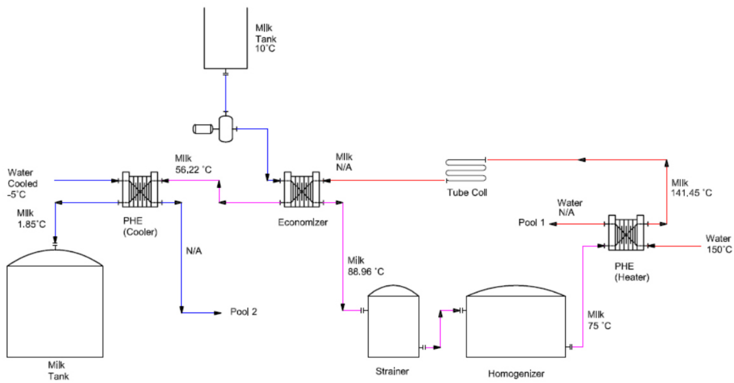
BAB IV
PEMBAHASAN

4.1 Menghitung Laju Perpindahan Panas & LMTD

Laju perpindahan panas atau *heat transfer* adalah jumlah energi panas yang dilepas atau diterima saatterjadi perubahan suhu. Nantinya laju perpindahan panas inilah yang akan ditanggung oleh HE tersebut dalam transfer panas. Karena pada skripsi ini akan ada 3 fungsi HE yang akan dibahas, maka akan ada 3 Laju Perpindahan Panas juga yang akan dihitung. Pada bab ini akan membahas laju perpindahan panas dan perubahan suhu air susu pada masing-masing HE.



Gambar 4.1 Flow Diagram Pengolahan Air Susu KUD Batu

Tabel 4.1 Suhu fluida pada tiap HE

		Heater		Economizer		Cooler	
		Fluida	Suhu (°C)	Fluida	Suhu (°C)	Fluida	Suhu (°C)
Panas	In	Uap Jenuh	175	Susu	N/A	Susu	N/A
	Out	Uap Jenuh	N/A	Susu	N/A	Susu	2
Dingin	In	Susu	N/A	Susu	10	Air	-5
	Out	SUsu	140	Susu	N/A	Air	N/A

$$Q = m \times Cp \times (T_2 - T_1)$$

Keterangan:

Q	: Perpindahan panas	(J)
m	: Massa fluida	(kg)
Cp	: Kalor jenis fluida	(J/kg. °C)
T_2 - T_1	: Perubahan temperature	(°C)

Sedangkan pada skripsi ini, rumus yang akan banyak dipakai adalah:

$$q = \dot{m} \times Cp \times (T_2 - T_1)$$

Keterangan:

q	: Laju perpindahan panas	(kJ/h)
$\dot{m}$	: Laju massa fluida	(kg/h)
Cp	: Kalor jenis fluida	(kJ/kg. °C)
T_2 - T_1	: Perubahan temperature	(°C)

Massa jenis benda berubah-ubah sesuai suhu benda pada saat itu. Hal itu dapat dijelaskan dengan rumus berikut:

$$\rho_2 = \frac{\rho_1}{1 + \beta(T_2 - T_1)}$$

Keterangan:

ρ_2	: Massa jenis akhir fluida	(kg/m^3)
ρ_1	: Massa jenis awal fluida	(kg/m^3)
β	: Koefisien ekspansi volume	(m^3/m^3. °C)
T_2 - T_1	: Perubahan temperature	(°C)

Desain HE secara cross flow akan menemui masalah saat akan menghitung luas area HE yang dibutuhkan untuk perpindahan panas. Hal ini dikarenakan dalam menghitung luas area yang dibutuhkan, LMTD harus diketahui. Pada skripsi ini beberapa suhu akan diestimasi untuk memudahkan dalam menghitung perubahan massa pada tiap suhu.

LMTD atau Log Mean Temperature Difference adalah perbedaan suhu rata-rata antara sisi panas dan sisi dingin HE yang digunakan untuk menentukan luas area HE yang dibutuhkan untuk perpindahan panas. Semakin besar nilai LMTD, maka semakin besar pula panas yang dipindahkan dalam suatu sistem HE.

$$\Delta \mathrm{Tm} = \frac{(\mathrm{T}_1 - \mathrm{t}_2) - (\mathrm{T}_2 - \mathrm{t}_1)}{\ln \frac{(\mathrm{T}_1 - \mathrm{t}_2)}{(\mathrm{T}_2 - \mathrm{t}_1)}}$$

Keterangan:

ΔTm	: Log Mean Differential Temperature	(°C)
T_1	: Inlet fluida panas	(°C)
T_2	: Outlet fluida panas	(°C)
t_1	: Inlet fluida dingin	(°C)
t_2	: Outlet fluida dingin	(°C)

4.1.1 Laju Perpindahan Panas dan LMTD Heater

Steam pada boiler Toma dengan kapasitas 1000 kg/h dan tekanan 10 bar milik KUD merupakan sumber panas pada proses pengolahan air susu. Desain HE ini akan mengacu pada steam output pada boiler tersebut, sehingga laju perpindahan panas pada HE heater sama dengan laju panas steam boiler. Namun mengingat boiler tersebut sudar beroperasi lebih dari 20 tahun sehingga efisiensinya menurun, properties steam yang akan digunakan pada perhitungan sebagai berikut:

- Tekanan Absolut = 9 bar
- Suhu Saturasi = 175 °C (Mengambil acuan dari tabel steam)
- Panas Laten = 2029 kJ/kg (Mengambil acuan dari tabel steam)
- Laju massa = 600 kg/h

Dengan spesifikasi diatas maka didapatkan:

$$q = \dot{m} \times he$$
$$q = 600 \times 2029$$
$$q = 1217400 \text{ kJ/h}$$

$$V_s = \frac{m_s}{\rho_s}$$
$$V_s = \frac{600}{5.15}$$
$$V_s = 116.5 \text{ m}^3/\text{h}$$

Efisiensi boiler berdasarkan steam terpakai pada HE adalah sebagai berikut:

$$\eta_B = \frac{q}{q_B}$$
$$\eta_B = \frac{\dot{m} \times he}{\dot{m}_B \times he_B}$$
$$\eta_B = \frac{600 \times 2029}{1000 \times 2013} \times 100\%$$
$$\eta_B = 60.5\%$$

Fluida input pada sisi dingin HE Heater adalah output HE Economizer pada sisi dingin. Dengan menghitung suhu fluida inputsisi dingin HE heater, maka otomatis akan didapatkan juga suhu output HE economizer disisi dingin. Hal ini nantinya diperlukan untuk menghitung laju perpindahan panas pada HE economizer.

Seperti yang telah dibahas sebelumnya, massa jenis fluida dapat berubah sesuai suhu pada saat itu. Karena t_{h1}belum diketahui, maka:

$$\dot{m} = \dot{V} \times \rho$$

$$\dot{m}_h \times Cp_h \times (t_{h2} - t_{h1}) = q$$
$$\dot{V} \times \rho_{2h} \times Cp_h \times (t_{h2} - t_{h1}) = q$$

$$\dot{V} \times \frac{\rho_0}{1 + \beta(T_1 - T_0)} \times Cp_h \times (t_{h2} - t_{h1}) = q$$
$$5 \times \frac{1030}{1 + 0.0008(T_1 - 20)} \times 3.77 \times (140 - t_{h1}) = 1217400$$
$$t_{h1} = 72.65\ °C$$

$$\Delta Tm_h = \frac{(t_{h2} - t_{h1})}{\ln \frac{(T_s - t_{h1})}{(T_s - t_{h2})}}$$
$$\Delta Tm_h = \frac{(140 - 72.65)}{\ln \frac{(175 - 72.65)}{(175 - 140)}}$$
$$\Delta Tm_h = 62.77°C$$

4.1.2 Laju Perpindahan Panas Economizer

Suhu air susu ouput pada sisi dingin HE economizer sama dengan air susu input sisi dingin HE heater seperti yang telah dijelaskan di sub bab sebelumnya. Sedangkan suhu air susu input sisi panas HE economizer sama dengan suhu air susu output sisi dingin HE heater. Maka dari itu didapatkan:

$$t_{e2} = t_{h1}$$
$$t_{e2} = 72.65\ °C$$

$$T_{e1} = t_{h2}$$
$$T_{e1} = 140\ °C$$

$$\rho_{1ed} = \frac{\rho_0}{1 + \beta(T_1 - T_0)}$$
$$\rho_{1ed} = \frac{1030}{1 + 0.0008(10 - 20)}$$
$$\rho_{1ed} = 1036.29\ kg/m^3$$
$$\dot{m}_{ed} = 5 \times 1036.29$$
$$\dot{m}_{ed} = 5181.45\ kg$$

$\dot{m}_{ed} \times Cp_e \times (t_{e2} - t_{e1}) = q$
$5181.45 \times 3.77 \times (72.65 - 10) = q$
$q = 1223809.27 \text{ kJ/h}$

$$\rho_{1ep} = \frac{\rho_0}{1 + \beta(T_1 - T_0)}$$
$$\rho_{1ep} = \frac{1030}{1 + 0.0008(140 - 20)}$$
$\rho_{1ep} = 937.96 \text{ kg/m}^3$
$\dot{m}_{ep} = 5 \times 937.96$
$\dot{m}_{ep} = 4689.80 \text{ kg}$
$\dot{m}_{ep} \times Cp_e \times (T_{e2} - T_{e1}) = q$
$4689.80 \times 3.77 \times (T_{e2} - 140) = -1223809.27$
$(T_{e2} - 140) = -58.84$
$T_{e2} = 79.22\ °C$

$$\Delta Tm_e = \frac{(T_{e1} - t_{e2}) - (T_{e2} - t_{e1})}{\ln \frac{(T_{e1} - t_{e2})}{(T_{e2} - t_{e1})}}$$
$$\Delta Tm_e = \frac{(140 - 72.65) - (79.22 - 10)}{\ln \frac{(140 - 72.65)}{(79.22 - 10)}}$$
$\Delta Tm_e = 2594.83°C$

4.1.3 Laju Perpindahan Panas Cooler

Fluida pendingin HE cooler berasal dari kolam air yang didinginkan menggunakan chiller. Suhu air diatur ke suhu -2°C dan untuk mencegah terjadi pembekuan, kolam diberi agitator agar air selalu bergerak. Fluida yang masuk di sisi panas adalah output sisi dingin HE economizer. Maka dari itu didapatkan:

$T_{c1} = T_{e2}$
$T_{c1} = 79.22\ °C$

$$\rho_{1cd} = \frac{\rho_0}{1 + \beta(T_1 - T_0)}$$
$$\rho_{1cd} = \frac{1030}{1 + 0.0008(79.22 - 20)}$$
$$\rho_{1cd} = 981.50 \text{ kg/m}^3$$
$$\dot{m}_{cd} = 5 \times 980.05$$
$$\dot{m}_{cd} = 4907.5 \text{ kg}$$
$$\dot{m}_{cd} \times Cp_c \times (t_{c2} - t_{c1}) = q$$
$$4907.5\ 3.77 \times (2 - 79.22) = q$$
$$q = -1428668.46 \text{ kJ/h}$$

$$\rho_{1a} = \frac{\rho_0}{1 + \beta(T_1 - T_0)}$$
$$\rho_{1a} = \frac{998.2}{1 + 0.0002(-5 - 20)}$$
$$\rho_{1a} = 1003.22 \text{ kg/m}^3$$
$$\dot{m}_a \times Cp_a \times (T_{c2} - T_{c1}) = q$$
$$\dot{m}_a \times 4.18 \times (60 + 5) = 1428668.46$$
$$\dot{m}_a = 5258.26 \text{ kg/h}$$

$$\Delta Tm_c = \frac{(T_{c1} - t_{c2}) - (T_{c2} - t_{c1})}{\ln \frac{(T_{c1} - t_{c2})}{(T_{c2} - t_{c1})}}$$
$$\Delta Tm_c = \frac{(79.22 - 60) - (2 + 5)}{\ln \frac{(79.22 - 60)}{(2 + 5)}}$$
$$\Delta Tm_c = 12.29°C$$

Dari perhitungan yang telah dilakukan diatas, maka didapatkan data sebagai berikut ini:

Tabel 4.2 Suhu, *flowrate, density,* laju kalor fluida pada tiap HE

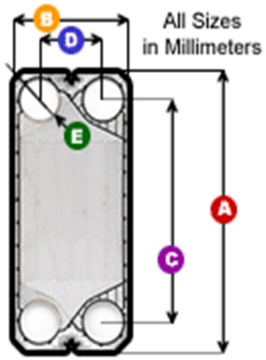
HE	In/Out		Fluida	Temp (°C)	m (kg/h)	q (kJ/h)	ΔTm (°C)
Heater	Hot Side	In	Uap Jenuh	175	600.00	-1,217,400.00	62.77
		Out	Uap Jenuh		600.00	-1,217,400.00	
	Cold Side	In	Susu	72.65	4,923.35	1,217,400.00	
		Out	Susu	140	4,689.80	1,217,400.00	
Economiz	Hot Side	In	Susu	140	4,689.80	-1,223,809.27	2594.83
		Out	Susu	79.22	4,907.50	-1,223,809.27	
	Cold Side	In	Susu	10	5,181.45	1,223,809.27	
		Out	Susu	72.65	4,932.25	1,223,809.27	
Cooler	Hot Side	In	Susu	79.22	4,907.50	-1,428,668.46	12.29
		Out	Susu	2	5,215.10	-1,428,668.46	
	Cold Side	In	Air	-5	5,258.26	1,428,668.46	
		Out	Air	60	5,189.07	1,428,668.46	

4.2 Menghitung Kebutuhan Luas Area HE

Kebutuhan luas HE ditentukan oleh LMTD, koefisien konduksi material, koefisien konveksi fluida, dan laju panas yang terjadi. Semakin besar LMTD, maka semakin kecil kebutuhan luas area HE sehingga biaya yang harus dikeluarkan untuk membeli HE semakin murah. Pada sub bab ini, penulis akan menghitung kebutuhan luas area HE untuk HE Heater, HE Economizer, dan HE Cooler.

4.2.1 Menghitung Kebutuhan Luas Area PHE

Data plat yang digunaan pada perhitungan PHE menggunakan beberapa referensi dan didapatkan data sebagai berikut.



Gambar 4.2 Plat PHE GEA

Tabel 4.3 Dimensi plat PHE GEA

Model	Area	Size A	Size B	Size C	Size D	Size E
GEA VT-4	0.07	549	128	480	61	32
GEA FA-159	0.342	1080	318	984	221	50
GEA VT-10	0.167	785	215	691	118	50
GEA VT-20 P	0.334	1000	338	868	212	75
GEA VT-20 C	0.333	993	340	868	212	78
GEA VT-20	0.332	999	337	868	212	79

Tabel 4.4 Spesifikasi plat PHE yang digunakan

Plate Properties	Simbol	Unit	Value
Material Plate	-		AISI 316
Tebal Plate	x	mm	0.6
Lebar Plate	w	mm	340
Tinggi Plate	L	mm	999
Luas Area Efektif	A	m^2	0.3318
Chevron Angle	-	deg	30
Jarak vertikal port	Lv	mm	868

Jarak horisontal port	Lh	mm	212
Konduktivitas termal plate	k	W/m^2	16.2
Jarak antar plate	d	m	0.005

$$\text{Ø} = \frac{\mathrm{w} \times \mathrm{L}}{\mathrm{A}}$$
$$\text{Ø} = \frac{337 \times 999}{331800}$$
$$\text{Ø} = 1.0147$$

4.2.1.1 Luas Area PHE Heater

a. Hot Side

$$\mathrm{v_s} = \frac{\mathrm{V_s}}{\mathrm{d} \times \mathrm{w}}$$
$$\mathrm{v_s} = \frac{116.5}{0.005 \times 0.337 \times 3600}$$
$$\mathrm{v_s} = 19.21\ \mathrm{m/s}$$

$$\mathrm{Re_s} = \frac{\rho_\mathrm{s} \times \mathrm{v_s} \times \mathrm{d}}{\nu_\mathrm{s}}$$
$$\mathrm{Re_s} = \frac{5.15 \times 19.21 \times 0.05}{0.00001472}$$
$$\mathrm{Re_s} = 33604.45$$

$$\mathrm{Pr_s} = \frac{\mathrm{c_s} \times \nu_\mathrm{s}}{\mathrm{k_s}}$$
$$\mathrm{Pr_s} = \frac{2550 \times 0.00001472}{0.035}$$
$$\mathrm{Pr_s} = 1.07$$

$$\mathrm{Nu_s} = 0.1 \times \mathrm{Re_s}^{0.76} \times \mathrm{Pr_s}^{0.33}$$
$$\mathrm{Nu_s} = 0.1 \times 33604.45^{0.76} \times 1.07^{0.33}$$
$$\mathrm{Nu_s} = 281.68$$

$$h_s = \frac{Nu_s \times k_s}{2 \times d \times \emptyset}$$
$$h_s = \frac{281.68 \times 0.035}{2 \times 0.005 \times 1.0147}$$
$$h_s = 1000.37\ W/m^2.°C$$

b. Cold Side

$$v_{Hc} = \frac{V_{Hc}}{d \times w}$$
$$v_{Hc} = \frac{5}{0.005 \times 0.337 \times 3600}$$
$$v_{Hc} = 0.82\ m/s$$

$$Re_{Hc} = \frac{\rho_{Hc} \times v_{Hc} \times d}{\nu_{Hc}}$$
$$Re_{Hc} = \frac{984.67 \times 0.82 \times 0.05}{0.002}$$
$$Re_{Hc} = 2018.57$$

$$Pr_{Hc} = \frac{c_s \times \nu_s}{k_s}$$
$$Pr_{Hc} = \frac{3770 \times 0.002}{0.53}$$
$$Pr_{Hc} = 14.23$$

$$Nu_{Hc} = 0.1 \times {Re_{Hc}}^{0.76} \times {Pr_{Hc}}^{0.33}$$
$$Nu_{Hc} = 0.1 \times 2018.57^{0.76} \times 14.23^{0.33}$$
$$Nu_{Hc} = 78.05$$

$$h_{Hc} = \frac{Nu_{Hc} \times k_{Hc}}{2 \times d \times \emptyset}$$
$$h_{Hc} = \frac{78.05 \times 0.53}{2 \times 0.005 \times 1.0147}$$
$$h_{Hc} = 4197.46\ W/m^2.°C$$

$$U_H = \frac{1}{{}^{1}/_{h_s} + {}^{x}/_{k} + {}^{1}/_{h_{Hc}}}$$
$$U_H = \frac{1}{{}^{1}/_{1000.37} + {}^{0.0006}/_{16.2} + {}^{1}/_{4197.46}}$$
$$U_H = 784.37\ W/m^2.\,°C$$

$$A_H = \frac{q_H \times SF}{U_H \times \Delta Tm_H}$$
$$A_H = \frac{1217400 \times 1000 \times 1.15}{784.37 \times 62.77 \times 3600}$$
$$A_H = 7.90\ m^2$$

4.2.1.2 Luas Area PHE Economizer

a. Hot Side

$$v_{Eh} = \frac{V_{Eh}}{d \times w}$$
$$v_{Eh} = \frac{5}{0.005 \times 0.337 \times 3600}$$
$$v_{Eh} = 0.82\ m/s$$

$$Re_{Eh} = \frac{\rho_{Eh} \times v_{Eh} \times d}{\nu_{Eh}}$$
$$Re_{Eh} = \frac{937.96 \times 0.82 \times 0.05}{0.002}$$
$$Re_{Eh} = 1922.82$$

$$Pr_{Eh} = \frac{c_{Eh} \times \nu_{Eh}}{k_{Eh}}$$
$$Pr_{Eh} = \frac{3770 \times 0.002}{0.53}$$
$$Pr_{Eh} = 14.23$$

$$Nu_{Eh} = 0.1 \times {Re_{Eh}}^{0.76} \times {Pr_{Eh}}^{0.33}$$

$$\mathrm{Nu_{Eh}} = 0.1 \times 1922.82^{0.76} \times 14.23^{0.33}$$
$$\mathrm{Nu_{Eh}} = 75.22$$

$$\mathrm{h_{Eh}} = \frac{\mathrm{Nu_{Eh}} \times \mathrm{k_{Eh}}}{2 \times \mathrm{d} \times \text{Ø}}$$
$$\mathrm{h_{Eh}} = \frac{75.22 \times 0.53}{2 \times 0.005 \times 1.0147}$$
$$\mathrm{h_{Eh}} = 4045.26\ \mathrm{W/m^2.°C}$$

b. Cold Side

$$\mathrm{v_{Ec}} = \frac{\mathrm{V_{Ec}}}{\mathrm{d} \times \mathrm{w}}$$
$$\mathrm{v_{Ec}} = \frac{5}{0.005 \times 0.337 \times 3600}$$
$$\mathrm{v_{Ec}} = 0.82\ \mathrm{m/s}$$

$$\mathrm{Re_{Ec}} = \frac{\rho_{\mathrm{Ec}} \times \mathrm{v_{Ec}} \times \mathrm{d}}{\nu_{\mathrm{Ec}}}$$
$$\mathrm{Re_{Ec}} = \frac{1036.29 \times 0.82 \times 0.05}{0.002}$$
$$\mathrm{Re_{Ec}} = 2124.39$$

$$\mathrm{Pr_{Ec}} = \frac{\mathrm{c_{Eh}} \times \nu_{\mathrm{Eh}}}{\mathrm{k_{Eh}}}$$
$$\mathrm{Pr_{Ec}} = \frac{3770 \times 0.002}{0.53}$$
$$\mathrm{Pr_{Ec}} = 14.23$$

$$\mathrm{Nu_{Ec}} = 0.1 \times \mathrm{Re_{Ec}}^{0.76} \times \mathrm{Pr_{Ec}}^{0.33}$$
$$\mathrm{Nu_{Ec}} = 0.1 \times 2124.39^{0.76} \times 14.23^{0.33}$$
$$\mathrm{Nu_{Ec}} = 81.14$$

$$\mathrm{h_{Ec}} = \frac{\mathrm{Nu_{Ec}} \times \mathrm{k_{Ec}}}{2 \times \mathrm{d} \times \text{Ø}}$$

$$h_{Ec} = \frac{81.14 \times 0.53}{2 \times 0.005 \times 1.0147}$$
$$h_{Ec} = 4363.64 \text{ W/m}^2.\text{°C}$$

$$U_E = \frac{1}{1/h_{Eh} + x/k + 1/h_{Ec}}$$
$$U_E = \frac{1}{1/4045.26 + 0.0006/16.2 + 1/4363.64}$$
$$U_E = 1947.77 \text{ W/m}^2.\text{°C}$$

$$A_E = \frac{q_E \times SF}{U_E \times \Delta Tm_E}$$
$$A_E = \frac{1223809.27 \times 1000 \times 1.15}{1947.77 \times 2594.83 \times 3600}$$
$$A_E = 0.08 \text{ m}^2$$

4.2.1.3 Luas Area PHE Cooler

a. Hot Side

$$v_{Ch} = \frac{V_{Ch}}{d \times w}$$
$$v_{Ch} = \frac{5}{0.005 \times 0.337 \times 3600}$$
$$v_{Ch} = 0.82 \text{ m/s}$$

$$Re_{Ch} = \frac{\rho_{Ch} \times v_{Ch} \times d}{\nu_{Ch}}$$
$$Re_{Ch} = \frac{981.5 \times 0.82 \times 0.05}{0.002}$$
$$Re_{Ch} = 2012.08$$

$$Pr_{Ch} = \frac{c_{Ch} \times \nu_{Ch}}{k_{Ch}}$$

$$\text{Pr}_{\text{Ch}} = \frac{3770 \times 0.002}{0.53}$$
$$\text{Pr}_{\text{Ch}} = 14.23$$

$$\text{Nu}_{\text{Ch}} = 0.1 \times {\text{Re}_{\text{Ch}}}^{0.76} \times {\text{Pr}_{\text{Ch}}}^{0.33}$$
$$\text{Nu}_{\text{Ch}} = 0.1 \times 2012.08^{0.76} \times 14.23^{0.33}$$
$$\text{Nu}_{\text{Ch}} = 77.86$$

$$\text{h}_{\text{Ch}} = \frac{\text{Nu}_{\text{Ch}} \times \text{k}_{\text{Ch}}}{2 \times \text{d} \times \text{Ø}}$$
$$\text{h}_{\text{Ch}} = \frac{77.86 \times 0.53}{2 \times 0.005 \times 1.0147}$$
$$\text{h}_{\text{Ch}} = 4187.24\ \text{W/m}^2.\text{°C}$$

b. Cold Side

$$\text{v}_{\text{W}} = \frac{\text{V}_{\text{W}}}{\text{d} \times \text{w}}$$
$$\text{v}_{\text{W}} = \frac{5.24}{0.005 \times 0.337 \times 3600}$$
$$\text{v}_{\text{W}} = 0.86\ \text{m/s}$$

$$\text{Re}_{\text{W}} = \frac{\rho_{\text{W}} \times \text{v}_{\text{W}} \times \text{d}}{\nu_{\text{W}}}$$
$$\text{Re}_{\text{W}} = \frac{1003.22 \times 0.86 \times 0.05}{0.002}$$
$$\text{Re}_{\text{W}} = 4313.85$$

$$\text{Pr}_{\text{W}} = \frac{\text{c}_{\text{Ch}} \times \nu_{\text{Ch}}}{\text{k}_{\text{Ch}}}$$
$$\text{Pr}_{\text{W}} = \frac{4180 \times 0.002}{0.613}$$
$$\text{Pr}_{\text{W}} = 6.82$$

$$\text{Nu}_{\text{W}} = 0.1 \times {\text{Re}_{\text{W}}}^{0.76} \times {\text{Pr}_{\text{W}}}^{0.33}$$

$$\mathrm{Nu_W} = 0.1 \times 4313.85^{0.76} \times 6.82^{0.33}$$
$$\mathrm{Nu_W} = 109.06$$

$$h_W = \frac{\mathrm{Nu_W} \times k_W}{2 \times d \times \text{Ø}}$$
$$h_W = \frac{109.06 \times 0.613}{2 \times 0.005 \times 1.0147}$$
$$h_W = 6783.65\ \mathrm{W/m^2.°C}$$

$$U_C = \frac{1}{{}^{1}/_{h_{Ch}} + {}^{x}/_{k} + {}^{1}/_{h_W}}$$
$$U_C = \frac{1}{{}^{1}/_{4187.24} + {}^{0.0006}/_{16.2} + {}^{1}/_{6783.65}}$$
$$U_C = 2362.55\ \mathrm{W/m^2.°C}$$

$$A_C = \frac{q_E \times SF}{U_E \times \Delta Tm_E}$$
$$A_C = \frac{1428668.45 \times 1000 \times 1.15}{2362.55 \times 2381.66 \times 3600}$$
$$A_C = 15.72\ \mathrm{m^2}$$

Dari perhitungan yang telah dilakukan diatas, maka didapatkanlah data pada tabel berikut:

Tabel 4.5 Koefisien Perpinahan Panas dan Luas Area PHE

In/Out	h (W/m².°C)	U (W/m².°C)	A (m²)
Hot Side	1000.37	678.01	9.14
Cold Side	4197.46		
Hot Side	4045.26	1401.73	0.11
Cold Side	4363.64		
Hot Side	4187.24	1604.44	23.14
Cold Side	6783.65		

4.2.2 Menghitung Kebutuhan Luas Area DPHE

Pipa atau tube yang akan digunakan pada perhitungan ini mengambil dari ukuran yang banyak pada pasaran dan menggunakan scheule 40S dari jenis Stainless Steel SUS316. Hal ini agar perbandingan antara PHE dan DPHE bisa *apple to apple*.

Tabel 4.6 Spesifikasi Pipa yang Digunakan

Pipe Properties	Simbol	Unit	Value
Material Pipe	-		AISI 316
Diameter Luar Outer Pipe	D2	mm	88.9
Diameter Dalam Outer Pipe	D1	mm	77.92
Tebal Outer Pipe	xo	mm	5.49
Luas Annular Outer Pipe	Ao	m2	0.00125
Berat Outer Pipe	Wo	kg/m	11.3
Diameter Luar Inner Pipe	Do	mm	73.03
Diameter Dalam Inner Pipe	Di	mm	66.93
Tebal Inner Pipe	x1	mm	3.05
Luas Annular Inner Pipe	Ai	m2	0.00352
Berat Inner Pipe	Wi	kg/m	5.26
Konduktivitas Termal Pipe	k	W/m2	16.2

Tabel 4.7 Spesifikasi pipa stainless steel SUS316

Nominal BORE mm	IN	Nominal O.D mm	SCHEDULE 10S WALL mm	SCHEDULE 10S WEIGHT KG / M	SCHEDULE 10S PRESSURE kPa*	SCHEDULE 40S WALL mm	SCHEDULE 40S WEIGHT KG / M	SCHEDULE 40S PRESSURE kPa*
6	1/8	10.29	1.24	0.277	125139	1.73	0.365	173575
8	1/4	13.72	1.65	0.491	124450	2.24	0.634	168576
10	3/8	17.15	1.65	0.631	99629	2.31	0.845	139446
15	1/2	21.34	2.11	1.000	102214	2.77	1.270	134275
20	3/4	26.67	2.11	1.280	81702	2.87	1.680	111350
25	1	33.40	2.77	2.090	85839	3.38	2.500	104628
32	1 1/4	42.16	2.77	2.690	67913	3.56	3.390	87218
40	1 1/2	48.26	2.77	3.110	59295	3.68	4.050	78945
50	2	60.33	2.77	3.930	47401	3.91	5.440	67224
65	2 1/2	73.03	3.05	5.260	43092	5.16	8.640	73084
80	3	88.90	3.05	6.460	35508	5.49	11.300	63776
100	4	114.30	3.05	8.370	27579	6.02	16.100	54468
125	5	141.30	3.40	11.600	24993	6.55	21.800	47918
150	6	168.28	3.40	13.300	21029	7.11	28.300	43782
200	8	219.08	3.76	20.000	17754	8.18	42.500	38610
250	10	273.05	4.19	27.800	15857	9.27	60.300	35163
300	12	323.85	4.57	36.000	14651	9.52	73.800	30337
350	14	355.60	4.78	41.400	13967			
400	16	406.40	4.78	47.300	12238			
450	18	457.20	4.78	53.300	10859			
500	20	508.00	5.54	68.600	11204			

*Theoretical internal bursting pressure calc

$$D_e = D_1 - D_o$$
$$D_e = 77.92 - 73.03$$
$$D_e = 4.89 \text{ mm}$$
$$D_e = 0.00489 \text{ m}$$

4.2.2.1. Luas Area DPHE Heater

a. Hot Side

$$v_s = \frac{V_s}{A_i}$$
$$v_s = \frac{116.5}{0.00352 \times 3600}$$
$$v_s = 9.19 \text{ m/s}$$

$$Re_s = \frac{\rho_s \times v_s \times D_i}{\nu_s}$$

$$\mathrm{Re_s} = \frac{5.15 \times 9.19 \times 0.06693}{0.00001472}$$
$$\mathrm{Re_s} = 215196.77$$

$$\mathrm{Pr_s} = \frac{c_s \times \nu_s}{k_s}$$
$$\mathrm{Pr_s} = \frac{2550 \times 0.00001472}{0.035}$$
$$\mathrm{Pr_s} = 1.07$$

$$\mathrm{Nu_s} = 0.1 \times \mathrm{Re_s}^{0.76} \times \mathrm{Pr_s}^{0.33}$$
$$\mathrm{Nu_s} = 0.1 \times 215196.77^{0.76} \times 1.07^{0.33}$$
$$\mathrm{Nu_s} = 1155.19$$

$$h_s = \frac{\mathrm{Nu_s} \times k_s}{D_i}$$
$$h_s = \frac{1155.19 \times 0.035}{0.06693}$$
$$h_s = 604.09\ \mathrm{W/m^2.°C}$$

b. Cold Side

$$v_{Hc} = \frac{V_{Hc}}{A_o}$$
$$v_{Hc} = \frac{5}{0.00125 \times 3600}$$
$$v_{Hc} = 1.11\ \mathrm{m/s}$$

$$\mathrm{Re_{Hc}} = \frac{\rho_{Hc} \times v_{Hc} \times D_e}{\nu_{Hc}}$$
$$\mathrm{Re_{Hc}} = \frac{984.67 \times 1.11 \times 0.00489}{0.002}$$
$$\mathrm{Re_{Hc}} = 2672.35$$

$$\mathrm{Pr_{Hc}} = \frac{\mathrm{c_s \times \nu_s}}{\mathrm{k_s}}$$
$$\mathrm{Pr_{Hc}} = \frac{3770 \times 0.002}{0.53}$$
$$\mathrm{Pr_{Hc}} = 14.23$$

$$\mathrm{Nu_{Hc}} = 0.1 \times \mathrm{Re_{Hc}}^{0.76} \times \mathrm{Pr_{Hc}}^{0.33}$$
$$\mathrm{Nu_{Hc}} = 0.1 \times 2672.35^{0.76} \times 14.23^{0.33}$$
$$\mathrm{Nu_{Hc}} = 96.6$$

$$\mathrm{h_{Hc}} = \frac{\mathrm{Nu_{Hc} \times k_{Hc}}}{\mathrm{D_e}}$$
$$\mathrm{h_{Hc}} = \frac{96.6 \times 0.53}{0.00489}$$
$$\mathrm{h_{Hc}} = 10469.94\ \mathrm{W/m^2.{}^\circ C}$$

$$\mathrm{U_H} = \frac{1}{{}^{1}/_{\mathrm{h_s}} + {}^{\mathrm{x}}/_{\mathrm{k}} + {}^{1}/_{\mathrm{h_{Hc}}}}$$
$$\mathrm{U_H} = \frac{1}{{}^{1}/_{108969.61} + {}^{0.00305}/_{16.2} + {}^{1}/_{10469.94}}$$
$$\mathrm{U_H} = 467.47\ \mathrm{W/m^2.{}^\circ C}$$

$$\mathrm{A_H} = \frac{\mathrm{q_H \times SF}}{\mathrm{U_H \times \Delta Tm_H}}$$
$$\mathrm{A_H} = \frac{1217400 \times 1000 \times 1.15}{467.47 \times 62.77 \times 3600}$$
$$\mathrm{A_H} = 13.25\ \mathrm{m^2}$$

4.2.2.2. Luas Area DPHE Economizer

a. Hot Side

$$\mathrm{v_{Eh}} = \frac{\mathrm{V_{Eh}}}{\mathrm{A_i}}$$
$$\mathrm{v_{Eh}} = \frac{5}{0.00352 \times 3600}$$

$$v_{Eh} = 0.39 \text{ m/s}$$

$$Re_{Eh} = \frac{\rho_{Eh} \times v_{Eh} \times D_i}{\nu_{Eh}}$$
$$Re_{Eh} = \frac{937.96 \times 0.39 \times 0.06693}{0.002}$$
$$Re_{Eh} = 12241.64$$

$$Pr_{Eh} = \frac{c_{Eh} \times \nu_{Eh}}{k_{Eh}}$$
$$Pr_{Eh} = \frac{3770 \times 0.002}{0.53}$$
$$Pr_{Eh} = 14.23$$

$$Nu_{Eh} = 0.1 \times {Re_{Eh}}^{0.76} \times {Pr_{Eh}}^{0.33}$$
$$Nu_{Eh} = 0.1 \times 12241.64^{0.76} \times 14.23^{0.33}$$
$$Nu_{Eh} = 307.13$$

$$h_{Eh} = \frac{Nu_{Eh} \times k_{Eh}}{D_i}$$
$$h_{Eh} = \frac{307.13 \times 0.53}{0.06693}$$
$$h_{Eh} = 33288.12 \text{ W/m}^2.°\text{C}$$

b. Cold Side

$$v_{Ec} = \frac{V_{Ec}}{A_o}$$
$$v_{Ec} = \frac{5}{0.00125 \times 3600}$$
$$v_{Ec} = 1.11 \text{ m/s}$$

$$Re_{Ec} = \frac{\rho_{Ec} \times v_{Ec} \times D_e}{\nu_{Ec}}$$

$$Re_{Ec} = \frac{1036.29 \times 1.11 \times 0.00489}{0.002}$$
$$Re_{Ec} = 2812.44$$
$$Pr_{Ec} = \frac{c_{Eh} \times \nu_{Eh}}{k_{Eh}}$$
$$Pr_{Ec} = \frac{3770 \times 0.002}{0.53}$$
$$Pr_{Ec} = 14.23$$

$$Nu_{Ec} = 0.1 \times {Re_{Ec}}^{0.76} \times {Pr_{Ec}}^{0.33}$$
$$Nu_{Ec} = 0.1 \times 2812.44^{0.76} \times 14.23^{0.33}$$
$$Nu_{Ec} = 100.43$$

$$h_{Ec} = \frac{Nu_{Ec} \times k_{Ec}}{D_e}$$
$$h_{Ec} = \frac{100.43 \times 0.53}{0.00489}$$
$$h_{Ec} = 795.28\ \mathrm{W/m^2.°C}$$

$$U_E = \frac{1}{1/h_{Eh} + x/k + 1/h_{Ec}}$$
$$U_E = \frac{1}{1/33288.12 + 0.00305/16.2 + 1/795.28}$$
$$U_E = 596.75\ \mathrm{W/m^2.°C}$$

$$A_E = \frac{q_E \times SF}{U_E \times \Delta Tm_E}$$
$$A_E = \frac{1223809.27 \times 1000 \times 1.15}{596.75 \times 2594.83 \times 3600}$$
$$A_E = 0.25\ \mathrm{m^2}$$

4.2.2.3. Luas Area DPHE Cooler

a. Hot Side

$$v_{Ch} = \frac{V_{Ch}}{A_o}$$
$$v_{Ch} = \frac{5}{0.00125 \times 3600}$$
$$v_{Ch} = 1.11 \text{ m/s}$$

$$Re_{Ch} = \frac{\rho_{Ch} \times v_{Ch} \times D_e}{\nu_{Ch}}$$
$$Re_{Ch} = \frac{981.5 \times 1.11 \times 0.00489}{0.002}$$
$$Re_{Ch} = 2663.74$$

$$Pr_{Ch} = \frac{c_{Ch} \times \nu_{Ch}}{k_{Ch}}$$
$$Pr_{Ch} = \frac{3770 \times 0.002}{0.53}$$
$$Pr_{Ch} = 14.23$$

$$Nu_{Ch} = 0.1 \times {Re_{Ch}}^{0.76} \times {Pr_{Ch}}^{0.33}$$
$$Nu_{Ch} = 0.1 \times 2663.74^{0.76} \times 14.23^{0.33}$$
$$Nu_{Ch} = 96.37$$

$$h_{Ch} = \frac{Nu_{Ch} \times k_{Ch}}{D_e}$$
$$h_{Ch} = \frac{96.37 \times 0.53}{0.00489}$$
$$h_{Ch} = 10445.01 \text{ W/m}^2.\text{°C}$$

b. Cold Side

$$v_W = \frac{V_W}{A_i}$$
$$v_W = \frac{5.24}{0.00352 \times 3600}$$
$$v_W = 0.41 \text{ m/s}$$

$$\mathrm{Re_W} = \frac{\rho_W \times v_W \times D_i}{\nu_W}$$
$$\mathrm{Re_W} = \frac{1003.22 \times 0.41 \times 0.06693}{0.002}$$
$$\mathrm{Re_W} = 27529.66$$

$$\mathrm{Pr_W} = \frac{c_{Ch} \times \nu_{Ch}}{k_{Ch}}$$
$$\mathrm{Pr_W} = \frac{4180 \times 0.002}{0.613}$$
$$\mathrm{Pr_W} = 6.82$$

$$\mathrm{Nu_W} = 0.1 \times \mathrm{Re_W}^{0.76} \times \mathrm{Pr_W}^{0.33}$$
$$\mathrm{Nu_W} = 0.1 \times 27529.66^{0.76} \times 6.82^{0.33}$$
$$\mathrm{Nu_W} = 446.06$$

$$h_W = \frac{\mathrm{Nu_W} \times k_W}{D_i}$$
$$h_W = \frac{446.06 \times 0.613}{0.0409}$$
$$h_W = 4085.38\ \mathrm{W/m^2.{}^\circ C}$$

$$U_C = \frac{1}{1/h_{Ch} + x/k + 1/h_W}$$
$$U_C = \frac{1}{1/10445.01 + 0.00305/16.2 + 1/4085.38}$$
$$U_C = 1372.14\ \mathrm{W/m^2.{}^\circ C}$$

$$A_C = \frac{q_E \times SF}{U_E \times \Delta Tm_E}$$
$$A_C = \frac{1428668.45 \times 1000 \times 1.15}{1372.14 \times 2381.66 \times 3600}$$
$$A_C = 27.06\ \mathrm{m^2}$$

Dari perhitungan yang telah dilakukan diatas, maka didapatkanlah data sebagai berikut:

Tabel 4.8 Koefisien Perpindahan Panas dan Luas Area DPHE

In/Out	h (W/m².°C)	U (W/m².°C)	A (m²)
Hot Side	1000.37	678.01	9.14
Cold Side	4197.46		
Hot Side	4045.26	1401.73	0.11
Cold Side	4363.64		
Hot Side	4187.24	1604.44	23.14
Cold Side	6783.65		

Setelah menghitung luas area yang dibutuhkan pada DPHE, maka selanjutnya adalah memastikan dimensi pipa yang dipilih sudah tepat. Hal ini dapat dilakukan dengan menghitung *pressure drop* pada aliran didalam pipa. Adapun ketentuannya adalah sebagai berikut:

Tabel 4.9 Batas *Pressure Drop*

Fluida	Pressure Drop (psi)
Aliran cair tanpa perubahan fase	10
Aliran uap tanpa perubahan fase	2
Aliran kondensasi	2
Aliran cair yang mendidih	1

$$L_H = \frac{A_H \times 1000}{3.14 \times \left(D_i + {}^{x_1}/_2\right)}$$

$$L_H = \frac{13.25 \times 1000}{3.14 \times \left(66.93 + {}^{3.05}/_2\right)}$$

$$L_H = 60.30 \text{ m}$$

$$PD_{Hh} = \frac{0.6753 \times 10^6 \times {m_s}^2 \times L_H \times \left(1 + {}^{91.4}/_{D_i}\right)}{\rho \times {D_i}^5}$$
$$PD_{Hh} = \frac{0.6753 \times 10^6 \times 600^2 \times 60.30 \times \left(1 + {}^{91.4}/_{66.93}\right)}{5.15 \times 66.93^5}$$
$$PD_{Hh} = 5013.52 \text{ Pa}$$
$$PD_{Hh} = 0.73 \text{ Psi}$$

$$f_{Hc} = 0.3673 \times {Re_{Hc}}^{-0.2314}$$
$$f_{Hc} = 0.3673 \times 2672.35^{-0.2314}$$
$$f_{Hc} = 0.0592$$

$$PD_{Hc} = \frac{f_{Hc} \times L_H \times {v_{Hc}}^2}{D_e \times 2}$$
$$PD_{Hc} = \frac{0.0592 \times 60.30 \times 1.11^2}{0.00489 \times 2}$$
$$PD_{Hc} = 449.72 \text{ Pa}$$
$$PD_{Hc} = 0.06523 \text{ Psi}$$

$$L_E = \frac{A_E \times 1000}{3.14 \times \left(D_i + {}^{x_1}/_2\right)}$$
$$L_E = \frac{A_E \times 1000}{3.14 \times \left(66.93 + {}^{3.05}/_2\right)}$$
$$L_E = 1.14 \text{ m}$$

$$f_{Eh} = 0.3673 \times {Re_{Eh}}^{-0.2314}$$
$$f_{Eh} = 0.3673 \times 12241.64^{-0.2314}$$
$$f_{Eh} = 0.0416$$

$$PD_{Eh} = \frac{f_{Eh} \times L_E \times {v_{Eh}}^2}{D_i \times 2}$$
$$PD_{Eh} = \frac{0.0416 \times 1.14 \times 0.39^2}{0.06693 \times 2}$$

$$PD_{Eh} = 0.05378 \text{ Pa}$$
$$PD_{Eh} = 0.00001 \text{ Psi}$$

$$f_{Ec} = 0.3673 \times {Re_{Ec}}^{-0.2314}$$
$$f_{Ec} = 0.3673 \times 2812.44^{-0.2314}$$
$$f_{Ec} = 0.61261$$

$$PD_{Ec} = \frac{f_{Ec} \times L_E \times {v_{Ec}}^2}{D_e \times 2}$$
$$PD_{Ec} = \frac{0.61261 \times 0.0416 \times 1.11^2}{0.00489 \times 2}$$
$$PD_{Ec} = 0.61261 \text{ Pa}$$
$$PD_{Ec} = 0.00009 \text{ Psi}$$

$$L_C = \frac{A_C \times 1000}{3.14 \times \left(D_i + {}^{x_1}/_2\right)}$$
$$L_C = \frac{27.06 \times 1000}{3.14 \times \left(66.93 + {}^{3.05}/_2\right)}$$
$$L_C = 123.15 \text{ m}$$

$$f_{Ch} = 0.3673 \times {Re_{Ch}}^{-0.2314}$$
$$f_{Ch} = 0.3673 \times 2663.74^{-0.2314}$$
$$f_{Ch} = 0.0592$$

$$PD_{Ch} = \frac{f_{Ch} \times L_C \times {v_{Ch}}^2}{D_e \times 2}$$
$$PD_{Eh} = \frac{0.0416 \times 123.15 \times 1.11^2}{0.00489 \times 2}$$
$$PD_{Eh} = 918.44 \text{ Pa}$$
$$PD_{Eh} = 0.13321 \text{ Psi}$$

$$f_{Cc} = 0.3673 \times {Re_{Cc}}^{-0.2314}$$
$$f_{Cc} = 0.3673 \times 27529.66^{-0.2314}$$

$$f_{Ch} = 0.0345$$

$$PD_{Cc} = \frac{f_{Cc} \times L_C \times v_{Cc}^2}{D_i \times 2}$$

$$PD_{Eh} = \frac{0.0416 \times 123.15 \times 1.11^2}{0.06693 \times 2}$$

$$PD_{Eh} = 5.33532Pa$$

$$PD_{Eh} = 0.00077\ Psi$$

Dari perhitungan diatas, didapatkan hasil sebagai berikut. Pressure drop pada setiap sisi DPHE menunjukkan bahwa pemilihan dimensi pipa yang digunakan sudah sesuai atau dibawah batas pressure drop yang diijinkan.

Tabel 4.9 Batas *Pressure Drop*

Fluida	L (m)	PD (psi)	PD Limit (psi)	Keterangan
Uap Jenuh	60.30	0.73	2.00	Sesuai
Air susu		0.07	10.00	Sesuai
Air susu	1.14	0.00	10.00	Sesuai
Air susu		0.00	10.00	Sesuai
Air susu	123.15	0.13	10.00	Sesuai
Air		0.00	10.00	Sesuai