

LAMPIRAN REAKTOR

Perhitungan Reaktor

Jenis : Reaktor *Fixed Bed Multitube*

Kondisi Operasi : Suhu = 560°C

Tekanan = 1.2 atm

Reaksi = Eksotermis

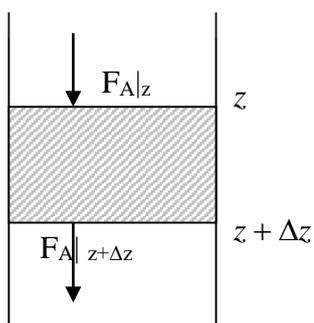
Produk : *formaldehyde*

Neraca Massa di Reaktor

Komponen	Input, kj/jam	Output, kj/jam
CH ₃ OH	-7.332.524,67	2.223.672,713
CH ₂ O	0	5.021.478,712
H ₂ O	-192.720,962	3.969.236,464
O ₂	-1.341.783,453	406.911,314
N ₂	-4.272.654,807	4.272.654,807
H ₂	0	1.173.763,705
Q rx	-7.540.374,221	
Q pendingin		3.612.340,40
TOTAL	-2.068.0058,12	20.680.058,12

1. Persamaan-persamaan Matematis Reaktor

a. Persamaan neraca massa pada elemen volum



Rate of input – rate of output – rate of reaction = rate of accumulation

$$F_A|_Z - F_A|_{Z+\Delta Z} - (-r_A).V = 0$$

$$F_A|_Z - F_A|_{Z+\Delta Z} - (-r_A). \frac{\pi.ID^2}{4} .\Delta Z.Nt = 0$$

$$F_A|_Z - F_A|_{Z+\Delta Z} = (-r_A). \frac{\pi.ID^2}{4} .\Delta Z.Nt$$

$$\frac{F_A|_Z - F_A|_{Z+\Delta Z}}{\Delta Z} = (-r_A). \frac{\pi.ID^2}{4} .Nt$$

$$\lim_{\Delta Z \rightarrow 0} \frac{F_A|_Z - F_A|_{Z+\Delta Z}}{\Delta Z} = (-r_A). \frac{\pi.ID^2}{4} .Nt$$

$$-\frac{dF_A}{dZ} = (-r_A). \frac{\pi.ID^2}{4} .Nt$$

Dimana: $F_A = F_{A0}(1-x)$

$$dF_A = -F_{A0}.dx$$

Sehingga diperoleh:

$$\frac{F_{A0}.dx}{dZ} = (-r_A). \frac{\pi.ID^2}{4} .Nt$$

$$\frac{dx}{dZ} = (-r_A). \frac{\pi.ID^2 .Nt}{4.F_{A0}}$$

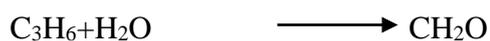
* Kecepatan reaksi (-r_A):

$$-r_A = k_o \cdot \exp\left[\frac{-E_a}{RT}\right] \cdot P_{propylene}$$

K_o = 3,13E+04 m³/kmol.jam

E_a = 15,8Kj/mol

P_{metanol} = y_{water}.P



Komponen	Mula-mula	bereaksi	sisanya
Methanol (A)	F _{A0}	-F _{A0} X	F _{A0} - F _{A0} X
Water (B)	F _{B0}	½ F _{B0} X	F _{B0} + ½ F _{B0} X

$$\text{Total } (F_{T0}) = F_{A0} + F_{B0}$$

$$y_{\text{methanol}} = \frac{F_{A0} - F_{A0}X}{F_{A0} + F_{B0} + F_{A0}X}$$

$$y_{\text{methanol}} = \frac{F_{A0} \cdot (1 - X)}{F_{T0}}$$

jadi:

$$P_{\text{methanol}} = \frac{F_{A0} \cdot (1 - X)}{F_{T0}} \cdot P$$

Sehingga kecepatan reaksi menjadi

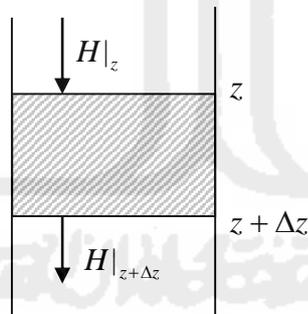
$$-r_A = k_o \cdot \exp\left[\frac{-E_a}{R.T}\right] \cdot \frac{F_{A0} \cdot (1 - X)}{F_{T0}} \cdot P$$

Dari penjabaran di atas didapat:

$$\frac{dx}{dZ} = (-r_A) \cdot \frac{\pi \cdot ID^2 \cdot Nt}{4 \cdot F_{A0}} \quad \dots(1)$$

$$\frac{dx}{dZ} = k_o \cdot \exp\left[\frac{-E_a}{R.T}\right] \cdot \frac{F_{A0} \cdot (1 - x)}{F_{T0}} \cdot P \cdot \frac{\pi \cdot ID^2 \cdot Nt}{4 \cdot F_{A0}}$$

b. Persamaan neraca panas pada elemen volum



Heat of input - Heat of output + Heat of generation - Heat transfer = Acc

$$H|_z - H|_{z+\Delta z} + (-r_A) \cdot \Delta H_R \cdot V - U d \cdot N t \cdot \Delta z \cdot \pi \cdot OD \cdot (T - T_p) = 0$$

$$H|_z - H|_{z+\Delta z} + (-r_A) \cdot \Delta H_R \cdot \frac{\pi}{4} \cdot ID^2 \cdot \Delta z \cdot N t - U d \cdot N t \cdot \Delta z \cdot \pi \cdot OD \cdot (T - T_p) = 0$$

$$H|_z - H|_{z+\Delta z} = -(-r_A) \cdot \Delta H_R \cdot \frac{\pi}{4} \cdot ID^2 \cdot \Delta z \cdot N t + U d \cdot N t \cdot \Delta z \cdot \pi \cdot OD \cdot (T - T_p)$$

$$\frac{H|_z - H|_{z+\Delta z}}{\Delta z} = -(-r_A) \cdot \Delta H_R \cdot \frac{\pi}{4} \cdot ID^2 \cdot N t + U d \cdot N t \cdot \pi \cdot OD \cdot (T - T_p)$$

$$\lim_{\Delta z \rightarrow 0} \frac{H|_z - H|_{z+\Delta z}}{\Delta z} = -(-r_A) \cdot \Delta H_R \cdot \frac{\pi}{4} \cdot ID^2 \cdot N t + U d \cdot N t \cdot \pi \cdot OD \cdot (T - T_p)$$

$$-\frac{dH}{dz} = -(-r_A) \cdot \Delta H_R \cdot \frac{\pi}{4} \cdot ID^2 \cdot N t + U d \cdot N t \cdot \pi \cdot OD \cdot (T - T_p)$$

$$\frac{dH}{dz} = (-r_A) \cdot \Delta H_R \cdot \frac{\pi}{4} \cdot ID^2 \cdot N t - U d \cdot N t \cdot \pi \cdot OD \cdot (T - T_p)$$

Dimana :

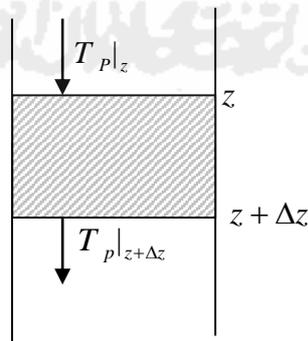
$$H = Q = \sum Fi \cdot Cpi \cdot (T - T_{ref})$$

$$dH = \sum Fi \cdot Cpi \cdot dT$$

$$\sum Fi \cdot Cpi \cdot \frac{dT}{dz} = (-r_A) \cdot \Delta H_R \cdot \frac{\pi}{4} \cdot ID^2 \cdot N t - U d \cdot N t \cdot \pi \cdot OD \cdot (T - T_p)$$

$$\frac{dT}{dz} = \frac{F_{A0} \cdot (\Delta H_R) \cdot \frac{dx}{dz} - U d \cdot N t \cdot \pi \cdot OD \cdot (T - T_p)}{\sum Fi \cdot Cpi} \quad \dots\dots(2)$$

c. Persamaan neraca panas pendingin



Heat of input – Heat of output + Heat transfer = Acc

$$Wp.Cp_p.Tp|_z - Wp.Cp_p.Tp|_{z+\Delta z} + Ud.Nt.\Delta z.\pi.OD.(T - T_p) = 0$$

$$Wp.Cp_p.Tp|_z - Wp.Cp_p.Tp|_{z+\Delta z} = -Ud.Nt.\Delta z.\pi.OD.(T - T_p)$$

$$Wp.Cp_p.Tp|_z - Wp.Cp_p.Tp|_{z+\Delta z} = \dots\dots(3)$$

$$\frac{Wp.Cp_p.Tp|_z - Wp.Cp_p.Tp|_{z+\Delta z}}{\Delta z} = -Ud.Nt.\pi.OD.(T - T_p)$$

$$\lim_{\Delta z \rightarrow 0} \frac{Wp.Cp_p.Tp|_z - Wp.Cp_p.Tp|_{z+\Delta z}}{\Delta z} = -Ud.Nt.\pi.OD.(T - T_p)$$

$$\frac{dT_p}{dz} = -\frac{Ud.Nt.\pi.OD.(T - T_p)}{Wp.Cp_p}$$

$$\frac{dT_p}{dz} = \frac{Ud.Nt.\pi.OD.(T - T_p)}{Wp.Cp_p}$$

d. Pressure drop

Pressure drop pada reaktor dicari menggunakan persamaan Ergun (Fogler, p.159)

$$\frac{dP}{dz} = -\frac{Gt}{\rho_g \cdot g \cdot D_p} \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot \left[\frac{150 \cdot (1-\varepsilon) \cdot \mu}{D_p} + 1.75 \cdot Gt \right] \dots(4)$$

Persamaan 1, 2, 3 dan 4 merupakan persamaan diferensial simultan maka digunakan metode Euler untuk menyelesaikannya, sehingga diperoleh konversi reaksi, panjang reaktor, suhu reaksi keluar dan suhu pendingin keluar.

2. Data-data Sifat Fisis Bahan

a. viskositas gas

$$\eta_{\text{gas}} = A + BT + CT^2 \text{ (micropoise)}$$

Formula	A	B	C
Methanol	0,00171	0,000005434	1,3154E-07
Water	0,00234	0,000086157	-1,3348E-08
Oksigen	0,00121	0,00007593	-1,1014E-08
Nitrogen	0,00309	0,00045918	-6,4933E-08
Hydrogen	0,03951	0,000047093	4,9551E-08
formaldehyde	0,00053	0,000019431	9,5287E-08

b. Kapasitas panas gas umpan

$$C_p = A + BT + CT^2 + DT^3 + ET^4 \text{ (Joule/mol.K)}$$

komponen	A	B	C	D	E
Methanol	40,0460	-0,0383	2,4529E-04	-2,1679E-07	5,9909E-11
Oksigen	29,3420	-0,0035	1,0076E-05	-8,2872E-08	2,4424E-11
Nitrogen	25,3990	0,0202	-3,8549E-05	3,1880E-08	-8,7585E-12
Water	29,5260	-0,0089	3,8083E-05	-3,2629E-08	8,8607E-12

c. Panas Reaksi

Reaksi yang terjadi bersifat eksotermis, panas yang dikeluarkan adalah sebagai berikut:

$$\Delta H_R = \Delta H_{R298} + \int_{298}^T \Delta C_p . dT$$

Panas pembentukan pada keadaan standar ΔH_f (coulson and richardson,2005)

Komponen	ΔH_f (KJ/Kmol)
Formaldehyde	-115.900
Methanol	-201.170
Water	-241.800
Oksigen	0
Nitrogen	0
Hydrogen	0
Total	-558.870

$$\Delta H_{R298} = (\Delta H_f \text{ CH}_2\text{O}) - (\Delta H_f \text{ CH}_3\text{OH} + \text{H}_2\text{O} + \text{O}_2)$$

$$\int_{T_{ref}}^T \Delta C_p . dT = \int_{T_{ref}}^T \Delta a . dT + \int_{T_{ref}}^T \Delta b . T . dT + \int_{T_{ref}}^T \Delta c . T^2 . dT + \int_{T_{ref}}^T \Delta d . T^3 . dT + \int_{T_{ref}}^T \Delta e . T^4 . dT$$

$$\Delta H_{R298} = -71.260 \text{ KJ/Kmol}$$

d. Data sifat katalis (perak)

$$\text{Diameter} = 0,46 \text{ cm}$$

Densitas Partikel = 834 kg/m³

Porositas = 0,5

3. Dimensi Reaktor

a. Menentukan ukuran dan jumlah tube

* Menentukan ukuran tube

Diameter dipilih berdasarkan pertimbangan agar perpindahan panas berjalan baik. Pengaruh rasio D_p/D_t terhadap koefisien perpindahan panas dalam pipa yang berisi katalisator dan pipa kosong, telah diteliti oleh Colburn's (Smith, 1981).

D_p/D_t	0,05	0,10	0,15	0,20	0,25	0,30
hw/h	5,50	7,00	7,80	7,50	7,00	6,60

Dipilih $D_p/D_t = 0,15$ karena memberikan nilai hw/h yang paling besar (transfer panas yang baik). Perbandingan diameter katalisator dan diameter pipa $D_p/D_t = 0,15$, diameter katalisator = 0,46cm sehingga diperoleh diameter pipa = 3,07cm (1,207in).

Dari tabel 11 (Kern, 1950) diambil spesifikasi pipa sebagai berikut :

Schedule number = 40

Nominal pipe size, IPS = 1 in

Diameter dalam, ID = 0.864 in

Diameter luar, OD = 1,049 in

Flow area per pipe = 0.864 in²

Weight per lin ft = 1.6800 lbsteel/ft

* Menentukan jumlah tube

1. Jumlah tube maksimum (Nt max)

- Kecepatan massa per satuan luas (Gt)

$$Gt = \frac{Re \cdot \mu g}{Dp}$$

$$Dp$$

Asumsi : $Re = 3.100$

$$\mu g = 0,00023962 \text{ g/cm.s}$$

$$Dp = 0,46 \text{ cm}$$

sehingga diperoleh $Gt = 1,614826984 \text{ g/cm}^2.\text{s}$

- Luas penampang total (At)

$$At = \frac{G}{Gt}$$

$G = \text{umpan total} = 20.459,5231 \text{ kg/jam}$

Sehingga diperoleh $At = 3.519,38686 \text{ cm}^2$

- Luas Penampang pipa (Ao)

$$Ao = \frac{\pi}{4} \cdot IDt^2 \cdot \varepsilon$$

$$IDt = 0,9533 \text{ in} = 2,66446 \text{ cm}^2$$

$\varepsilon = \text{porositas katalis} = 0,5$

Sehingga diperoleh $Ao = 2,6527 \text{ cm}^2$

Jadi jumlah tube maksimum :

$$Nt \text{ max} = \frac{At}{Ao}$$

$$Nt \text{ max} = 1327 \approx 1071 \text{ tube}$$

2. Jumlah tube minimum (Nt min)

Bulk density (ρ_B) = $\rho_s \cdot (1 - \varepsilon)$

$$= 3.00544 \text{ gr/cm}^3$$

Debit (Q_v) = $\underline{G} = 387,6776497 \text{ m}^3/\text{jam}$

$$\text{Kecepatan maksimum (Vmax)} = \sqrt{\frac{4 \cdot (\rho_B - \rho_g) \cdot g \cdot Dp}{3 \cdot \rho_g \cdot Fo}}$$

$Fo = \text{friction factor} = 0,4$

Sehingga diperoleh $V_{\text{max}} = 1363,8664 \text{ m/jam}$

$$\begin{aligned} \text{Luas penampang total (At)} &= \frac{Q_v}{V_{\max}} \\ &= 0,2841 \text{m}^2 \end{aligned}$$

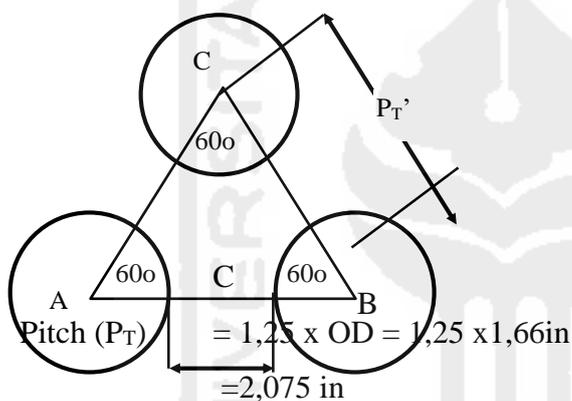
Jumlah tube minimum :

$$\begin{aligned} N_t \text{ min} &= \frac{At}{A_o} \\ &= 1072 \text{ tube} \end{aligned}$$

Dari perhitungan jumlah tube diatas maka diambil jumlah tube sebanyak 1072 buah.

b. Menghitung diameter dalam reaktor (IDs)

Dipilih susunan tube : Triangular pitch



$$\begin{aligned} \text{Clarence (C')} &= P_T - OD = 1,65 \text{in} - 1,32 \text{ in} \\ &= 0,3300 \text{ in} \end{aligned}$$

$$\begin{aligned} \text{IDs} &= \sqrt{\frac{4 \cdot N_t \cdot P_T^2 \cdot 0,866}{\pi}} = 322,1267 \text{ cm} \\ &= 126,8215 \text{in} \end{aligned}$$

Jadi diameter dalam shell = 126,8215 in

c. Menghitung Tebal Dinding Reaktor

Tebal dinding reaktor (shell) dihitung dengan persamaan :

$$t_s = \frac{P \cdot r}{f \cdot E - 0,6 \cdot P} + C \quad (\text{Brownell, pers.13-1, p.254})$$

Dimana :

t_s = tebal shell, in

E = efisiensi pengelasan

f = maksimum allowable stress bahan yang digunakan

(Brownell,tabel 13-1, p.251)

r = jari-jari dalam shell, in

C = faktor korosi, in

P = tekanan design, Psi

Bahan yang digunakan Carbon Steel SA 283 Grade C

E = 0,85

f = 12650 psi

C = 0,125

r = ID/2 = (132/2) in= 66 in

P = 1,2 atm = 17,64psi (overdesign 20 %)

Jadi P = (120/100)*P = 21,168 psi

$$\begin{aligned} \text{maka } t_s &= \frac{21,168 * (132 / 2)}{12650 \cdot 0,85 - 0,6 * 441} + 0,125 \\ &= 0,25 \text{ in} \end{aligned}$$

dipilih tebal dinding reaktor standar 1 in

$$\begin{aligned} \text{Diameter luar reaktor} &= \text{ID} + 2 * t_s \\ &= 126,8215 \text{ in} + 2 * 1 \text{ in} \\ &= 128,8215 \text{ in} \end{aligned}$$

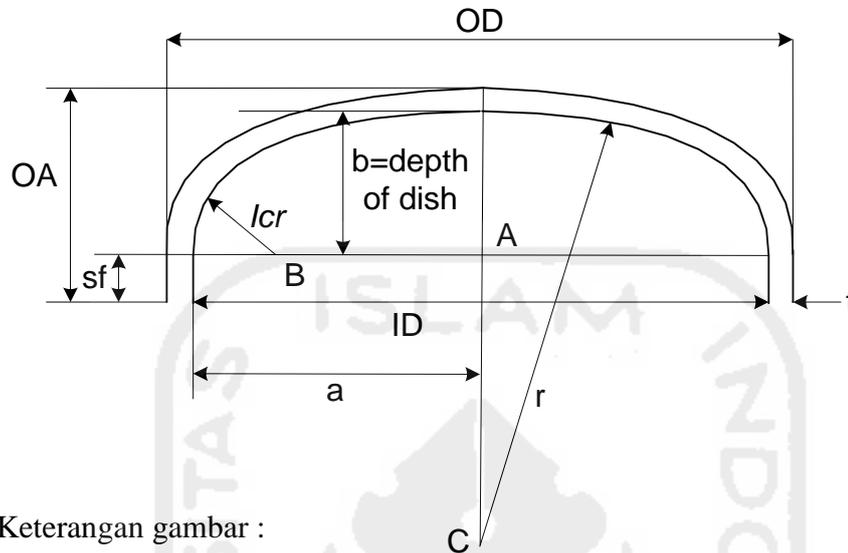
Maka digunakan diameter standar 132 in

d. Menghitung Head Reaktor

1. Menghitung Tebal Head Reaktor

Bentuk head : Elipstical Dished Head

Bahan yang digunakan: Carbon Steel SA 283 Grade C



Keterangan gambar :

- ID = diameter dalam head
- OD = diameter luar head
- a = jari-jari dalam head
- t = tebal head
- r = jari-jari luar dish
- icr = jari-jari dalam sudut icr
- b = tinggi head
- sf = straight flange
- OA = tinggi total head

Tebal head dihitung berdasarkan persamaan :

$$t_h = \frac{P.IDs}{2.f.E - 0,2.P} + C \quad (\text{Brownell, 1979})$$

P = tekanan design, psi = 21,168 psi

IDs = diameter dalam reaktor, in = 132in

f = maksimum allowable stress, psi = 12650 psi

E = efisiensi pengelasan = 0,85

C = faktor korosi, in = 0,125

$$\begin{aligned} \text{maka } th &= \frac{21,168 * 132}{2 * 12650 * 0,85 - 0,2 * 21,168} + 0,125 \\ &= 0,249858711 \text{ in} \end{aligned}$$

dipilih tebal head reaktor standar 1 in

2. Menghitung Tinggi Head Reaktor :

Dari tabel 5.7 Brownell p.90

$$\text{ODs} = 132 \text{ in}$$

$$ts = 1 \text{ in}$$

$$\text{didapat: } icr = 8 \text{ in}$$

$$r = 120 \text{ in}$$

$$a = \text{IDs}/2 = 65 \text{ in}$$

$$AB = a - icr = 57 \text{ in}$$

$$BC = r - icr = 112 \text{ in}$$

$$AC = (BC^2 - AB^2)^{1/2} = 96,4106 \text{ in}$$

$$b = r - AC = 23,5894 \text{ in}$$

Dari tabel 5.6 Brownell p.88 dengan $th = 1 \text{ in}$ didapat $sf = 1,5 - 4 \text{ in}$ perancang digunakan $sf = 4 \text{ in}$

Tinggi head reaktor dapat dihitung dengan persamaan :

$$hH = th + b + sf$$

$$= (1 + 23,5894 + 4) \text{ in}$$

$$= 28,5894 \text{ in}$$

$$= 0,72617126 \text{ m}$$

e. Tinggi Reaktor

Diketahui tinggi shell = 9,6024 m

Tinggi reaktor total = Panjang Tube + (2*tinggi head)

$$H_{\text{total}} = 320,8663 \text{ in} + (2 * 28,5894) \text{ m}$$

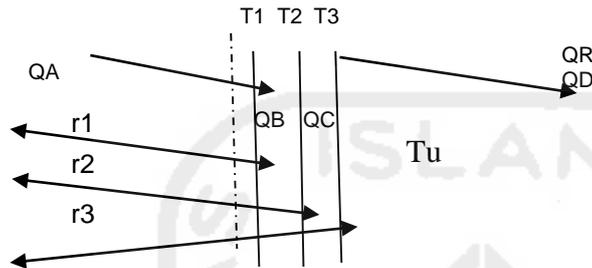
$$= 378,0452 \text{ in}$$

$$= 9,6024 \text{ m}$$

4. Tebal Isolasi Reaktor

Asumsi :

1. Suhu dalam reaktor = suhu permukaan dinding dalam shell = suhu pendingin rata-rata
2. Keadaan steady state $Q_A = Q_B = Q_C = (Q_D + Q_R)$
3. Suhu dinding luar isolasi isothermal



Keterangan :

r_1 = jari-jari dalam reaktor

r_2 = jari-jari luar reaktor

r_3 = jari-jari isolator luar

Q_A = Perp. Konveksi dari gas ke dinding dalam reaktor

Q_B = Perp. Konduksi melalui dinding reaktor

Q_C = Perp. Konduksi melalui isolator

Q_D = Perp. konveksi dari permukaan luar isolator

Q_R = Perp. Panas radiasi

T_1 = Suhu dinding dalam reaktor

T_2 = Suhu dinding luar reaktor

T_3 = Suhu isolator luar

T_u = Suhu udara luar

- sifat-sifat fisis bahan

* bahan isolasi : asbestos, dengan sifat-sifat fisis (kern) :

$$k_{is} = 0,1713 \text{ W/m} \cdot ^\circ\text{C}$$

$$\epsilon = 0,96$$

* carbon steel: $k_s = 41,99933919 \text{ W/m} \cdot ^\circ\text{C}$

* sifat-sifat fisis udara pada suhu T_f (Holman, 1988. Daftar A-5)

$$\begin{aligned}
 T_f &= 315,5 \text{ K} \\
 \nu &= 0,00002 \\
 k &= 0.0274149 \text{ W/m} \cdot ^\circ\text{C} \\
 Pr &= 0.70459 \\
 \beta &= 0.00316957 \text{ K}^{-1} \\
 \mu &= 0.000019 \text{ kg/m} \cdot \text{s} \\
 g &= 9,8 \text{ m/s}^2
 \end{aligned}$$

$$r_3 = r_2 + x$$

$$r_1 = 0,4826 \text{ m}$$

$$r_2 = 0,5080 \text{ m}$$

$$L = 8,15 \text{ m}$$

1. Perpindahan panas konduksi

$$Q_B = \frac{2 \cdot \pi \cdot k_s \cdot L \cdot (T_1 - T_2)}{\ln\left(\frac{r_2}{r_1}\right)} \quad \dots\dots(a)$$

$$Q_C = \frac{2 \cdot \pi \cdot k_{is} \cdot L \cdot (T_2 - T_3)}{\ln\left(\frac{r_3}{r_2}\right)} \quad \dots\dots(b)$$

2. Perpindahan panas konveksi

$$Q_D = hc \cdot A \cdot (T_3 - T_4) \quad \dots\dots(c)$$

$$Q_D = hc \cdot 2 \cdot \pi \cdot r_3 \cdot L \cdot (T_3 - T_4)$$

Karena $Gr_L \cdot Pr > 10^9$, sehingga :

$$hc = 1,31 \cdot (\Delta T)^{\frac{1}{3}}$$

$$Gr_L = \frac{g \cdot \beta \cdot (T_3 - T_u) \cdot L^3}{\nu^2}$$

3. Panas Radiasi

$$Q_R = \varepsilon \cdot \sigma \cdot A \cdot (T_3^4 - T_4^4) \quad \dots\dots(d)$$

$$Q_R = \varepsilon \cdot \sigma \cdot 2 \cdot \pi \cdot r_3 \cdot L \cdot (T_3^4 - T_4^4)$$

$$\sigma = 5,669 \times 10^{-8} \text{ w/m}^2 \cdot \text{k}^4$$

kemudian persamaan a, b, c dan d ditrial menggunakan solver dan didapat :

$$T_2 = 459,2345 \text{ K}$$

Tebal isolasi (x) = 26.4322cm

Tabel Perubahan Konversi, Suhu Dan Tekanan Terhadap Panjang Reaktor

z (m)	X	T (K)	Ts (K)	P (atm)
0	0	833	303,0000	1,2
0,2500	0,070796315	832,7476	334,5475	1,2
0,5000	0,141592428	832,5111	364,2019	1,2
0,7500	0,212388357	832,2972	392,0774	1,2
1,0000	0,283184122	832,1056	418,2812	1,2
1,2500	0,353979739	831,9361	442,9141	1,2
1,5000	0,424775227	831,7885	466,0710	1,2
1,7500	0,495570603	831,6627	487,8410	1,2
2,0000	0,566365886	831,5598	508,3080	1,2
2,4600	0,69662902	831,4257	542,8235	1,2

Dari tabel diatas diketahui :

Konversi (x) = 0.6967

Suhu gas masuk (Tin) = 833K

Suhu gas keluar (Tout) = 833K

Panjang tube reaktor (z) = 8,15m

Tekanan masuk (Pin) = 1,2 atm

Tekanan keluar (Pout) = 1,2 atm

Suhu pendingin masuk (Tp in) = 303.00K

Suhu pendingin keluar (Tp out) = 523K