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A P P E N D I C E S

APPENDIX A

A.1 Calculation for the Size of Retort

Basis   Operating Condition at 30°C and 1 atm.

Data :

From the experimental data (4.1, Chapter IV) :-

Density of oil shale, $\rho_s = 2.47$ gm/cm^3

$\phi = 0.604$

From Eq. 2.7 :-

$$\varepsilon_{mf} = 1 - \frac{100}{2.47 \times 116.59}$$

$$= 0.653$$

Operating data :-

Nitrogen used as fluidizing gas.

$\bar{d}_p = 0.0576$ cm.

V_{mb} = Volume occupied by solid particles.

$= 116.59$ cm^3.

F is the maximum flow rate of gas that the rotameter can be used.

$= 180{,}000$ cm^3/min.

From Perry et al (23) :-

Density of nitrogen, $\rho_g = 1.127 \times 10^{-3}$ gm/cm^3.

Viscosity of nitrogen, $\mu = 1.76 \times 10^{-4}$ poise

CALCULATION :

1. Minimum fluidizing velocity

From Eq. 2.8 :

$$1.75\ \rho_g U_{mf}^2 + \frac{180(1-\varepsilon_{mf}).\mu}{d} . U_{mf} - \varepsilon_{mf}^3 . d.(\rho_s - \rho_g)g = 0$$

and

$$d = \phi . \bar{d}_p = 0.604 \times 0.0576 = 0.0348 \text{ cm.}$$

by substituting in Eq. 2.8

$$\therefore\ 1.75(11.268 \times 10^{-4})U_{mf}^2 + \frac{(180)(0.347) \times 1.76 \times 10^{-4}.U_{mf}}{0.0348}$$

$$= 0.278 \times 0.0348 \times 2.47 \times 980$$

$$1.97 \times 10^{-3}U_{mf}^2 + 315.89 \times 10^{-3}\ U_{mf} = 23417.79 \times 10^{-3}$$

by trial and error, we obtained

$$U_{mf} = 55.2 \quad \text{cm/sec.}$$

Checking $Re_{mf} = \frac{\rho_g U_{mf} d}{\mu} = \frac{11.268 \times 55.2 \times 0.0348 \times 10^{-4}}{1.76 \times 10^{-4}}$

$$= 12.3 > 0.2$$

Therefore Eq. 2.8 can be applied.

From $U_{min} = 1.5\ U_{mf} = 1.5 \times 55.2$ .... Geldart (15)

$$= 82.8 \quad \text{cm/sec}$$

2. Maximum diameter and minimum height of bed

From $F = 1.8 \times 10^5 \quad \text{cm}^3/\text{min}$

$$\text{or} \quad = \quad 3000 \quad cm^3/sec$$

$$\text{and} \quad F = \frac{\pi}{4} D_{max}^2 \cdot U_{min}$$

$$\therefore D_{max} = \left[3000 \times \frac{4}{\pi} \times \frac{1}{82.8}\right]^{\frac{1}{2}}$$

$$= 6.79 \quad cm.$$

$$\text{From} \quad V_{mb} = \frac{\pi D_{max}^2}{4} \cdot L_{min}$$

$$\therefore L_{min} = \frac{116.59 \times 4}{\pi (6.79)^2}$$

$$= 3.22 \quad cm.$$

3. <u>Checking size of bed for slugging condition</u>

Slugging condition is likely to occur (15) if

$$\frac{U_o - U_{mf}}{0.35(gD)^{\frac{1}{2}}} > 0.2$$

let $U_o = U_{max}$ and $D = D_s$ = bed diameter for slugging condition, then : $U_{max} = 0.07 \, (g \, D_s)^{\frac{1}{2}} + U_{mf}$

Substituting $\dfrac{F}{\frac{\pi}{4} D_s^2}$ for U_{max} ,

$$\therefore F = \frac{\pi}{4} \cdot 0.07 \sqrt{g} \cdot D_s^{2.5} + \frac{\pi}{4} D_s^2 \, U_{mf}$$

$$\frac{1.8 \times 10^5}{60} = (1.7215 \, D_s^{\frac{1}{2}} + 43.37143) \, D_s^2$$

Solving D_s by trial and error ; then

$$D_s = 7.9 \text{ cm.}$$

$$\therefore \quad U_{max} = \frac{3000}{\frac{\pi}{4}(7.9)^2} = 61.18 \text{ cm/sec.}$$

$$\text{and} \quad L_s = \frac{V_{mb}}{\frac{\pi}{4}(D_s)^2} = \frac{116.59}{\frac{\pi}{4}(7.9)^2}$$

$$= 2.38 \text{ cm.}$$

From the calculation $U_{max} < U_{min}$

$$D_s > D_{max}$$

$$\frac{L_s}{D_s} < 1$$

It means that slugging condition never occurs under these conditions.

From calculated values of $D_{max} = 6.79$ cm., and $L_{min} = 3.22$ cm. and nitrogen velocity at 55.2 cm/sec., the diameter of fluidized bed retort should be 2 inches ID. (15) and the transport engaging height is 18 inches (14).

A.2 Determination of Power of Heater

Basis Retorting Temperature = 500 °C at 1 atm.

Data : Nitrogen used as fluidizing gas.

From previous calculation :

let $L_m = L_{mf} = 5.75$ cm.

and $U_o = U_{mf} = 55.2$ cm/sec.

$D = 5.08$ cm.

$A_w = 91.72$ cm^2.

From the experiment :

$\phi = 0.604$

Density of oil shale , $\rho_s = 2.47$ gm/cm^3

$\varepsilon_{mf} = 0.653$

$\bar{d}_p = 0.0576$ cm.

From Perry et al (23), at 500 °C, 1 atm. :-

Thermal Conductivity of N_2, $k_g = 1.30 \times 10^{-4}$ Cal/sec.cm. °C

Specific heat of N_2, $C_g = 0.27$ Cal/gm. °C

Density of N_2, $\rho_g = 4.37 \times 10^{-4}$ gm/cm^3.

Viscosity of N_2, $\mu = 0.36$ centipoise

From Eq. 2.2 :

Specific heat of oil shale, $C_s = 0.34$ Cal/gm. °C

CALCULATION :

$$\text{From } Re_p = \frac{\rho_g U_o d}{\mu} = \frac{4.47 \times 10^{-4} \times 55.2\ (0.0576 \times 0.604)}{3.6 \times 10^{-4}}$$

$$= 2.33$$

using Fig. 2.3 then

$$\left(\frac{h_w d}{k_g}\right) \cdot \frac{1}{(1 - \varepsilon_{mf})} \cdot \left(\frac{C_g\ \rho_g}{C_s\ \rho_s}\right) \cdot \frac{1}{1 + 7.5 \exp(-\ 0.44\frac{L_m}{D} \cdot \frac{C_g}{C_s})}$$

$$= 1.5 \times 10^{-3}$$

$$\therefore\ h_w = \frac{1.5 \times 10^{-3} \times 0.347 \times 1.014}{267.62 \times 1.045 \times 10^{-4}}$$

$$= 1.89 \times 10^{-2} \qquad \text{Cal/sec.cm}^2\,{}^\circ\text{C}$$

Assume ΔT = 50°C to be temperature difference between bed and wall,

From Eq. 2.10 :

$$q = A_w h_w \Delta T$$

$$= 91.72 \times 0.0189 \times 50$$

$$= 86.68 \qquad \text{Cal/sec.}$$

$$\text{or} \quad = 1238.29 \qquad \text{BTU/hr.}$$

$$= 362.9 \qquad \text{Watts}$$

Let efficiency of the heater about 12%

∴ The power of Heater is about 3024.17 Watts

Say 3000 Watts.

A.3 Calculation for Preheating Time

Basis Temperature of fluidizing gas is the same as the heater = 550 °C

Data : N_2 used as fluidizing gas

$\rho_g = 4.37 \times 10^{-4}$ gm/cm.³

$\rho_s = 2.47$ gm/cm.³

$C_g = 0.27$ Cal/gm. ° C,

$C_s = 0.34$ Cal/gm. ° C, (from Eq.2.2)

let $\varepsilon = \varepsilon_{mf} = 0.653$

$L_m = L_{mf} = 5.75$ cm.

and $U_o = U_{mf} = 55.2$ cm/sec.

$T_{gi} = 550\ °C.$

$T_{so} = 30\ °C.$

$T_s = 500\ °C.$

CALCULATION :

From Eq. 2.15 :

$$\frac{T_{gi} - T_s}{T_{gi} - T_{so}} = \exp\left[- \frac{\rho_g C_g}{\rho_s C_s} \cdot \frac{U_o \cdot t}{(1-\varepsilon) L_m}\right] \quad ....(2.15)$$

gives $\left(\frac{550 - 500}{550 - 30}\right) = \exp\left[- \frac{4.37 \times 10^{-4} \times 0.27}{2.47 \times 0.34} \cdot \frac{55.2\ t}{0.347(5.75)}\right]$

or $\ln\left(\frac{5}{52}\right) = -\ 2.34 = -\ 38.87 \times 10^{-4} \cdot t$

$\therefore t = 602$ sec. or 10.03 min.

or time for preheating oil shale to 500 °C is 10.03 min.

Say 10 min.

A.4 Determination of Retorting Time

Basis 500°C and 1 atm.

Data : $\rho_g = 4.37 \times 10^{-4}$ gm/cm^3

$\rho_s = 2.47$ gm/cm^3

$C_g = 0.27$ Cal/gm.°C

let $\varepsilon = \varepsilon_{mf} = 0.653$

let $L_m = L_{mf} = 5.75$ cm.

and $U_o = U_{mf} = 55.2$ cm/sec.

$T_{gi} = 550°C$

$T_{ge} = 500°C$

17.38% Product Yield from Fischer assay (Appendix B.5)

CALCULATION :

From Eq. 2.17 :

$$Q_o - Q = \frac{\rho_g \; C_g (T_{gi} - T_{ge})}{\rho_s \quad \Delta H_s} \cdot \frac{t}{(1 - \varepsilon) L_m / U_o} \qquad ....(2.17)$$

Where $Q_o - Q = \frac{17.38}{100} = 0.1738$

$\Delta H_s = 182.4$ Cal/gm. .... (from Eq. 2.1)

Then

$$t = \frac{0.1738 \times 182.4 \times 2.47 \times 0.347 \times 5.75}{4.37 \times 10^{-4} \times 0.27(50) \times 55.2}$$

$= 479.732$ sec. or 7.996 min.

or time used to decompose kerogen from oil shale at 500°C is 7.996 min. Say 8 min.

From Appendix A.3 and A.4, operating time used 18 min.

Say 30 min.

A.5 Determination of Actual Velocity of Fluidizing Medium in the Fluidized-Bed Retort as Operating at U_{mf} of Raw Oil Shale Particles.

Basis 100.00 gm of raw oil shale, operating time of 30 minutes and condition at 500°C, 1 atm.

Data :

Operating velocity of nitrogen gas, U_1 = 20.56 cm/sec.

From the experimental data (4.2, Chapter IV) :-

Minimum fluidizing velocity for raw oil shale mean particle size of 0.576 mm., $U_{mf1} = U_1 = 20.56$ cm/sec

Minimum fluidizing velocity for spent shale of the 100.00 gm raw oil shale particles, $U_{mf2} = 14.16$ cm/sec

From Oilshale Exploitation Company (26) report :-

Gas Production at N.T.P. = 1009 cm^3/sample 20 gm

or = 5045 cm^3/sample 100 gm

From Hendrickson (10) :-

Molecular weight of crude shale oil = 306

From Appendix B.5 :-

Oil content = 11.69 %

Water content = 4.15 %

Diameter of the retort, D = 5.08 cm

CALCULATION :

1. Average minimum fluidizing velocity, U_{mf}

$$U_{mf} = \frac{U_{mf1} + U_{mf2}}{2}$$

$$= \frac{20.56 + 14.16}{2}$$

$$= 17.36 \quad \text{cm/sec}$$

2. Volume of gas at 500°C and 1 atm., V_1

From gas's law, $$\frac{P_o V_o}{T_o} = \frac{P_1 V_1}{T_1}$$

Where P_o, P_1 = absolute pressure, 1 atm.

P_o, V_1 = Volume of gas at 273°K, and 773°K

T_o, T_1 = Temperature of gas in °K, at 273°K and 773°K

$\therefore V_1 = \frac{5045}{273} \times 773$

$= 14,284.93 \quad cm^3$

3. Volume of oil vapour at 500°C and 1 atm., V_2

From 1 gm. mol. gas is equivalent to 22.4 liters at N.T.P.

Oil vapour $= \frac{11.69}{306} = 0.0382$ gm. mol.

or $= 855.74 \quad cm^3$ at N.T.P.

$\therefore V_2 = 2423.02 \quad cm^3$

4. Volume of H_2O vapour at 500°C and 1 atm., V_3

$H_2O = \frac{4.15}{18} = 0.23$ gm. mol.

or $= 5152 \quad cm^3$ at N.T.P.

$V_3 = 14,587.90$

5. Velocity of gas, oil vapour, and H_2O vapour in the retort, U_2

$$\text{Velocity} = \frac{\text{Flow rate}}{\text{Cross sectional area}}$$

$$\text{Flow rate} = \frac{V_1 + V_2 + V_3}{30 \times 60}$$

$$= \frac{31568.85}{1800}$$

$$= 17.54 \quad cm^3/sec$$

$$\therefore U_2 = \frac{17.54}{\frac{\pi}{4}(5.08)^2}$$

$$= 0.865 \quad cm/sec$$

Therefore, actual velocity of fluidizing medium in the retort

$$= U_1 + U_2$$

$$= 21.425 \quad cm/sec$$

or $$= 1.234 \ \overline{U}_{mf}$$

Assumption of the Equipment Design

1. The surrounding temperature is about 30 °C
2. The frictional force due to distributor reaction and surface friction lost are negligible.
3. Nitrogen gas used is pure nitrogen.
4. No reaction between nitrogen and oil shale or its products.
5. Mass transfer of oil shale retorting is a physical transfer process.
6. The properties of oil shale in Thailand are the same as Green River or Colorado oil shale having nearly the same modified Fischer assay, for example specific heat of oil shale and heat requirement for oil shale retorting.
7. The thermal expansion of stainless steel is negligible.
8. The properties of oil shale particles are the same throughout the operating time.
9. The oil shale particles are non-porous.
10. Gases in the process are ideal.

APPENDIX B

Table B.1 Sieve Analysis of Raw Shale Particles

Run No.	Sample No.	Sieves Mesh No.	Sieves mm.	d_{pi} (mm.)	Weight in Interval of Sieve (gm)	x_i	$(\frac{x}{d_p})_i$	$\bar{d}_p = \frac{1}{\Sigma_{all\ i}(x/d_p)_i}$ (mm.)
		16	1.19					
				1.095	-	-	-	
		18	1.00					
				0.920	-	-	-	
1	1	20	0.841					0.715
				0.774	168.9	0.563	0.7274	
		25	0.707					
				0.651	131.1	0.437	0.6713	
		30	0.595					
		25	0.707					
				0.651	58.98	0.1966	0.302	
		30	0.595					
				0.548	197.28	0.6576	1.200	
2	2	35	0.500					0.576
				0.460	43.74	0.1458	0.235	
		40	0.420					
				0.387	0.00	0.00	0.00	
		45	0.354					
		45	0.354					
				0.326	0.30	0.001	0.003	
		50	0.297					
3	3			0.274	144.00	0.480	1.752	0.249
		60	0.250					
				0.230	155.70	0.519	2.261	
		70	0.210					

Table B.1 (continued)

Run No.	Sample No.	Sieves: Mesh No.	Sieves: mm.	d_{pi} (mm.)	Weight in Interval of Sieve (gm)	x_i	$(\frac{x}{d_p})_i$	$\bar{d}_p = \frac{1}{\Sigma_{all\ i}(x/d_p)_i}$ (mm.)
		20	0.841					
				0.718	30.30	0.101	0.141	
		30	0.595					
				0.474	43.20	0.144	0.324	
4	4	45	0.354					0.310
				0.325	135.60	0.452	1.518	
		50	0.297					
				0.253	90.90	0.303	1.243	
		70	0.210					

Note : d_{pi} = Arithmetic mean of diameter range of sieve aperture

for example d_{pi} = (Aperture of sieve No. 16 + of sieve No.18)/2

$$= \frac{(1.19 + 1.00)}{2}$$

$$= 1.095 \text{ mm.}$$

Table B.2 Pressure Drop across the Empty Column.

Run No.	U_o (cm/sec)	ΔP (mm. H_2O)
1	1.87	0.35
2	3.93	0.60
3	7.08	0.80
4	8.23	0.90
5	10.47	1.00
6	12.90	1.15
7	15.37	1.33
8	20.16	1.57
9	23.37	1.70
10	26.17	1.82
11	29.44	2.02
12	34.57	2.40

Table B.3 Sieve Analysis of Spent Shale Particles.

Run No.	Sample No.	Sieves: Mesh No.	Sieves: mm.	d_{pi} (mm.)	Weight in Interval of Sieve (gm)	x_i	$(\frac{x}{d_p})_i$	$\bar{d}_p = \frac{1}{\sum_{all\ i}(x/d_p)_i}$ (mm.)
		18	1.00					
				0.920	-	-	-	
		20	0.841					
				0.774	123.00	0.410	0.530	
1	1	25	0.707					0.680
				0.651	162.90	0.543	0.854	
		30	0.595					
				0.548	14.10	0.047	0.086	
		35	0.500					
		25	0.707					
				0.651	9.20	0.034	0.052	
		30	0.595					
				0.548	211.20	0.704	1.186	
2	2	35	0.500					0.542
				0.460	36.60	0.122	0.262	
		40	0.420					
				0.387	42.00	0.140	0.345	
		45	0.354					
		45	0.354					
				0.326	-	-	-	
		50	0.297					
				0.274	37.2	0.124	0.453	
3	3	60	0.250					0.214
				0.230	96.0	0.320	1.352	
		70	0.210					
				0.193	156.8	0.556	2.875	
		80	0.177					

Table B.4 Conversion of U_{mf} at Various Operating Temperatures to U_o at 30°C.

Sample No.	Operating Temperature (°C)	U_o at 30°C (cm/sec)	U_{mf} at Operating temperature (cm/sec)
1	400	16.21	36.00
	450	14.93	
	500	14.16	
	550	13.25	
	600	12.49	
	650	11.82	
2	400	9.35	20.56
	450	8.62	
	500	8.00	
	550	7.57	
	600	7.14	
	650	6.76	
3	400	4.41	9.80
	450	4.11	
	500	3.73	
	550	3.61	
	600	3.40	
	650	3.22	

Table B.5 Fischer Assay Analysis (25)

Run No.	Sample	Oil ml.	Oil gal/ton	Oil wt %	Water wt %	Spent Shale wt %	Gas & losses (wt %)
1	Mae Sot	14.27	34.21	11.42	4.10	82.77	1.71
2	Oil	14.61	35.02	11.69	4.20	82.55	1.56
3	Shale	14.36	34.41	11.49	4.50	82.53	1.48
4		14.78	35.42	11.82	3.70	82.79	1.69
5		15.02	36.01	12.02	4.25	82.46	1.27
Average		14.61	35.01	11.69	4.15	82.62	1.54

Note :

$$\text{Gallons of oil per ton of shale} = \frac{\text{Milliliters of oil} \times 239.7}{\text{Grams of oil shale charge}}$$

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