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APPENDICES

APPENDIX A

NOMENCLATURE

a = Coefficient in equation 3.6

Ar = Archimedes number = $g.d^3 (\rho_s - \rho_f) / \mu_f^2 . \rho_f$

b = Coefficient in equation 3.6

C_A = Concentration of diffusing substance A at a point in a solid, gm/cm^3

$\overline{C}_A$ = Average concentration of A in a solid, gm/cm^3

C_{Ao} = Intial, uniform concentration, gm/cm^3

C_{As} = Concentration of A at the bounding surface, gm/cm^3

C_c = Heat capacity of dry corn, cal/gm. °C

Cp = Heat capacity of dry air, cal/gm.°C

Cw = Heat capacity of water, cal/gm.°C

d = Particle diameter, cm

D, Dc = Column diameter, cm

Di = Diameter of gas-inlet orifice, cm

Dv = Particle diameter measured as the diameter of an equi-volumed sphere, cm

$\mathcal{D}$ = Diffusion coefficient, cm^2/sec

$\mathcal{D}_o$ = Diffusion constant in Arrhenius equation, cm^2/sec

E = Activation energy, cal/mole

f = Function

$f', f'', \ldots,$ = First, second, ... derivatives of f

g = Acceleration of gravity, cm/sec^2

G = Mass dry air velocity, gm/cm^2.sec

h_{fg} = Latent heat of vapourization, cal/gm

$\bar{h}_d$ = Average net heat of desorption, cal/gm

H = bed depth, cm

H_{sm} = Maximum spoutable bed depth, cm

K = Coefficient in equation 3.6

$\bar{m}$ = Average moisture content of a drying particle, dry basis, gm/gm

$\bar{\bar{m}}$ = Average moisture content of a statistical population of drying particles, dry basis, gm/gm

m_o = Initial, uniform moisture content, dry basis, gm/gm

m_s = Moisture content at the bounding surface, dry basis, gm/gm

$\bar{\bar{M}}$ = free moisture ratio = $\dfrac{\bar{\bar{m}} - m_s}{m_o - m_s}$

n = An integer

P = Pressure at any point, gm/cm^2

ΔP = Pressure drop across bed, gm/cm^2

ΔP_{max} = Peak pressure drop, prior to spouting, gm/cm^2

r = Special coordinate, cm

r_s = Radius of a particle measured as that of an equi-volumed sphere, cm

$\mathcal{R}$ = Gas constant = 1.9872 cal/mol. ^oK

Re_{ms} = Reynolds number at minimum spouting = $\dfrac{u_i \cdot d \cdot \rho_f}{\mu_f}$

s = Special coordinate, cm

S = Exposed surface area of a solid, cm^2

t = Temperature, ^oC

t_e = Equilibrium temperature of air and particles leaving the heater, ^oC

t_i = Temperature of air entering the heater, ^oC

t_o = Initial temperature of particles; temperature of particles entering the heater, ^oC

T = Absolute temperature, ^oK

U_{mf} = Minimum fluidizing velocity-superficial, cm/sec

U_{ms} = Minimum spouting velocity-superficial, cm/sec

V = Volume of a solid, cm^3

W = Feed rate, gm/ sec

Z = Verticle distance from gas-inlet orifice (bed level), cm

Θ = Time, sec

Θ_c = Particle cycle time in bed, sec

γ = Included cone angle

ρ = Density of moist solid, gm/cm^3

ρ_f = Fluid density, gm/cm^3

ρ_p = Bulk density of particulate solids, gm/cm^3

ρ_s = Particle density or moisture-free density, gm/cm^3

μ_f = Fluid viscosity, gm/cm.sec

α = Angle of internal friction of solids

ε_o = Fractional voids in loosely packed bed

ψ = Surface sphericity

APPENDIX B

CALCULATION

1. Screen Analysis

Opening (cm.)	$\bar{D}_n$ Mean diameter (cm.)	$\Delta \phi_n$ Wt. fraction	$\Delta \phi_n / \bar{D}_n$
0.952/0.792	0.872	0.0704	0.081
0.792/0.635	0.714	0.3401	0.476
0.635/0.475	0.555	0.5895	1.062

$$\sum_{n=1}^{n_T} \Delta \phi_n / \bar{D}_n = 1.619$$

$$\bar{D}_v = \frac{1}{\sum^{n_T} \Delta \phi_n / \bar{D}_n} = \frac{1}{1.619} = 0.6187 \text{ cm}$$

2. Minimum Spouting Velocity

2.1 Experimental

The air flow rates measured with the rotameter were 8.5 - 9.5 cm. readings. From the calibration curve in Appendix D, the readings are equivalent to 1270 - 1370 lit./min. The column diameter was 4 inches; so the cross-sectional area was $\frac{\pi}{4} \times \frac{4^2}{144}$ or 0.0873 ft^2.

Therefore, the experimental spouting velocity at a flow rate of 1270 lit/min was

$$1270 \; \frac{\text{lit}}{\text{min}} \times \frac{1}{60} \frac{\text{min}}{\text{sec}} \times 0.03532 \; \frac{\text{ft}^3}{\text{lit}} \times \frac{1}{0.0873 \; \text{ft}^2}$$

$$= 8.56 \text{ ft/sec.}$$

Similarly, the spouting velocity at a flow rate of 1370 lit/min was 9.23 ft/sec.

2.2 Theoretical

From equation (2.1.5),

$$U_{ms} = \left(\frac{d}{D}\right)\left(\frac{Di}{D}\right)^{1/3} \sqrt{\frac{2.\, g.\, H\, (\rho_s - \rho_f)}{\rho_f}}$$

Since

$$d = 0.6187 \text{ cm or } 0.6187/30 \text{ ft}$$

$$D = 4 \text{ in. or } 4/12 \text{ ft}$$

$$Di = 0.5 \text{ in. or } 0.5/12 \text{ ft}$$

$$g = 32 \text{ ft/sec}^2$$

$$H = 20 \text{ cm or } 2/3 \text{ ft}$$

$$\rho_s = 78.7 \text{ lb/ft}^3$$

$$\rho_f = 0.0694 \text{ lb/ft}^3 \text{ at 1 atm, } 45^\circ\text{C}$$

$$U_{ms} = \left(\frac{0.6187/30}{4/12}\right)\left(\frac{0.5}{4}\right)^{1/3} \sqrt{\frac{2 \times 32 \times 20 \times 78.7}{0.0694 \times 30}}$$

$$= 6.73 \text{ ft/sec}$$

Therefore, the theoretical, minimum spouting velocity of the experiment was 6.73 ft/sec.

3. Drying Equation

The experimental data were first plotted to show $k = (m_o - \bar{\bar{m}})/\sqrt{\theta}$ as a function of $\sqrt{\theta}$ at different operating temperatures (Fig. B-1, B-2, and B-3) according to equation (4.51). The result was found to be linear in the neighbourhood of $\theta = 0$. The slope -b and the intercept k_o were therefore calculated statistically (Table B-4)

The dynamic surface moisture content, given by equation (4.54) was next calculated at each temperature. Fig B-4 shows that k_o is a linear function of initial moisture contents ranging from 0.20 to 0.26 gm/gm. Statistical calculation of the intercept $k_o = 0$ gave surface moisture contents of 0.1495 - 0.1535gm/gm(Table B-5). The slope -b was also found to be a linear function of the initial moisture contents (Fig. B-5) and statistical calculation of the intercepts at b=0 gave nearly equal surface moisture contents averaging 0.1640gm/gm(Table B-5). The apparent disagreement here with the values obtained from k_o is negligible according to practical considerations.

To evaluate the diffusion coefficient, the mean value of $k_o/(m_o - m_s)$ was first calculated for each temperature and then diffusion coefficients were calculated from equation (4.54) (Table B-6). The relation between the diffusion coefficient and the absolute temperature (Fig B-6) follows the Arrhenius-type equation:

$$\mathcal{D} = \mathcal{D}_o \exp(-E/\mathcal{R}T)$$

where $\mathcal{D}_o = 4080\ cm^2/sec$ and $E = 13.93$ k.cal/mole

The diffusion constant, f" (0), in equation (4.54) was then evaluated. The calculation followed equation (4.55). The mean value of $\frac{f''(0)}{2}$ = 0.236 calculated at each temperarure was obtained in Table B-7. The diffusion equation for spouted-bed drying of corn kernel in the neighbourhood of $\theta = 0$ is therefore

$$\bar{\bar{M}} = 1 - \frac{2}{\sqrt{\pi}} X + 0.236 X^2$$

where $X = \frac{S}{V} \sqrt{\mathcal{D} \theta}$

The correlation is used in designing the performance of a spouted-bed dryers for shelled corn.

Table B-1

Calculation of $k^{(*)}$ at 40°C

$\sqrt{\theta}$ $sec^{\frac{1}{2}}$	m_o = 0.2605 gm/gm d.b.		m_o = 0.2469 gm/gm d.b.		m_o = 0.2191 gm/gm d.b.	
	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)
18.9736	0.2343	13.81	0.2246	11.75	0.2032	8.38
24.4949	0.2269	13.72	0.2180	11.80	0.2001	7.76
30.0000	0.2193	13.73	0.2130	11.30	0.1952	7.97
34.6411	0.2147	13.22	0.2082	11.17	0.1918	7.88
38.7298	0.2108	12.83	0.2051	10.79	0.1911	7.23
42.4264	0.2056	12.94	0.2007	10.89	0.1860	7.80
60.0000	0.1863	12.37	0.1842	10.45	0.1755	7.27

$^{*}k = (m_o - \bar{\bar{m}}) / \sqrt{\theta}$

Table B-2

Calculation of k at 45°C

$\sqrt{\theta}$ ($sec^{\frac{1}{2}}$)	m_o = 0.2462gm/gm d.b.		m_o = 0.2339gm/gm d.b.		m_o = 0.2256gm/gm d.b.		m_o = 0.2038gm/gm d.b.	
	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)
18.9736	0.2199	13.86	0.2115	11.81	0.2060	10.33	0.1904	7.06
24.4949	0.2131	13.51	0.2065	11.19	0.2011	10.00	0.1856	7.43
30.0000	0.2071	13.03	0.2004	11.17	0.1958	9.93	0.1824	7.13
34.6411	0.2008	13.11	0.1952	11.17	0.1921	9.67	0.1795	7.01
38.7298	0.1963	12.88	0.1920	10.82	0.1897	9.27	0.1770	6.92
42.4264	0.1915	12.89	0.1885	10.70	0.1868	9.15	0.1753	6.72
60.0000	0.1753	11.82	0.1749	9.83	0.1728	8.80	0.1644	6.57

Table B-3

Calculation of k at 50°C

$\sqrt{\theta}$ ($sec^{\frac{1}{2}}$)	m_o = 0.2412 gm/gm d.b.		m_o = 0.2208 gm/gm d.b.		m_o = 0.2070 gm/gm d.b.		m_o = 0.2016 gm/gm d.b.	
	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)	$\bar{\bar{m}}$ (gm/gm d.b.)	$10^4 k$ ($sec^{-\frac{1}{2}}$)
18.9736	0.2118	15.49	0.1982	11.91	0.1876	10.22	0.1877	7.33
24.4949	0.2048	14.86	0.1916	11.92	0.1822	10.12	0.1829	7.63
30.0000	0.1967	14.83	0.1864	11.47	0.1767	10.10	0.1798	7.27
34.6411	0.1919	14.23	0.1817	11.29	0.1737	9.61	0.1762	7.33
38.7298	0.1870	13.97	0.1785	10.92	0.1698	9.61	0.1732	7.33
42.4264	0.1838	13.53	0.1736	11.12	0.1662	9.62	0.1712	7.16
60.0000	0.1663	12.48	0.1606	10.03	0.1540	8.83	0.1627	6.48

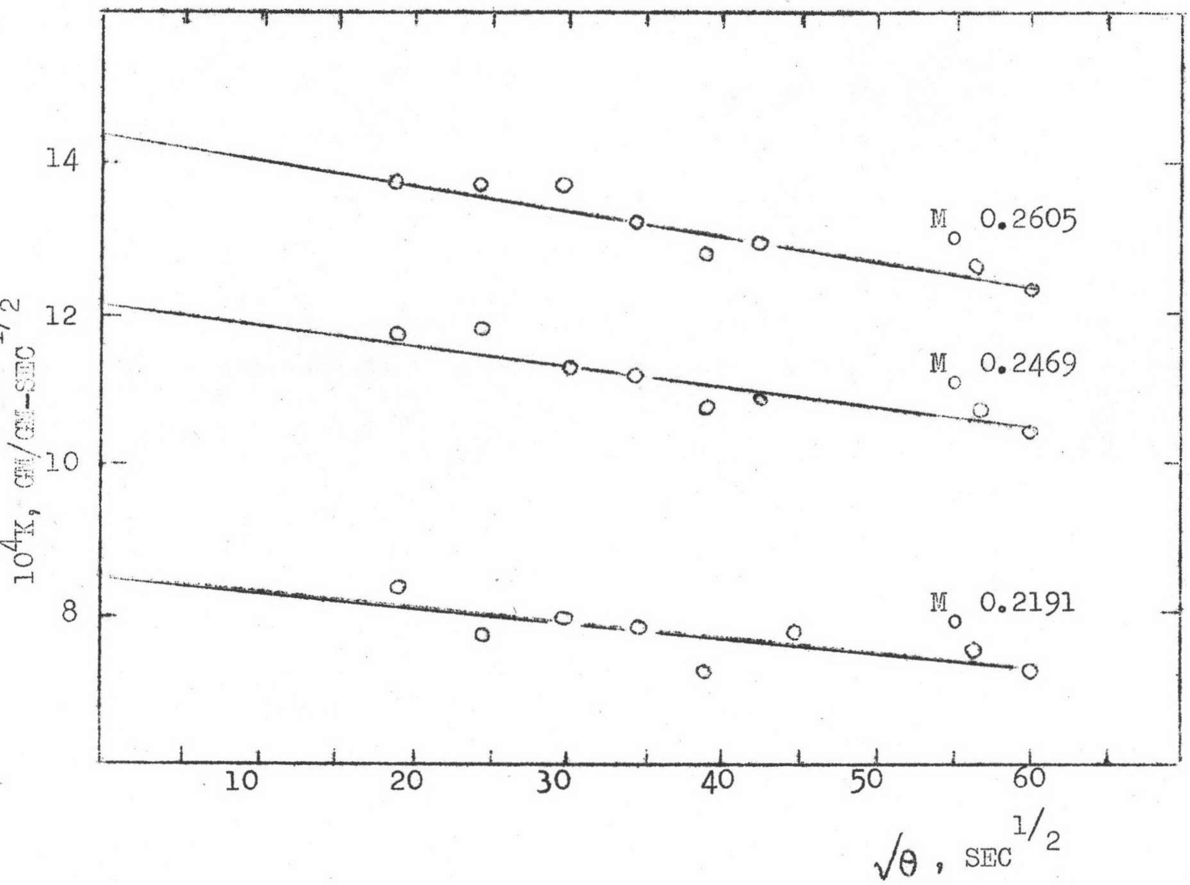


Fig. B-1 $k = (m_o - \bar{\bar{m}}) / \sqrt{\theta}$ as a function of $\sqrt{\theta}$ and m_o for the spouted-bed drying of corn at 40°C.

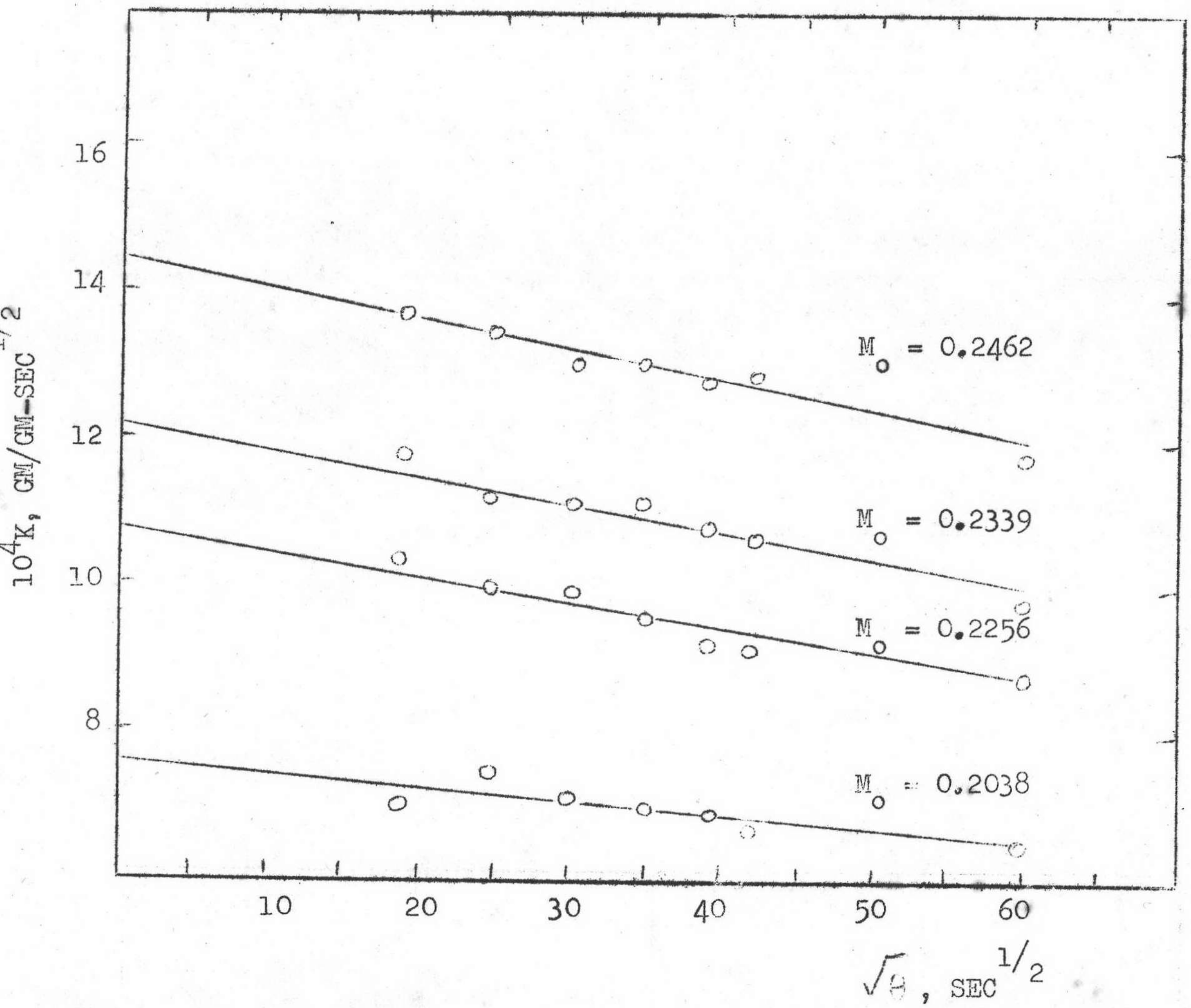


Fig. B-2 $k = (m_o - \bar{\bar{m}}) / \sqrt{\theta}$ as a function of $\sqrt{\theta}$ and m_o for the spouted-bed drying of corn at 45°C.

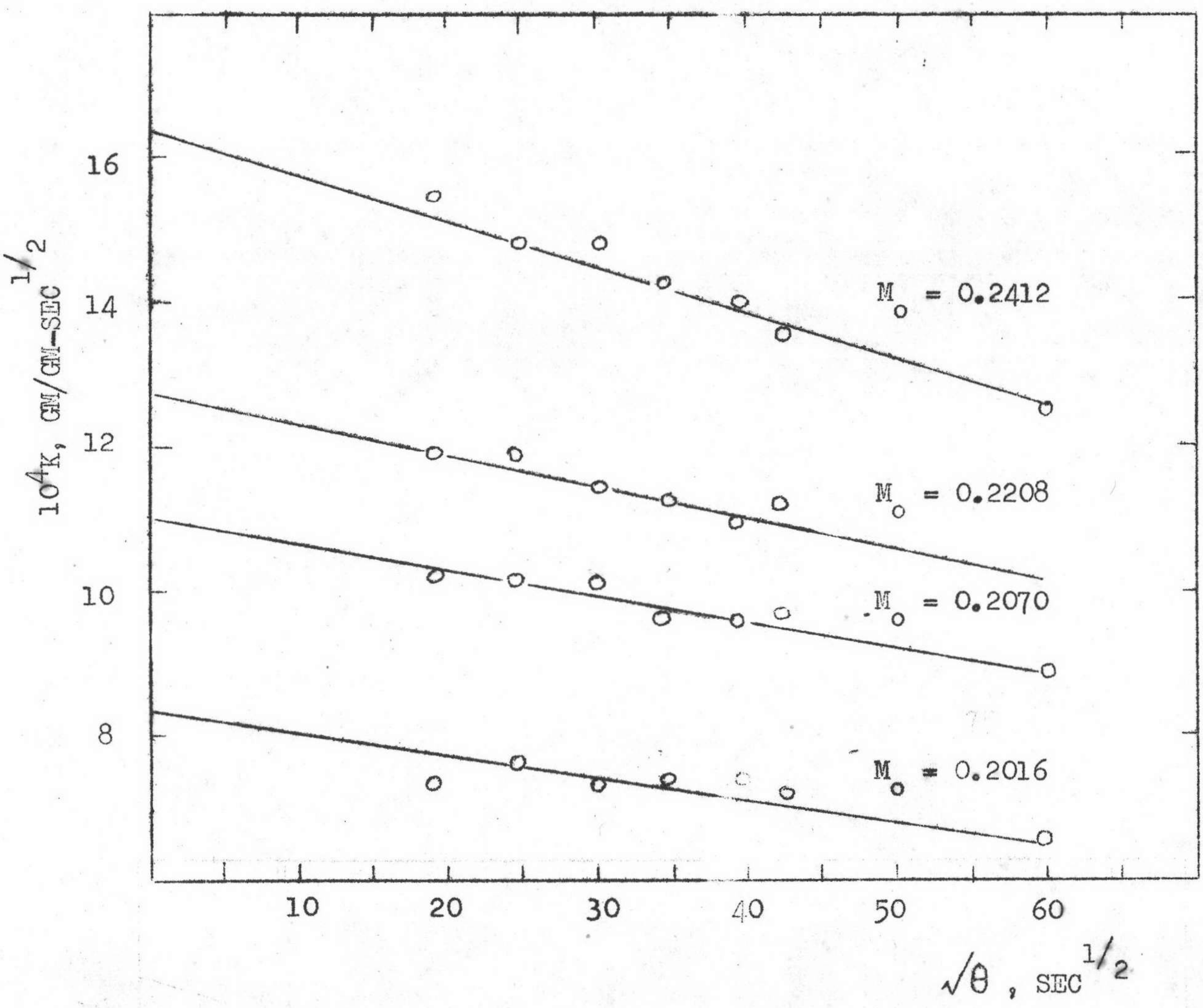


Fig B-3 $k = (m_o - \bar{\bar{m}}) / \sqrt{\theta}$ as a function of $\sqrt{\theta}$ and m_o for the spouted-bed drying of corn at 50°C.

Table B-4

Values of $k_o^{(*)}$ and $b^{(**)}$ Obtained from Figures B1 - B3

t = 40°C			t = 45°C			t = 50°C		
m_o (gm/gm)	$10^4 k_o$ ($sec^{-\frac{1}{2}}$)	$10^6 b$ (sec^{-1})	m_o (gm/gm)	$10^4 k_o$ ($sec^{-\frac{1}{2}}$)	$10^6 b$ (sec^{-1})	m_o (gm/gm)	$10^4 k_o$ ($sec^{-\frac{1}{2}}$)	$10^6 b$ (sec^{-1})
0.2191	8.52	2.06	0.2038	7.64	1.84	0.2016	8.36	3.14
0.2469	12.12	2.80	0.2256	10.79	3.31	0.2070	11.05	3.66
0.2605	14.34	3.26	0.2339	12.26	3.68	0.2208	12.73	4.27
-	-	-	0.2462	14.50	4.11	0.2412	16.39	6.25

* k_o = intercept

** b = slope

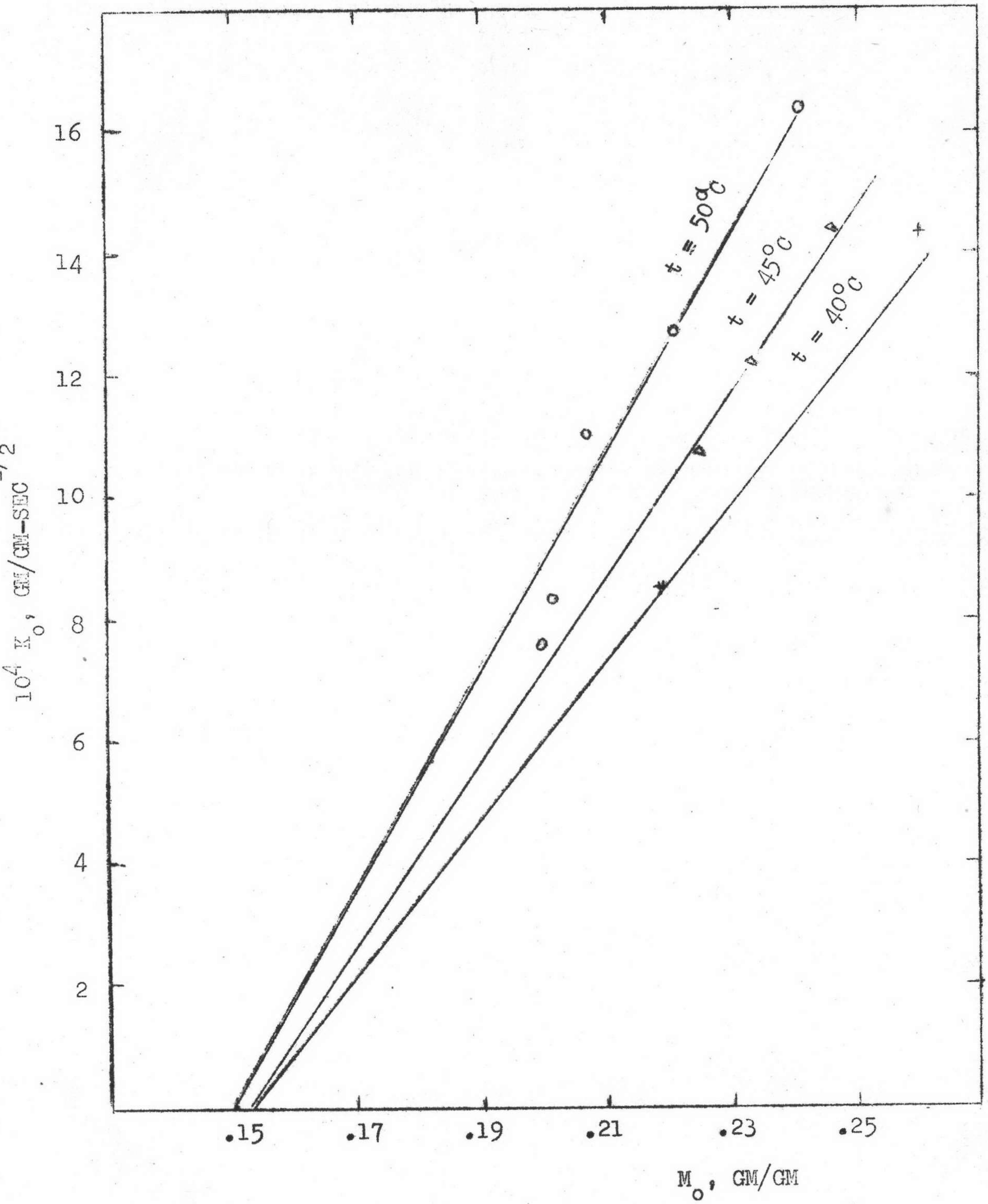


Fig. B-4 The intercept k_o as a function of initial moisture content and temperature.

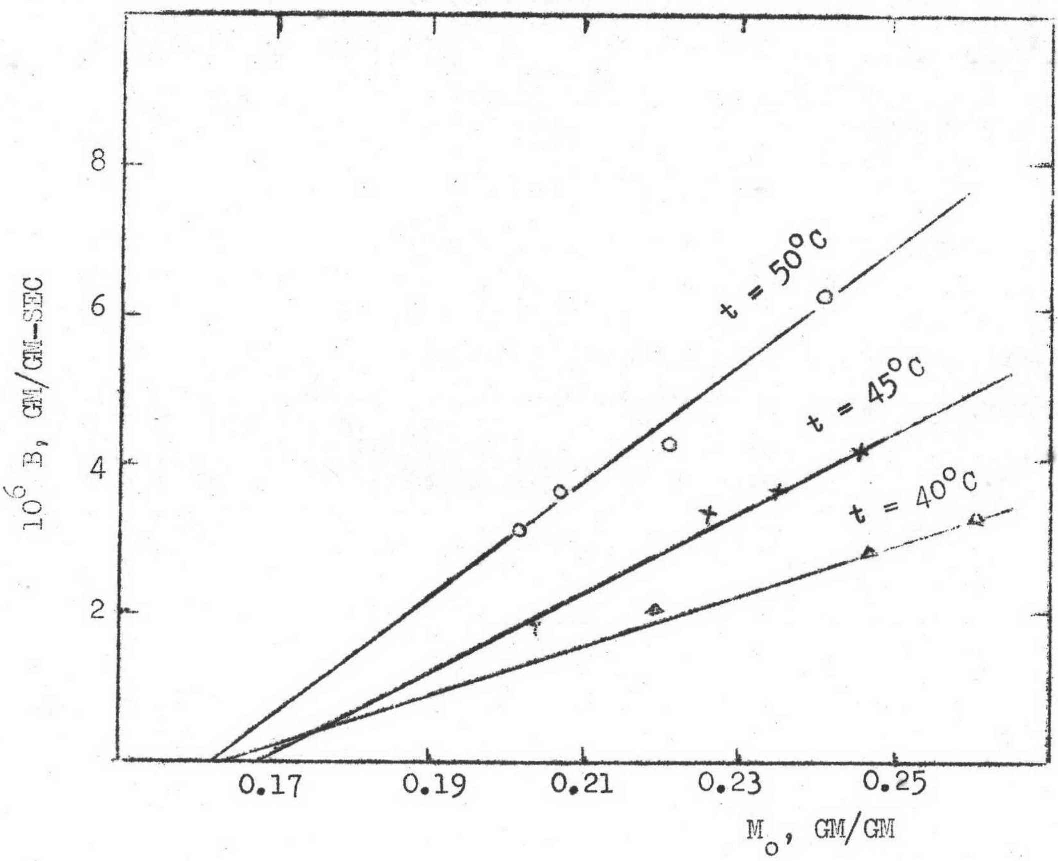


Fig. B-5 The slope b as a function of initial moisture content and temperature.

Table B - 5

Dynamic Surface Moisture Contents in the Spouted-Bed Drying of Corn

t (°C)	m_s (gm/gm)	
	$k_o = 0$	$b = 0$
40	0.1535	0.1630
45	0.1525	0.1675
50	0.1495	0.1615
	0.1518	0.1640

Table B-6

Diffusion Coefficients in the Spouted-Bed Drying of Corn

t ($^\circ$C)	$10^3/T$ ($^\circ K^{-1}$)	m_o (gm/gm)	$10^4 k_o$ ($sec^{-\frac{1}{2}}$)	$\frac{10^2 k_o}{m_o - m_s}$ (*) ($sec^{-\frac{1}{2}}$)	$10^7 \mathcal{D}$ (**) (cm^2/sec)
40	3.195	0.2191	8.52	1.266	
		0.2469	12.12	1.274	
		0.2605	14.34	1.319	
				1.286	7.726
45	3.145	0.2038	7.64	1.469	
		0.2256	10.79	1.462	
		0.2339	12.26	1.493	
		2462	14.50	1.536	
				1.490	10.36
50	3.096	0.2016	8.36	1.679	
		0.2070	11.05	2.002	
		0.2208	12.73	1.845	
		0.2412	16.39	1.833	
				1.839	15.80

* $m_s = 0.1518$ gm/gm

** $$\mathcal{D} = \left[\frac{\sqrt{\pi}}{2} \cdot \frac{k_o}{(m_o - m_s)} \cdot \frac{V}{S} \right]^2$$

$$\frac{V}{S} = \frac{r_s}{3} \cdot \psi$$

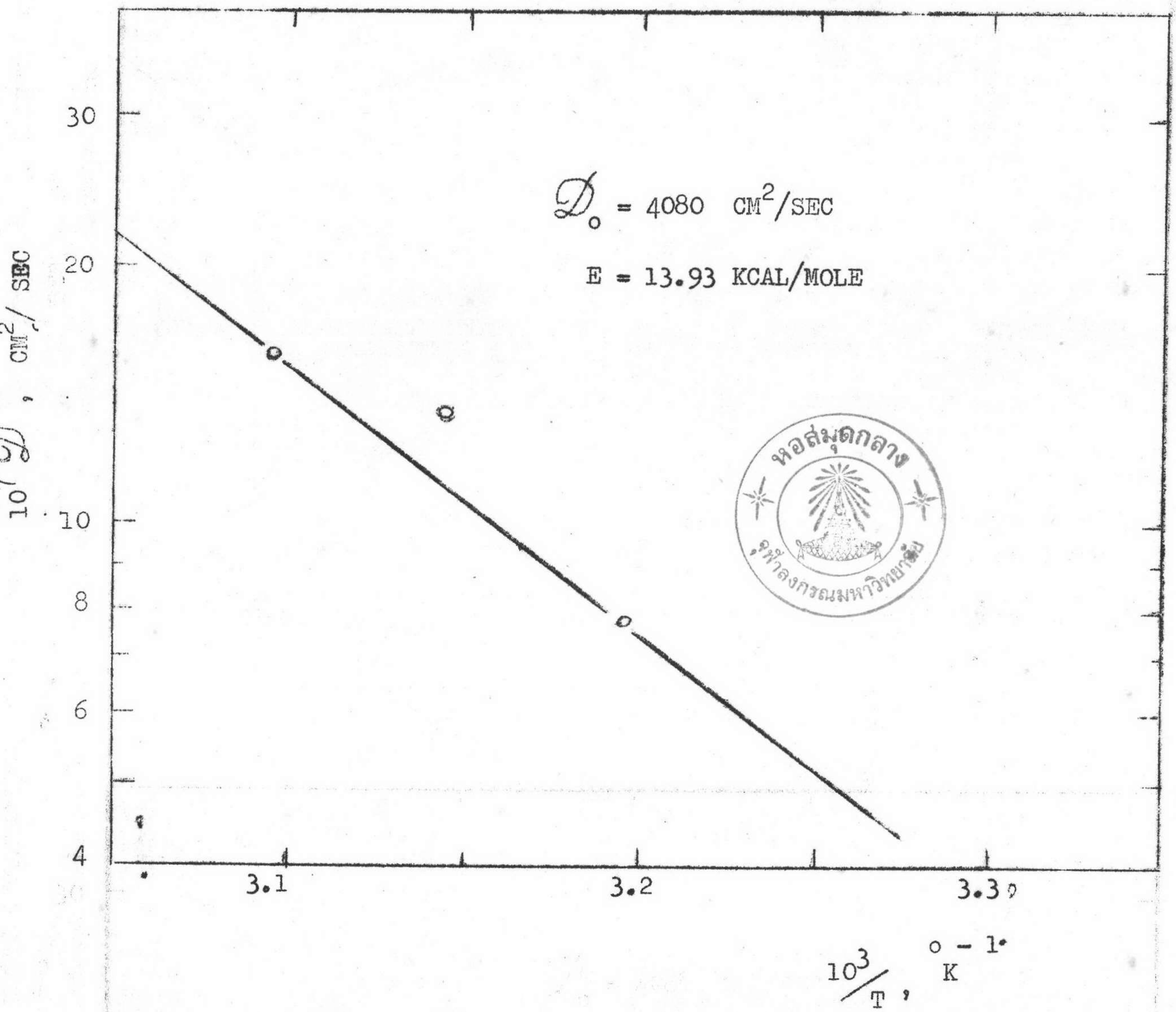


Fig. B – 6 The diffusion coefficient as a function of the reciprocal of the absolute temperature.

Table B-7

Diffusion Constants in the Spouted-Bed Drying

t (^{o}C)	$10^7 \mathcal{D}$ (cm^2/sec)	$\frac{10^5 b}{m_o - m_s}$ (sec^{-1})	$\frac{f''(0)}{2}$ (*)
40	7.726	3.001	0.231
45	10.36	4.215	0.242
50	15.80	6.528	0.236
			0.236

$$* \quad \frac{f''(0)}{2} = \frac{1}{\mathcal{D}} \cdot \frac{b}{(m_o - m_s)} \left(\frac{V}{S}\right)^2$$

APPENDIX C

THE PRACTICAL USE OF THE DRYING EQUATION

A problem illustrating the practical use of the correlation for drying corn in a spouted heater is given as follows:

A feasible heater for a practical drying consists of a column 60 cm in diameter with a 90° conical bottom and a 10 cm diameter air inlet. The heater is to be operated at a bed depth of 120 cm. Corn at 20°C with a moisture content of 0.230 gm/gm is to be dried to the maximum safe storage moisture of 0.163 gm/gm (14 per cent wet basis) and cooled to the maximum safe storage temperature of 10°C above the atmospheric temperature. At a moisture of 0.063 gm/gm, dry basis, the kernel diameter of corn is 0.6187 cm and the density 1.301 gm/cm^3. The atmospheric temperature, pressure, and relative humidity are respectively 19°C, 760 mm. Hg and 10 per cent. The minimum mass air velocity required to spout the heater bed, G, is 0.1 $gm/sec.\ cm^2$.

Problem

Find the maximum safe drying rate, the thermal energy requirements, and the inlet air temperature of the heater.

Solution

(I) Assume that the equilibrium moisture content is 0.063 gm/gm. The reduced free moisture content of the heater product is

$$\bar{\bar{M}} = \frac{\bar{\bar{m}} - m_s}{m_o - m_s} = \frac{0.163 - 0.063}{0.230 - 0.063}$$

$$= 0.599 \qquad (1)$$

Substituting $\bar{\bar{M}}$ into the drying equation, we get

$$0.599 = 1 - \frac{2}{\sqrt{\pi}} X + 0.236\, X^2 \qquad (2)$$

therefore,

$$X = 0.39 \qquad (3)$$

or

$$\frac{S}{V}\sqrt{\mathcal{D}\theta} = 0.39 \qquad (4)$$

Since the safe grain temperature of corn in the heater is $130^{\circ}F$ or $54^{\circ}C$,[17] the outlet grain temperature is assumed to be $54^{\circ}C$ or $327^{\circ}K$.

By the Arrhenius equation,

$$\mathcal{D} = \mathcal{D}_o \exp\left(\frac{-E}{\mathcal{R}T}\right)$$

$$= 4080 \exp\left(\frac{-13930}{1.982 \times 327}\right)$$

$$= 1.9 \times 10^{-6}\ cm^2/sec. \qquad (5)$$

The volume-to-surface ratio of the corn is (the surface sphericity being = 0.75)

$$\frac{V}{S} = \frac{Dv.\psi}{6} = \frac{0.6187 \times 0.75}{6}$$

$$= 0.07734\ cm \qquad (6)$$

By substituting eq's (5) and (6) into (4), we get

$$\theta = \frac{\left(X.\frac{V}{S}\right)^2}{\mathcal{D}} = \frac{(0.39)^2(0.07734)^2}{1.9 \times 10^{-6}}$$

$$= 479 \text{ sec or } 7.98 \text{ min.}$$

(II) The volume of the heater bed is

$$A\left(L - \frac{2}{3}\cdot\frac{D}{2}\right) = \pi \times 30^2\left(120 - \frac{2}{3} \times 30\right)$$

$$= 2.83 \times 10^5\ cm^3$$

The fraction void of a spouting bed is approximately 0.45[7].

The volume of corn in the heater is

$$2.83 \times 10^5 (1 - 0.45) = 1.56 \times 10^5 \ \text{cm}^3$$

The absolute density of the heater product is 1.301 gm/cm^3 at a moisture content of 0.063 gm/gm dry basis.

The hold-up in the heater is $1.56 \times 10^5 \times 1.301$

$$= 2.03 \times 10^5 \ \text{gm, wet basis}$$

$$\text{or} \quad \frac{2.03 \times 10^5}{1 + \bar{\bar{m}}} = \frac{2.03 \times 10^5}{1 + 0.163}$$

$$= 1.75 \times 10^5 \ \text{gm, dry basis.}$$

Therefore, the feed rate is $\frac{1.75 \times 10^5}{479} = 365$ gm/sec, dry basis.

(III) The thermal energy requirements of the heater are

(a) To heat the feed to heater outlet temperature

$$W(C_c + m_o C_w)(t_e - t_e) = 365 (0.17 + 0.230 \times 1.0)(54 - 19)$$

$$= 5110 \ \text{cal/sec.}$$

where W is the feed rate, gm/sec.

(b) To evaporate moisture in the heater, h_{fg} = 560 cal/gm,[12]

$$W(m_o - \bar{\bar{m}})(h_{fg}) = 365 (0.230 - 0.163) \times 560$$

$$= 13695 \ \text{cal/sec.}$$

Therefore, the total energy requirements = 5110 + 13695 = 18805 cal/sec.

(IV) Allowing 10% excess air, the total air flow to the heater is

$$GA = 1.1 \times 0.1 \times \quad \times 30^2$$

$$= 311 \text{ gm/sec.}$$

The heater inlet air temperature is

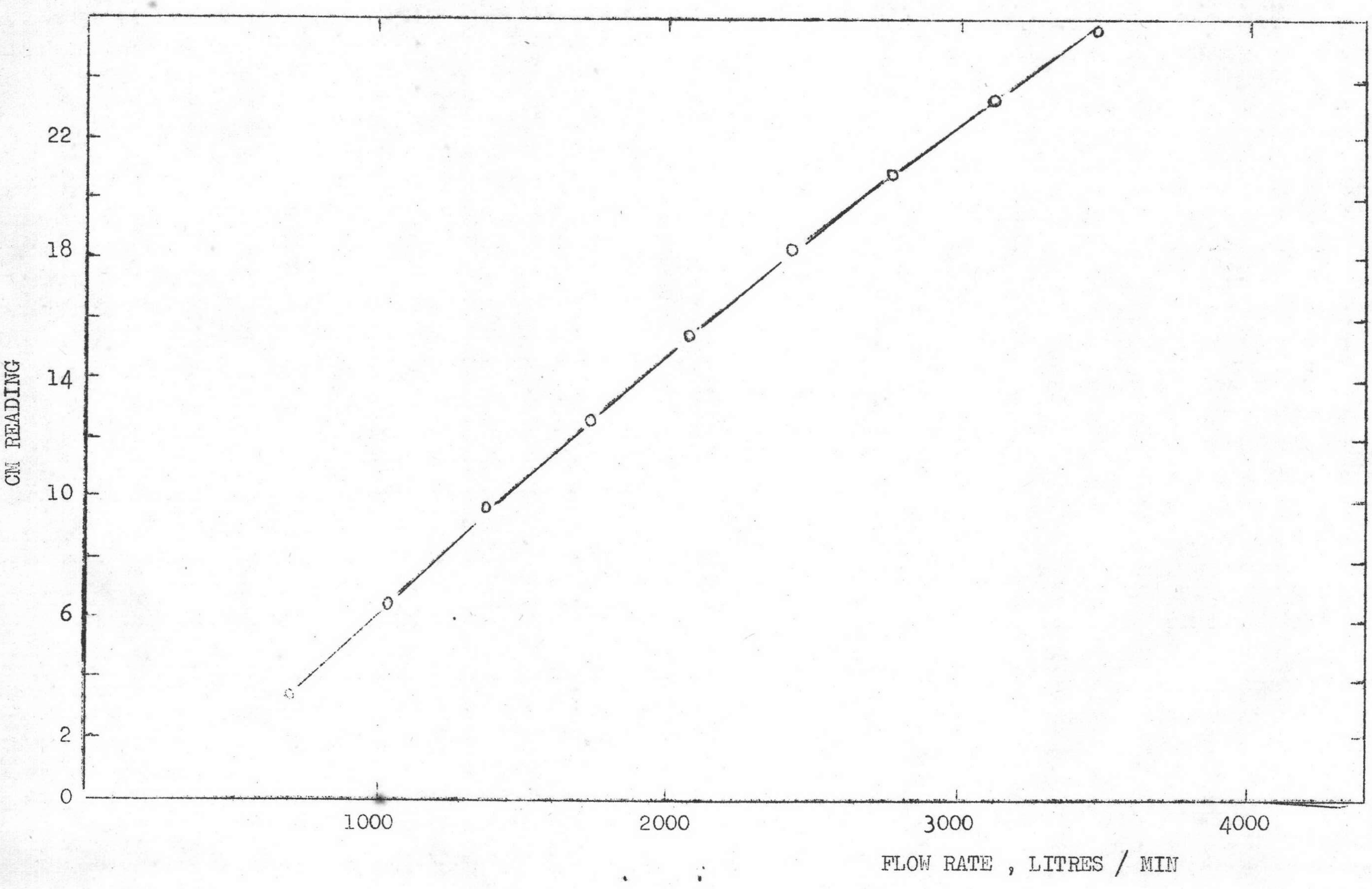
$$t_i = t_e + \frac{(\text{total heat from item III})}{G.\ A.\ Cp}$$

$$= \frac{54 + 18805}{311 \times 0.24} = 253$$

Therefore, the heater inlet air temperature is 253°C.

APPENDIX D

CALIBRATION CURVE OF ROTAMETER



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