_8	ξ_9	ξ_{10}
1000	3.1998	6.3084	9.4366	12.5697	15.7050	18.8414	21.9782	25.1156	28.2531	31.3909
5000	3.2021	6.3134	9.4441	12.5797	15.7175	18.8564	21.9958	25.1357	28.2758	31.4160
10000	3.2025	6.3142	9.4450	12.5810	15.7192	18.8583	21.9980	25.1382	28.2786	31.4191
50000	3.2027	6.3145	9.4458	12.5820	15.7203	18.8598	21.9999	25.1401	28.2808	31.4216
100000	3.2027	6.3145	9.4458	12.5822	15.7205	18.8600	22.0001	25.1405	28.2811	31.4220

Table D.5 Positive roots of equation (4.2), ξ_n, when M = 10 and $1 \le n \le 10$

B	ξ_1	ξ_2	ξ_3	ξ_4	ξ_5	ξ_6	ξ_7	ξ_8	ξ_9	ξ_{10}
1000	3.1697	6.2927	9.4260	12.5617	15.6987	18.8360	21.9738	25.1116	28.2497	31.3876
5000	3.1722	6.2979	9.4335	12.5718	15.7111	18.8512	21.9912	25.1317	28.2721	31.4128
10000	3.1726	6.2984	9.4345	12.5730	15.7127	18.8529	21.9935	25.1342	28.2750	31.4160
50000	3.1728	6.2988	9.4352	12.5741	15.7140	18.8544	21.9953	25.1363	28.2773	31.4185
100000	3.1728	6.2990	9.4352	12.5741	15.7142	18.8546	21.9955	25.1365	28.2775	31.4187

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