Delft University of Technology

Equipment for Heat and Mass Transfer
ME45165

Equipment for Heat Transfer - Assignment 2

Design of plate heat exchanger
E350 - Water-heated ammonia evaporator

Authors

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Design Procedure

Steps:

1. Calculate duty, the rate of heat transfer required.

2. If the specification is incomplete, determine the unknown fluid temperature or fluid flow rate from a heat balance.

3. Calculate the log mean temperature difference, ΔT_{lm}.

4. Determine the log mean temperature correction factor, F_t.

5. Calculate the corrected mean temperature difference, $\Delta T_m = F_t \times \Delta T_{lm}$.

6. Estimate the overall heat-transfer coefficient.

7. Calculate the surface area required.

8. Determine the number of plates required = total surface area/area of one plate.

9. Decide the flow arrangement and number of passes.

10. Calculate the film heat-transfer coefficients for each stream.

11. Calculate the overall coefficient, allowing for fouling factors.

12. Compare the calculated with the assumed overall coefficient. If satisfactory, say -10% to $+10\%$ error, proceed. If unsatisfactory, return to step 8 and increase or decrease the number of plates.

13. Check the pressure drop for each stream.

Step 1

1.1 Specification

The given specifications for the design of E350 plate heat exchanger are as follows:

S.No.	Fluid	Phase Change	Flow Rate (kg/s)	Temperature In (°C)	Temperature Out (°C)
1	Ammonia	Evaporating	15	23.5	23.5
2	Water	1-Phase	1400	28	-

Table 1: Given Fluid Properties

1.2 Determination of Duty

An estimate of the heat duty (total heat transferred) can be determined from the following equation. Due to evaporation (phase change) in the fluid, the duty can be determined by the product of mass flow rate and change in enthalpies of the fluid undergoing phase change.

$$\dot{Q} = \dot{m}_{amm}(h_{amm,g} - h_{amm,l}) \tag{1}$$

From the property table for ammonia, we determine $h_{amm,g}$ = 1625.7 kJ/kg and $h_{amm,l}$ = 453.64 kJ/kg. Substituting the obtained values in Equation (1), we get,

$$\boxed{\dot{Q} = 17.58 \text{ MW}} \tag{2}$$

Step 2

2.1 Physical Properties

The physical properties of the working fluids, ammonia and water, are determined at their arithmetic mean temperatures and tabulated below.

S. No.	Property	Symbol	Units	Fluid	
				Ammonia	Water
1	Liquid Density	ρ_l	kg/m^3	605.01	996.61
2	Vapor Density	ρ_v	kg/m^3	7.4613	-
3	Liquid Dynamic Viscosity	μ_l	Pa s	1.3363e-4	8.6047e-4
4	Vapor Dynamic Viscosity	μ_v	Pa s	9.7869e-6	-
5	Liquid Thermal Conductivity	k_l	W/mK	0.4898	0.60969
6	Liquid Specific Heat Capacity	$C_{p,l}$	J/kg	4772.1	4180.6

Table 2: Physical Properties

2.2 Determination of outlet temperature of water

Performing an energy balance on the system, we can determine the outlet temperature of water as follows.

$$\dot{Q} = \dot{m}_w \; C_{p,w} \; (T_{in,w} - T_{out,w})$$

$$\implies \quad T_{out,w} = T_{in,w} - \frac{\dot{Q}}{\dot{m}_w \; C_{p,w}}$$

$$\therefore \quad \boxed{T_{out,w} = 298.1462 \text{ K} = 24.9962 \text{ °C}} \tag{3}$$

Step 3

Determination of LMTD

Assuming counter current flow, the logarithmic mean temperature difference is determined using the relation given below.

$$\Delta T_{lm} = \frac{(T_{in,w} - T_{out,amm}) - (T_{out,w} - T_{in,amm})}{\ln\left(\dfrac{T_{in,w} - T_{out,amm}}{T_{out,w} - T_{in,amm}}\right)}$$

Substituting the required values, we get,

$$\boxed{\Delta T_{lm} = 2.728\ ^\circ\mathrm{C}} \tag{4}$$

Step 4

Estimation of LMTD correction factor

For plate heat exchangers, the LMTD correction factor is a function of number of transfer units (NTU) and the flow arangement (number of passes) as shown in figure 1.

The number of transfer units (NTU) is given by the following equation.

$$NTU = \frac{T_{in,w} - T_{out,w}}{\Delta T_{lm}}$$

$$\boxed{NTU = 1.1012} \tag{5}$$

Assuming *1 pass/1 pass (1-1)*, the LMTD correction factor F_t can be obtained from the figure given below.

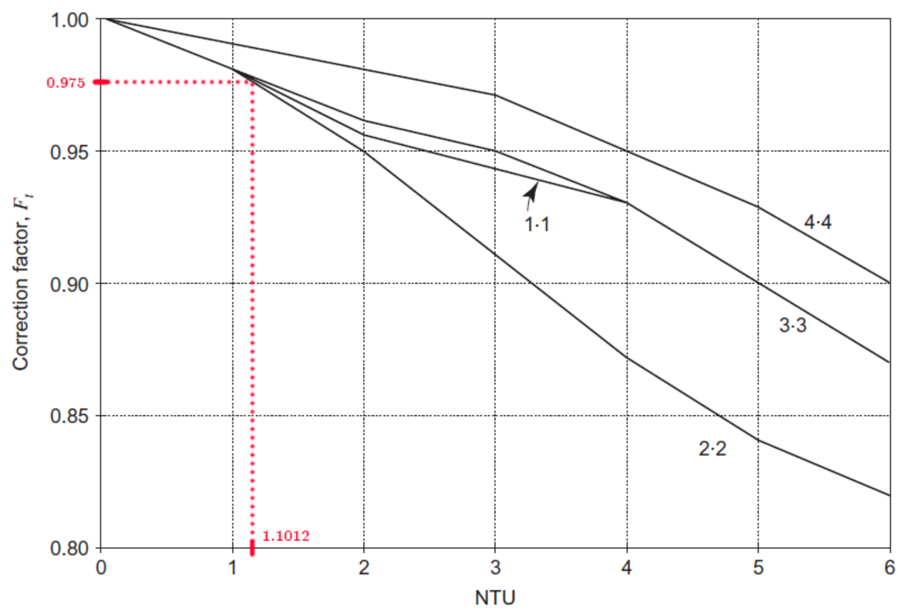


Figure 1: Correction factor for plate heat exchanger

$$\boxed{F_t = 0.975} \tag{6}$$

Step 5

Estimation of corrected mean temperature difference

The corrected mean temperature difference ΔT_m can be calculated using the below given expression.

$$\Delta T_m = F_t \times \Delta T_{lm}$$

$$\boxed{\Delta T_m = 2.6597\ ^\circ\mathrm{C}} \tag{7}$$

Step 6

Assumption of overall heat transfer coefficient

The initial value of the overall heat transfer coefficient is assumed as 2000 $\mathrm{W/m^2K}$ considering corrugated plates as shown in the figure given below.

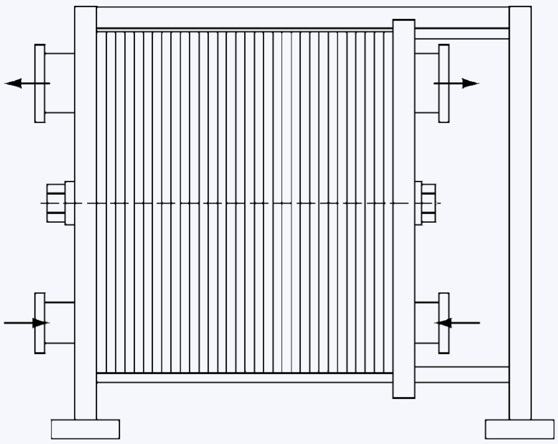
Type of exchanger	Conditions of heat transfer	Typical *k* value ($\mathrm{W/m^2\ K}$)
Plate heat exchanger Plate heat exchanger 	Flat channels, gas to water	20–60
	Flat channels, liquid to water	350–1,200
	Corrugated plates, liquid to liquid	1,000–4,000

Figure 2: Overall heat transfer coefficient

$$\boxed{U_{ass} = 2000\ \mathrm{W/m^2K}} \tag{8}$$

Step 7

Calculation of surface area

The surface area of heat transfer can be computed from the assumed heat transfer coefficient using the following relation.

$$A = \frac{\dot{Q}}{U_{ass}\ \Delta T_m}$$

Substituting the values of U_{ass} and ΔT_m, we get,

$$\boxed{A = 3305.1\ \mathrm{m^2}} \tag{9}$$

Step 8

8.1 Plate design

The plate design is made by considering suitable geometric parameters as listed below. The plate material is considered as Stainless Steel and Chevron-type.

Parameters	Symbols	Units	Values
Inclination Angle	β	deg	45
Plate Length	L_p	mm	2.8
Plate Width	B_p	mm	1.4
Plate Thickness	T_p	mm	1
Water Channel Spacing	$S_{p,w}$	mm	5
Ammonia Channel Spacing	$S_{p,a}$	mm	5
Enlargement Factor	ϕ	-	1.22

Table 3: Plate design parameters

8.2 Determination of number of plates

The total number of plates can be found as given below.

$$\text{Number of plates} = \frac{\text{Total heat transfer area}}{\text{Effective area of one plate}}$$

Area of one plate, $A_p = \phi L_p B_p = 4.7824\ m^2$
Total number of plates, $N_p = 691$
Effective number of plates, $N_{eff} = N_p - 2 = 689$

We assume the total number of heat exchangers as 5.
Total number of plates per heat exchanger, $N_{p_{hex}} = 139$
Total number of channels, $N_c = \dfrac{N_p - 1}{2N_{pass}} = 345$
Number of channels per heat exchanger, $N_{c_{hex}} = 69$

Step 9

Flow arrangement and number of passes

The flow arrangement is considered to be *1 pass/1 pass* ($N_{pass} = 1$) with both the fluids entering and exiting on the same side in a counter current flow as shown in Figure 3. It is the most common and convenient arrangement when it comes to adding more plates in the future as there is no need to alter the pipe layout in this case.

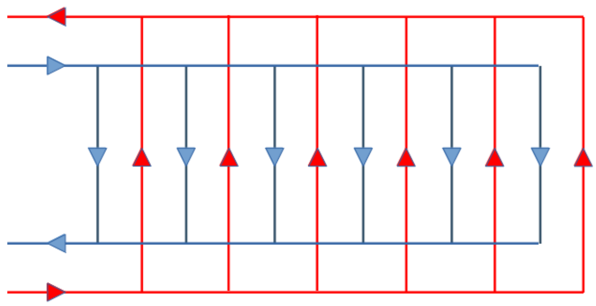


Figure 3: Flow arrangement (1-1)

Step 10

10.1 Calculation of heat transfer coefficient - Water

The correlations for heat transfer coefficients given by different investigators are shown below.

Investigator	**Correlation**	**Validation range**
Sinnott [53]	$\alpha_{sp,i} = \frac{\lambda_i}{d_e} 0.26 Re_i^{0.65} Pr_i^{0.4}$ (2.7)	Turbulent flow in a typical plate
VDI Heat Atlas [64]	$\alpha_{sp,i} = \frac{\lambda_i}{d_e} 1.615 [(\xi Re_{VDI,i}/64) Re_{VDI,i} Pr_i d_e / L_p]^{1/3}$ (2.8)	60 < Re < 30,000
Winkelmann [71]	$\alpha_{sp,i} = \frac{\lambda_i}{d_e} 0.60 Re_i^{0.51} Pr_i^c$ (2.9) $\alpha_{sp,i} = \frac{\lambda_i}{d_e} 0.22 Re_i^{0.68} Pr_i^c$ (2.10) $c = 0.4$ (2.11) (if fluid is being heated) $c = 1/3$ (2.12) (if fluid is being cooled)	10 < Re < 450 450 < Re < 13,000
Yan et al. [73]	$\alpha_{sp,i} = \frac{\lambda_i}{d_e} 0.2121 Re_i^{0.78} Pr_i^{1/3}$ (2.13)	Re > 200
Donowski and Kandlikar [15]	$\alpha_{sp,i} = \frac{\lambda_i}{d_e} 0.2875 Re_i^{0.78} Pr_i^{1/3}$ (2.14)	Re > 200

Figure 4: Correlations of heat transfer coefficients for single phase flow

Hydraulic diameter, $d_e = \frac{2S_{p_w}}{\phi} = 8.2\ mm$
Surface area of cross-section, $A_{cs} = S_{p_w} B_p = 0.0085\ m^2$

The channel velocity of water can be determined from the relation given below.

$$u_w = \frac{\dot{m}_w}{\rho_w A_{cs} N_c}$$

$$\boxed{u_w = 0.58 \text{ m/s}} \tag{10}$$

The Reynolds number for water can be determined using the expression given below.

$$Re_w = \frac{\rho_w u_w d_e}{\mu_w}$$

$$\boxed{Re_w = 5506.3} \tag{11}$$

The heat transfer coefficients are calculated using the correlations given in the figure above. Note that all the correlations are applicable for the Reynolds number obtained in this case.

Investigators	**Heat Transfer Coefficient** (in W/m^2K)
Sinnott	9.3547e+03
VDI Heat Atlas	2.2792e+03
Winkelmann	9.0523e+03
Yan et al	2.0251e+04
Donowski and Kandlikar	2.7451e+04

Table 4: Heat transfer coefficients for water

10.2 Calculation of heat transfer coefficient - Ammonia

The correlations for heat transfer coefficients given by different investigators for evaporators are shown below.

Investigator	Correlation	Validation range
Yan & Lin [72]	$\alpha_{evap,i} = \frac{\lambda_l}{d_e} 1.926 Re_{eq,i} Re_i^{-0.5} Pr_{l,i}^{1/3} Bo_{eq,i}^{-0.3}$ (2.30)	$Re > 200$
Yan & Lin times factor 10	$\alpha_{evap,i} = \frac{\lambda_l}{d_e} 19.26 Re_{eq,i} Re_i^{-0.5} Pr_{l,i}^{1/3} Bo_{eq,i}^{-0.3}$ (2.31)	$Re > 200$
Donowski and Kandlikar [15]	$\alpha_{evap,i} = 1.055[1.056 Co_i^{-0.4} + 1.02 Bo_i^{0.9}] q^{-0.12} \alpha_l^{0.98}$ (2.32)	$Re > 200$
	$\alpha_{evap,i} = [1.184 Co_i^{-0.3} + 225.5 Bo_i^{2.8}](1-q)^{0.0003} \alpha_l$ (2.33)	$Re > 200$ (another fit)
	$Co = (\rho_g / \rho_l)^{0.5} ((1-q)/q)^{0.8}$ (2.34)	
	$\alpha_l = 0.02875 Re^{0.78} Pr^{1/3} \frac{\lambda_l}{d_e}$ (2.35)	
Ayub [6]	$\alpha_{evap,i} = 0.025 C \frac{\lambda_l}{d_e} [Re_i^2 h_{lv} / L_p]^{0.4124} (P/P_c)^{0.12} (65/\beta)^{0.35}$ (2.36) C=0.1121 for flooded and thermo-syphon C=0.0675 for direct expansion	No limit defined
Okamota [46]	$\frac{\alpha_{evap,i}}{\alpha_l} = E(1/X_{tt})^m$ (2.37) $\alpha_l = 0.023 \frac{\lambda_l}{d_e} \left[\frac{G(1-q)d_e}{\mu_l}\right]^{0.8} Pr_l^{0.4}$ (2.38)	$200 < Re < 400$
Ventura [67]	$\alpha_{evap,i} = 1.92 \frac{\lambda}{d_e} Re_{eq}^{0.885} Pr^{1/3} Bo_{eq}^{0.536} z^{-22.3}$ (2.39)	$10 < Re < 200$
Palmer et al. [48]	$\alpha_{evap,i} = 2.7 \frac{\lambda}{d_e} Re_l^{0.55} Pr_l^{0.5}$ (2.40)	$13 < Re < 230$

Figure 5: Correlations of heat transfer coefficients for evaporator

Hydraulic diameter, $d_{amm,e} = \frac{2S_{p_a}}{\phi} = 8.2\ mm$

Surface area of cross-section, $A_{cs,amm} = S_{p_a} B_p = 0.0085\ m^2$

The channel velocity of ammonia can be determined from the relation given below.

$$u_{amm,l} = \frac{\dot{m}_{amm}}{\rho_{amm,l} A_{cs,amm} N_c}$$

$$\boxed{u_{amm,l} = 0.0084\ m/s} \tag{12}$$

The Reynolds number for ammonia (liquid) can be determined using the expression given below.

$$Re_{amm,l} = \frac{\rho_{amm,l} u_{amm,l} d_{amm,e}}{\mu_{amm,l}}$$

$$\boxed{Re_{amm,l} = 311.382} \tag{13}$$

The equivalent Reynolds number for ammonia assuming vapor quality as 0.5 can be determined using the expression given below.

$$Re_{eq} = \frac{G_{eq} d_e}{\mu_{amm,l}}$$

$$\boxed{Re_{eq} = 1557.7} \tag{14}$$

The heat transfer coefficients are calculated using the correlations given in the figure above. Note that all the correlations are applicable for the Reynolds number obtained in this case.

Investigators	**Heat Transfer Coefficient** (in W/m^2K)
Donowski and Kandlikar I	436.2421
Donowski and Kandlikar II	378.9377
Palmer et al	4.3355e+03

Table 5: Heat transfer coefficients for ammonia

Step 11

Calculation of overall heat transfer coefficient

The overall heat transfer coefficient U_0 can be calculated from the below given equation.

$$\frac{1}{U} = \frac{1}{\alpha_{amm}} + \frac{1}{f_{amm}} + \frac{T_p}{k_m} + \frac{1}{f_{water}} + \frac{1}{\alpha_{water}} \tag{15}$$

where

α_{amm} is the heat transfer coefficient for ammonia channels
α_{water} is the heat transfer coefficient for water channels
f_{amm} is the fouling factor for ammonia
f_{water} is the fouling factor for water
k_m is the conductivity of the material of the plate
T_p is the thickness of the plate

The fouling factors of water and ammonia are taken from the tables as 6000 W/m^{2}K and 5000 W/m^{2}K respectively. The values of heat transfer coefficient for water are taken from the correlation given by Sinnott as seen in Table 4 whereas the correlation given by Palmer et al from Table 5 is chosen for ammonia. Substituting the values in the above equation, we get,

$$\boxed{U = 1384.4 \text{ W/m}^2\text{K}} \tag{16}$$

Step 12

Calculation of error

The following condition is checked in order to justify our assumption of U.

$$0\% < \left| \frac{U - U_{ass}}{U_{ass}} \right| \times 100\% < 30\% \tag{17}$$

The error between the calculated and assumed value of overall heat transfer coefficient is found to be 30.7795%. The obtained value of U is very low for a flat plate heat exchanger and the percentile of error is also higher than the acceptable limits. Hence, some changes have to be made in the design to increase the value of U.

One of the major design changes was to incorporate a different channel spacing for the ammonia channel. This step has been performed to increase the velocity of the flow in the ammonia channel. Hence, a smaller value of $S_{p,a} = 1.5$ mm is used. Once the design changes were made, the correlation from Yan and Lin for estimation of heat transfer coefficient of ammonia was more suitable and hence, it was chosen. After the required modifications, the following parameter values are obtained for which the overall heat transfer coefficient is sufficient and acceptable for flat plate heat exchangers.

Parameters	**Symbols**	**Units**	**Values**
Design Parameters			
Inclination Angle	β	deg	45
Plate Length	L_p	m	2.8
Plate Width	B_p	m	1.4
Plate Thickness	T_p	mm	1
Area of Single Plate	A_p	m^2	4.7824
Water Channel Spacing	$S_{p,w}$	mm	5
Ammonia Channel Spacing	$S_{p,a}$	mm	1.5
Number of Plates	N_p	-	530
Number of Heat Exchangers	N_{hex}	-	10
Number of Plates per Heat Exchanger	$N_{p,hex}$	-	53
Total Number of Channels per Fluid	N_c	-	260
Number of Channels per Heat Exchanger	$N_{c,hex}$	-	52
Operational Parameters			
Heat Transfer Area	A	m^2	3305.1
Velocity of Water	u_w	m/s	0.7718
Velocity of Ammonia at Inlet	$u_{amm,in}$	m/s	0.0372
Velocity of Ammonia at Outlet	$u_{amm,out}$	m/s	3.018
Reynolds Number of Water	Re_w	-	7327.6
Reynolds Number of Ammonia at Inlet	$Re_{amm,in}$	-	414.3776
Reynolds Number of Ammonia at Outlet	$Re_{amm,out}$	-	5657.9
Heat Transfer Coefficient - Ammonia	α_{amm}	W/m^2K	2.049e+4
Heat Transfer Coefficient - Water	α_{water}	W/m^2K	1.2794e+4
Overall Heat Transfer Coefficient	U	W/m^2K	1956.3
Error	-	%	2.1861

Table 6: Values of parameters obtained after final iteration

Step 13

13.1 Determination of pressure drop - Water

The pressure drop is computed using the expression given below.

$$\Delta P = 2 f_w \rho_w u_w^2 \left(\frac{L_p}{d_e} \right) \tag{18}$$

The correlations for the friction factor given by different investigators are shown below.

Investigator	Correlation	Validation range
VDI Heat Atlas [64]	$\frac{1}{\sqrt{\xi}} = \frac{cos(\varphi)}{\sqrt{0.18tan(\varphi) + 0.36sin(\varphi) + \xi_0(Re_{VDI})/cos(\varphi)}} + \frac{1-cos(\varphi)}{\sqrt{3.8\xi_1(Re_{VDI})}}$ (2.46) $\xi_0 = \frac{64}{Re_{VDI}}$ (2.47) $\xi_1 = \frac{597}{Re_{VDI}} + 3.85$ (2.48)	$Re_{VDI} < 2000$
Kumar [35]	$f = 19.40Re^{-0.589}$ (2.49) $f = 2.990Re^{-0.183}$ (2.50)	$10 < Re < 100$ $Re > 100$ $\beta \leq 30°$
Wanniarachchi et al. [68]	$f = [f_1^3 + f_t^3]^{1/3}$ (2.51) $f_1 = 1774\beta^{-1.026}\Phi^2 Re^{-1}$ (2.52) $f_t = 46.6\beta^{-1.08}\Phi^{1+s}Re^{-s}$ (2.53) $s = 0.00423\beta + 0.0000223\beta^2$ (2.54)	$1 < Re < 10{,}000$ $20° < \beta < 62°$
Thonon [61]	$f = 45.57Re^{-0.670}$ (2.55) $f = 0.370Re^{-0.172}$ (2.56)	$Re < 160$ $Re > 160$
Focke et al. [16]	$f = 45.57Re^{-0.670}$ (2.57) $f = 6.7Re^{-0.209}$ (2.58)	$90 < Re < 400$ $400 < Re < 16{,}000$

Figure 6: Correlations of friction factors for single phase

Additionally, the pressure drop at the port has to be determined. The port diameter is assumed 0.3 m. Hence, the pressure drop at the port can be calculated as below.

$$A_{pt,water} = \frac{\pi d_{pt,water}^2}{4}$$

$$u_{pt,water} = \frac{\dot{m}}{\rho_w A_{pt} N_{hex}}$$

$$\Delta P_{pt,water} = 0.65\rho_w^2 u_{pt}^2$$

$$\therefore \quad \boxed{\Delta P_{pt,water} = 2.5585 \text{ kPa} = 0.02 \text{ bar}} \tag{19}$$

The correlations that are applicable for the current design are determined. The total pressure drop is then calculated as the sum of the pressure drop obtained from the correlations and the port pressure drop. The sum is then tabulated as below.

Investigators	**Pressure Drop** (in bar)
Thonon	0.3503
Focke	1.02
Sinnott and Towler	0.3627
VDI Heat Atlas	0.855

Table 7: Pressure drop values for water

It can be seen from the table that the values of pressure drop vary significantly with the correlation. However, the maximum pressure drop predicted is approximately 1 bar which is the upper limit for pressure. Also to be noted is that the mean pressure drop with different correlations is significantly lower and the design may be considered to be safe. The value from Sinnott and Towler is chosen as an optimal value for pressure drop for water and hence,

$$\boxed{\Delta P_{tot,water} = 0.3627 \text{ bar}} \tag{20}$$

13.2 Determination of pressure drop - Ammonia

The pressure drop is computed using the expression given below.

$$\Delta P = 2f\rho_{amm}u_{amm}^2\left(\frac{L_p}{d_e}\right) \tag{21}$$

The correlations for the friction factor given by different investigators are shown below.

Investigator	**Correlation**	**Validation range**
Ayub [6]	$f = (2.99Re^{-0.137})(-1.89 + 6.56(\beta/30) - 3.69(\beta/30)^2)$ (2.59)	Re < 4000 30° < β <65°
Han et al. [20]	$f = Ge_3 Re_{eq}^{Ge_4}$ (2.60) $Ge_3 = 64,710(\frac{p_{co}}{d_e})^{-5.27}(\frac{\pi}{2} - \beta)^{-3.03}$ (2.61) $Ge_4 = -1.314(\frac{p_{co}}{d_e})^{-0.62}(\frac{\pi}{2} - \beta)^{-0.47}$ (2.62)	250 < Re_{VDI} < 750 20° < β < 45°
Yan and Lin [72]	$f = 6.947 \cdot 10^5 Re_{eq}^{1.109} Re^{-0.5}$ (2.63) $f = 31.21 Re_{eq}^{0.04557} Re^{-0.5}$ (2.64)	Re_{eq} < 6000 $Re_{eq} \geq 6000$

Figure 7: Correlations of friction factors for evaporator

Similar to the water channel, the ammonia channel has a port pressure drop which has to be computed and then added to the determined pressure drop. However, the port side pressure drop for the ammonia channel is different due to varying flow velocities. This is accounted for by incorporating a different port diameter, viz. 0.1 m, and the pressure drop at the port is calculated using the same method to be as follows.

$$\boxed{\Delta P_{pt,amm} = 39.188 \text{ Pa}} \tag{22}$$

From the set of possible correlations, the correlation by Yan and Lin is chosen as it is the most suited for the flow parameters of the current design. Hence, from the selected correlation, the calculated pressure drop is

$$\boxed{\Delta P_{tot,amm} = 0.13709 \text{ bar}} \tag{23}$$

The obtained pressure drop is not too low and within acceptable limits.

Step 14

Verification of parameters using cell method

In the analysis above, an assumption for the vapor quality of 0.5 has been made. This is physically incorrect as the vapor quality increases continuously along the length of the plate. Hence, an integral analysis has to be performed incorporating the increase in vapor quality with length. This method can be used to verify the following:

- The total plate length has to be approximately equal to the design value
- The overall heat transfer coefficient has to be equal to the assumed value
- The total heat flux has to be equal to the given specification requirement

The cell method can be executed by dividing the length of the channel into ten parts, each corresponding to an increase in the vapor quality of 0.1. A simple energy balance is made, resembling the finite volume method, considering the difference in enthalpy of ammonia at the inlet and the outlet of the cell. From the determined heat flux value of the cell, the parameters of length required and the heat transfer coefficient can be computed.

Upon execution, the following values were obtained.

$$\begin{aligned} \dot{Q} &= 17.581 \text{ MW} \\ U &= 2017.1 \text{ W/m}^2\text{K} \\ L_p &= 2.798 \text{ m} \end{aligned} \tag{24}$$

It can be seen that the above values match closely with the determined values for the current design.

Step 15

Estimation of Cost

The equipment cost for the plate exchanger can be determined from the 2010 model from Sinnott and Towler as follows:

$$Cost_{equipment} = a + bS^n \tag{25}$$

Equipment	Units for Size, *S*	S_{lower}	S_{upper}	*a*	*b*	*n*	Note
Exchangers							
U-tube shell and tube	area, m^2	10	1,000	28,000	54	1.2	
Floating head shell and tube	area, m^2	10	1,000	32,000	70	1.2	
Double pipe	area, m^2	1.0	80	1,900	2,500	1.0	
Thermosiphon reboiler	area, m^2	10	500	30,400	122	1.1	
U-tube Kettle reboiler	area, m^2	10	500	29,000	400	0.9	
Plate and frame	area, m^2	1.0	500	1,600	210	0.95	2

Figure 8: Parameters for determining equipment cost

The values of a, b and n are obtained from the table given in Figure 8 as $a = 1600$, $b = 210$, $n = 0.95$ and S is the total area of heat transfer per heat exchanger.

The costs are then adjusted for inflation with an inflation factor of 1.14 and converted from USD to EUR based on the present day conversion rate. Hence, the total predicted costs for the equipment is calculated to be 0.54 million Euros.

$$\boxed{Cost_{equipment} \approx € \, 548,640} \tag{26}$$

Additionally, the costs for installation and maintenance are to be accounted for. Sinnott and Towler recommends using a factor of 3.5 with the equipment costs to estimate the total costs associated with the heat exchanger unit. Hence, the total costs are calculated to be as below.

$$\boxed{Cost_{total} \approx € \, 1,920,200} \tag{27}$$

Parameter Values of Final Design

Parameters	Symbols	Units	Values
Design Parameters			
Inclination Angle	β	deg	45
Plate Length	L_p	m	2.8
Plate Width	B_p	m	1.4
Plate Thickness	T_p	mm	1
Water Channel Spacing	$S_{p,w}$	mm	5
Ammonia Channel Spacing	$S_{p,a}$	mm	1.5
Number of Plates	N_p	-	530
Number of Heat Exchangers	N_{hex}	-	10
Number of Plates per Heat Exchanger	$N_{p,hex}$	-	53
Total Number of Channels per Fluid	N_c	-	260
Number of Channels per Heat Exchanger	$N_{c,hex}$	-	52
Port Diameter - Water	$d_{p,water}$	m	0.3
Port Diameter - Ammonia	$d_{p,amm}$	m	0.1
Operational Parameters			
Heat Duty	$\dot{Q}$	MW	17.58
Heat Transfer Area	A	m^2	3305.1
Velocity of Water	u_t	m/s	0.7718
Velocity of Ammonia at Inlet	$u_{amm,in}$	m/s	0.0372
Velocity of Ammonia at Outlet	$u_{amm,out}$	m/s	3.018
Reynolds Number of Water	Re_w	-	7327.6
Reynolds Number of Ammonia at Inlet	$Re_{amm,in}$	-	414.3776
Reynolds Number of Ammonia at Outlet	$Re_{amm,out}$	-	5657.9
Heat Transfer Coefficient - Ammonia	α_{amm}	W/m^{2}K	2.049e+4
Heat Transfer Coefficient - Water	α_{water}	W/m^{2}K	1.2794e+4
Overall Heat Transfer Coefficient	U	W/m^{2}K	2017.1
Total Pressure Drop - Water	P_w	bar	0.3627
Total Pressure Drop - Ammonia	P_{amm}	bar	0.1371
Cost Parameters			
Plate Material	-	-	Stainless Steel
Estimated Cost per Heat Exchanger	-	€	192,020
Inflation Factor	-	-	1.14
Estimated Total Equipment Costs	-	€	548,640
Total Estimated Costs	-	€	1,920,200

Table 8: Final parameter values for the plate heat exchanger

Appendix

E350 - Water-heated Ammonia Evaporator
MATLAB Live Script

Design of Flat Plate Heat Exchanger

E350 - Water Heated Ammonia Evaporator

Group 12: Aswin Raghunathan (5128188) & Shyam Sundar Hemamalini (5071984)

1.1. Estimating heat flux from given specification

We are given the following specifications.

```
m_amm = 15; % kg/s
h_amm_l = 453.64*1000; % J/kg
h_amm_g = 1625.7*1000; % J/kg
```

Now, the duty can be determined as:

```
Q_dot = m_amm*(h_amm_g - h_amm_l) % W
```

```
Q_dot = 17580900
```

1.2. Performing energy balance to determine outlet temperature

The following specifications are also provided.

```
m_water = 1400; % kg/s
T_in_water = 28 + 273.15; % K
Cp_water = 4180.6; % J/kgK
```

A simple substitution in the energy balance will give us the outlet temperature of water as:

```
T_out_water = T_in_water - Q_dot/(m_water*Cp_water) - 273.15 % °C
```

```
T_out_water = 24.9962
```

```
T_out_water = T_out_water + 273.15;
```

2. Physical Properties

The physical properties of both water and ammonia are evaluated at the mean temperature as:

```
rho_amm_l = 605.01; % kg/m^3
rho_water_l = 996.61; % kg/m^3
rho_amm_g = 7.4613; % kg/m^3
visc_amm_l = 1.3363e-4; % Pa s
visc_amm_g = 9.7869e-6; % Pa s
visc_amm_m = (visc_amm_g+visc_amm_l)/2;
visc_water_l = 8.6047e-4; % Pa s
k_amm_l = 0.4898; % W/mK
k_amm_g = 0.025962;
k_water_l = 0.60969; % W/mK
Cp_amm_l = 4.7721e3; % J/kg
Cp_amm_g = 3.1027e3; % J/kg
```

3. Determination of LMTD

The given specifications for temperature of both the fluids are:

```
T_in_amm = 23.5 + 273.15; % K
T_out_amm = 23.5 + 273.15; % K
T_mean_amm = (T_in_amm + T_out_amm)/2; % K
T_mean_water = (T_in_water + T_out_water)/2; % K
```

Now, we have the formula for logarithmic mean temperature difference as:

```
T_lmtd = ((T_in_water-T_out_amm)-(T_out_water-T_in_amm))...
    /log((T_in_water - T_out_amm)/...
    (T_out_water - T_in_amm)) % K
```

```
T_lmtd = 2.7279
```

4. Estimation of LMTD Correction Factor

We need a correction factor for the LMTD.

4.1. Determination of NTU

This depends on the NTU of the process. Hence, we first determine the NTU as:

```
NTU = (T_in_water - T_out_water)/T_lmtd
```

```
NTU = 1.1012
```

4.2 Assumption of Number of Passes

Since we need to design a vertical-collection evaporator, a single pass for both the fluids is enough and justified.

```
N_pass = 1;
```

4.3 Estimation of Correction Factor

The correction factor is determined from the graph as:

```
F_t = 0.975;
```

5. Estimation of Corrected Mean Temperature Difference

The correction factor is then implemented to estimate the realistic value for LMTD as:

```
T_m = F_t * T_lmtd % K
```

```
T_m = 2.6597
```

6. Initial Overall Heat Transfer Coefficient

The initial value has been assumed from the chart given in Sinnott and Towler as:

```
U_0_init = 2000 % W/m^2K
```

```
U_0_init = 2000
```

7. Determination of Heat Transfer Area

From the assumed value of heat transfer coefficient, the heat transfer area can be approximated as:

```
A = Q_dot / (U_0_init*T_m) % m^2
```

```
A = 3.3051e+03
```

8. Selection of Design Parameters

The basic design parameters have been assumed as:

```
Angle = pi/4; % Corrugation Angle, radians
L_p = 2.8; % Length of the plate, m
B_p = 1.4; % Width of the plate, m
T_p = 1e-3; % Thickness of the plate, m
S_p_a = 5e-3; % Spacing for ammonia channel, m
S_p = 5e-3; % Spacing for water channel, m
phi = 1.22; % Enlargement Factor
```

From the above design parameters, the value of the projected area can be found using the flat area and the enlargement factor 'phi'.

```
A_ref = L_p * B_p; % m^2
A_p = phi * A_ref % m^2
```

```
A_p = 4.7824
```

The total number of plates required can be estimated from the projected area and the total heat transfer area as:

```
N_plates = floor(A/A_p)
```

```
N_plates = 691
```

The above value is the initial value and is subject to changes as we iterate.

9. Selection of Flow Arrangement

The number of heat exchangers for the given duty is assumed to be 5, with the channels required determined from the relation given below.

```
N_hex = 5;
N_channels = ceil((N_plates - 1)/(2*N_pass))
```

```
N_channels = 345
```

```
N_channels_hex = floor(N_channels/N_hex) % per heat exchanger
```

```
N_channels_hex = 69
```

```
N_plates_hex = 2*N_pass*N_channels_hex + 1 % per heat exchanger
```

```
N_plates_hex = 139
```

It is to be noted that the above values are also subject to change in case the flow is not upto requirements.

10.1. Calculation of Heat Transfer Coefficient - Water

The equivalent diameter can be calculated as below.

```
d_e = 2*S_p/phi % m
```

```
d_e = 0.0082
```

```
A_cs = S_p * B_p * phi % m^2
```

```
A_cs = 0.0085
```

The mass flow rate of water in each channel can be determined as below.

```
m_channel_w = m_water/N_channels % kg/s
```

```
m_channel_w = 4.0580
```

Now, the velocity, the Reynolds number and the Prandtl number of the flow is determined as below.

```
velocity_water = (m_water/rho_water_l)/A_cs/N_channels
```

```
velocity_water = 0.4768
```

```
Reynolds_water = rho_water_l*velocity_water*d_e/visc_water_l
```

```
Reynolds_water = 4.5264e+03
```

```
Prandtl_water = visc_water_l*Cp_water/k_water_l;
```

There are different correlations for determining the heat transfer coefficient of water. A comparison has been made with the correlations that are applicable in our case. The different correlations and their corresponsing predicted heat transfer coefficients are given below.

1. Correlation from Sinnott

```
alpha_w_1 = (k_water_l/d_e)*0.26*(Reynolds_water^0.65)*(Prandtl_water^0.4)
```

```
alpha_w_1 = 9.3547e+03
```

2. Correlation from Winkelmann

```
alpha_w_2 = (k_water_l/d_e)*0.22*(Reynolds_water^0.68)*(Prandtl_water^(1/3))
```

```
alpha_w_2 = 9.0523e+03
```

3. Correlation from Yan et al

```
alpha_w_3 = (k_water_l/d_e)*0.2121*(Reynolds_water^0.78)*(Prandtl_water^(1/3))
```

```
alpha_w_3 = 2.0251e+04
```

4. Correlation from Donowski and Kandlikar

```
alpha_w_4 = (k_water_l/d_e)*0.2875*(Reynolds_water^0.78)*(Prandtl_water^(1/3))
```

```
alpha_w_4 = 2.7451e+04
```

5. Correlation from VDI Atlas

The determination of the heat transfer coefficient given by VDI Atlas requires a lot of intermediate parameters. They are determined in order to calculate the heat transfer coefficient.

The volume flow rate is first determined from the given specification as below.

```
V_gap = m_water/rho_water_l/N_channels; % m^3/s
amp = S_p/2; % Amplitude, m
```

The mean flow velocity is then determined as below.

```
w = V_gap/(2*amp*B_p) % m/s
```

```
w = 0.5817
```

We can then determine the Reynolds number from the determined parameters as below.

```
Reynolds_water_VDI = rho_water_l*w*d_e/visc_water_l;
```

The required flow parameters for determining the friction factor is then calculated as below.

```
xi_0 = (1.8*log10(Reynolds_water_VDI) - 1.5)^(-2);
xi_1 = 39/Reynolds_water_VDI^0.289;
```

We can then determine the friction factor from the correlation as below.

```
xi_r = cos(Angle)/(0.18*tan(Angle)+0.36*sin(Angle)+(xi_0)/...
    cos(Angle))^(0.5) + (1-cos(Angle))/(3.8*xi_1)^(0.5);
xi = 1/(xi_r^2);
```

We can then determine the heat transfer coefficient as below.

```
alpha_w_5 = (k_water_l/d_e)*1.615*((xi*Reynolds_water_VDI/64)...
    *Reynolds_water_VDI*Prandtl_water*d_e/L_p)^(1/3)
```

```
alpha_w_5 = 2.2792e+03
```

10.2 Calculation of Heat Transfer Coefficient - Ammonia

Since the channel for ammonia has a different spacing, we determine the equivalent diameter and the cross-sectional area for the ammonia channel as below.

```
d_e_a = 2*S_p_a/phi % m
```

```
d_e_a = 0.0082
```

```
A_cs_a = S_p_a * B_p * phi % m^2
```

```
A_cs_a = 0.0085
```

The mass flow rate per channel and the inlet and outlet velocities can then be determined as:

```
m_channel_a = m_amm/N_channels % kg/s
```

```
m_channel_a = 0.0435
```

```
velocity_amm_out = (m_amm/rho_amm_g)/A_cs_a/N_channels % m/s
```

```
velocity_amm_out = 0.6823
```

```
velocity_amm_in = (m_amm/rho_amm_l)/A_cs_a/N_channels % m/s
```

```
velocity_amm_in = 0.0084
```

Now, we can determine the liquid and vapor Reynolds number as below.

```
Reynolds_amm_l = rho_amm_l*velocity_amm_in*d_e_a/visc_amm_l
```

```
Reynolds_amm_l = 312.2845
```

```
Reynolds_amm_g = rho_amm_g*velocity_amm_out*d_e_a/visc_amm_g
```

```
Reynolds_amm_g = 4.2639e+03
```

The mass velocity of ammonia and subsequently, the boiling number are also determined as:

```
G_amm = m_channel_a/A_cs_a % kg/m^2s
```

```
G_amm = 5.0911
```

```
Bo = Q_dot/A/(h_amm_g - h_amm_l)/G_amm;
```

For the current iteration, we assume a constant vapor quality of 0.5 throughout the channel. A better assumption is done to later verify the obtained values. However, now, for simplicity, a vapor quality of 50% is considered and the equivalent parameters are then determined as below:

```
x = 0.5;
G_eq = G_amm*((1-x) + x*(rho_amm_l/rho_amm_g)^0.5); % kg/m^2s
R_eq = G_eq*d_e_a/visc_amm_l
```

```
R_eq = 1.5622e+03
```

```
Bo_eq = Q_dot/A/(h_amm_g-h_amm_l)/G_eq;
Prandtl_amm_l = visc_amm_l*Cp_amm_l/k_amm_l;
Prandtl_amm_g = visc_amm_g*Cp_amm_g/k_amm_g;
```

Similar to a single phase flow, there are numerous correlations for the estimation for heat transfer coefficient of evaporating ammonia flow. They are evaluated as below.

1. Yan and Lin

However, this may not be applicable owing to the low equivalent Reynolds number.

```
alpha_a_1 = (k_amm_l/d_e_a)*19.26*R_eq*(Reynolds_amm_l^(-0.5))*(Prandtl_amm_l^(1/3))*Bo_eq^0.3
```

```
alpha_a_1 = 8.3361e+03
```

2. Donowski and Kandlikar - I

```
Co_amm_l = (rho_amm_g/rho_amm_l)^(0.5)*((1 - x)/x)^(0.8);
alpha_l = 0.02875 * (Reynolds_amm_l^0.78)* (Prandtl_amm_l^(1/3))*k_amm_l/d_e_a;

alpha_a_2 = 1.055*(1.056*Co_amm_l^(-0.4)+ 1.02*Bo^(0.9))*x^(-0.12)*alpha_l^0.98
```

```
alpha_a_2 = 436.2421
```

3. Donowski and Kandlikar - II

```
alpha_a_3 = (1.184* Co_amm_l^(-0.3) + 225.5*Bo^2.8)*(1-x)^(0.0003)*alpha_l
```

```
alpha_a_3 = 378.9377
```

4. Palmer et al

```
alpha_a_4 = 2.7*k_amm_l*(Reynolds_amm_l^0.55)*(Prandtl_amm_l^0.5)/d_e_a
```

```
alpha_a_4 = 4.3355e+03
```

11. Overall Heat Transfer Coefficient

As we are considering warm surface water, it has a higher fouling resistance and hence, the following fouling resistances are assumed.

```
fouling_water = 6000; % W/m2K
fouling_ammonia = 5000; % W/m2K
k_metal = 57;
```

Now that we have the individual heat transfer coefficients, we can determine the overall heat transfer coefficient as below.

```
val = (alpha_a_4^-1) + (fouling_ammonia^-1) + T_p/k_metal +...
    1/(fouling_water) + (alpha_w_1^-1);
U1 = val^-1 % W/m2K
```

```
U1 = 1.3855e+03
```

12. Calculating Error

The error is calculated and for a good design, the error must be lower than 5%.

```
Error = abs(U1 - U_0_init)/U_0_init*100 % in percentage
```

```
Error = 30.7250
```

The error is higher than the limit and the obtained overall heat transfer coefficient is very low for a flat plate heat exchanger. Hence, we reiterate the design procedure to accomodate the error.

9*. Selection of Flow Arrangement

The number of heat exchangers for the given duty is assumed to be 5, with 265 channels per heat exchanger. Also, the ammonia channel is given a different spacing to account for the very low Reynolds number in the previous iteration.

```
S_p_a = 1.5e-3; % m
N_hex = 10;
A = A %/N_hex;
```

```
A = 3.3051e+03
```

```
N_channels = 260
```

```
N_channels = 260
```

```
N_channels_hex = floor(N_channels/N_hex) % per heat exchanger
```

```
N_channels_hex = 26
```

```
N_plates_hex = 2*N_pass*N_channels_hex + 1 % per heat exchanger
```

```
N_plates_hex = 53
```

```
N_plates = N_plates_hex * N_hex
```

```
N_plates = 530
```

10.1*. Calculation of Heat Transfer Coefficient - Water

The calculation is the same as the previous case except that some of the design values are changed. This is implemented and the updated values are determined the same way.

```
d_e = 2*S_p/phi % m
```

```
d_e = 0.0082
```

```
A_cs = S_p * B_p; % m^2
m_channel_w = m_water/N_channels % kg/s
```

```
m_channel_w = 5.3846
```

Now, the velocity, the Reynolds number and the Prandtl number of the flow is determined as below.

```
velocity_water = (m_water/rho_water_l)/A_cs/N_channels
```

```
velocity_water = 0.7718
```

```
Reynolds_water = rho_water_l*velocity_water*d_e/visc_water_l
```

```
Reynolds_water = 7.3276e+03
```

```
Prandtl_water = visc_water_l*Cp_water/k_water_l;
```

The different correlations and their corresponsing predicted heat transfer coefficients are given below.

1. Correlation from Sinnott

```
alpha_w_1 = (k_water_l/d_e)*0.26*(Reynolds_water^0.65)*(Prandtl_water^0.4)
```

```
alpha_w_1 = 1.2794e+04
```

2. Correlation from Winkelmann

```
alpha_w_2 = (k_water_l/d_e)*0.22*(Reynolds_water^0.68)*(Prandtl_water^(1/3))
```

```
alpha_w_2 = 1.2561e+04
```

3. Correlation from Yan et al

```
alpha_w_3 = (k_water_l/d_e)*0.2121*(Reynolds_water^0.78)*(Prandtl_water^(1/3))
```

```
alpha_w_3 = 2.9487e+04
```

4. Correlation from Donowski and Kandlikar

```
alpha_w_4 = (k_water_l/d_e)*0.2875*(Reynolds_water^0.78)*(Prandtl_water^(1/3))
```

```
alpha_w_4 = 3.9970e+04
```

5. Correlation from VDI Atlas

The volume flow rate is first determined from the given specification as below.

```
V_gap = m_water/rho_water_l/N_channels; % m^3/s
amp = S_p/2; % Amplitude, m
```

The mean flow velocity is then determined as below.

```
w = V_gap/(2*amp*B_p) % m/s
```

```
w = 0.7718
```

We can then determine the Reynolds number from the determined parameters as below.

```
Reynolds_water_VDI = rho_water_l*w*d_e/visc_water_l;
```

The required flow parameters for determining the friction factor is then calculated as below.

```
xi_0 = (1.8*log10(Reynolds_water_VDI) - 1.5)^(-2);
xi_1 = 39/Reynolds_water_VDI^0.289;
```

We can then determine the friction factor from the correlation as below.

```
xi_r = cos(Angle)/(0.18*tan(Angle)+0.36*sin(Angle)+(xi_0)/...
    cos(Angle))^(0.5) + (1-cos(Angle))/(3.8*xi_1)^(0.5);
xi = 1/(xi_r^2);
```

We can then determine the heat transfer coefficient as below.

```
alpha_w_5 = (k_water_l/d_e)*1.615*((xi*Reynolds_water_VDI/64)...
    *Reynolds_water_VDI*Prandtl_water*d_e/L_p)^(1/3)
```

```
alpha_w_5 = 2.7393e+03
```

10.2*. Calculation of Heat Transfer Coefficient - Ammonia

Since the channel for ammonia has a different spacing, we determine the equivalent diameter and the cross-sectional area for the ammonia channel as below.

```
d_e_a = 2*S_p_a/phi % m
```

```
d_e_a = 0.0025
```

```
A_cs_a = S_p_a * B_p * phi; % m^2
```

The mass flow rate per channel and the inlet and outlet velocities can then be determined as:

```
m_channel_a = m_amm/N_channels % kg/s
```

```
m_channel_a = 0.0577
```

```
velocity_amm_out = (m_amm/rho_amm_g)/A_cs_a/N_channels % m/s
```

```
velocity_amm_out = 3.0180
```

```
velocity_amm_in = (m_amm/rho_amm_l)/A_cs_a/N_channels % m/s
```

```
velocity_amm_in = 0.0372
```

Now, we can determine the liquid and vapor Reynolds number as below.

```
Reynolds_amm_l = rho_amm_l*velocity_amm_in*d_e_a/visc_amm_l
```

```
Reynolds_amm_l = 414.3776
```

```
Reynolds_amm_g = rho_amm_g*velocity_amm_out*d_e_a/visc_amm_g
```

```
Reynolds_amm_g = 5.6579e+03
```

The mass velocity of ammonia and subsequently, the boiling number are also determined as:

```
G_amm = m_channel_a/A_cs_a % kg/m^2s
```

```
G_amm = 22.5185
```

```
Bo = Q_dot/A/(h_amm_g - h_amm_l)/G_amm;
```

For the current iteration, we assume a constant vapor quality of 0.5 throughout the channel. A better assumption is done to later verify the obtained values. However, now, for simplicity, a vapor quality of 50% is considered and the equivalent parameters are then determined as below:

```
x = 0.5;
G_eq = G_amm*((1-x) + x*(rho_amm_l/rho_amm_g)^0.5); % kg/m^2s
R_eq = G_eq*d_e_a/visc_amm_l
```

```
R_eq = 2.0729e+03
```

```
Bo_eq = Q_dot/A/(h_amm_g-h_amm_l)/G_eq;
Prandtl_amm_l = visc_amm_l*Cp_amm_l/k_amm_l;
Prandtl_amm_g = visc_amm_g*Cp_amm_g/k_amm_g;
```

Similar to a single phase flow, there are numerous correlations for the estimation for heat transfer coefficient of evaporating ammonia flow. They are evaluated as below.

1. Yan and Lin

```
alpha_a_1 = (k_amm_l/d_e_a)*19.26*R_eq*(Reynolds_amm_l^(-0.5))*(Prandtl_amm_l^(1/3))*Bo_eq^0.3
```

```
alpha_a_1 = 2.0490e+04
```

2. Donowski and Kandlikar - I

```
Co_amm_l = (rho_amm_g/rho_amm_l)^(0.5)*((1 - x)/x)^(0.8);
alpha_l = 0.02875 * (Reynolds_amm_l^0.78)* (Prandtl_amm_l^(1/3))*k_amm_l/d_e_a;

alpha_a_2 = 1.055*(1.056*Co_amm_l^(-0.4)+ 1.02*Bo^(0.9))*x^(-0.12)*alpha_l^0.98
```

```
alpha_a_2 = 1.7613e+03
```

3. Donowski and Kandlikar - II

```
alpha_a_3 = (1.184* Co_amm_l^(-0.3) + 225.5*Bo^2.8)*(1-x)^(0.0003)*alpha_l
```

```
alpha_a_3 = 1.5749e+03
```

4. Palmer et al

```
alpha_a_4 = 2.7*k_amm_l*(Reynolds_amm_l^0.55)*(Prandtl_amm_l^0.5)/d_e_a
```

```
alpha_a_4 = 1.6884e+04
```

11*. Overall Heat Transfer Coefficient

Now that we have the individual heat transfer coefficients, we can determine the overall heat transfer coefficient as below.

```
val = (alpha_a_1^-1) + (fouling_ammonia^-1) + T_p/k_metal +...
    1/(fouling_water) + (alpha_w_1^-1);
U1 = val^-1 % W/m2K
```

```
U1 = 1.9563e+03
```

12*. Calculating Error

```
Error = abs(U1 - U_0_init)/U_0_init*100 % in percentage
```

```
Error = 2.1861
```

The error is lower than the limit and hence, the design is fixed and we can determine the pressure drop associated.

13.1. Determination of Pressure Drop - Water

The port side pressure drop is an important pressure drop in the heat exchangers. A diameter of 40cm is assumed as the port diameter and the port side pressure drop is determined as below.

```
L_path = L_p*N_pass; % m
d_pt = 0.3; % m
A_pt = pi*(d_pt^2)/4; % m^2
velocity_water_pt = m_water/(rho_water_l*A_pt*N_hex) % m/s
```

```
velocity_water_pt = 1.9873
```

```
p_pt = 1.3*rho_water_l*(velocity_water_pt^2)*N_pass/2 % Pa
```

```
p_pt = 2.5585e+03
```

There are several correlations to determine the pressure drop in the water channel. The following are the correlations applicable to the current design.

1. Thonon:

```
f_1 = 0.37*(Reynolds_water^-0.172);
p_1 = 2*f_1*rho_water_l*(velocity_water^2)*L_p/d_e % Pa
```

```
p_1 = 3.2476e+04
```

```
P_1 = p_1 + p_pt % Pa
```

```
P_1 = 3.5035e+04
```

2. Focke:

```
f_2 = 6.3*(Reynolds_water^-0.209)
```

```
f_2 = 0.9808
```

```
p_2 = 0.5*f_2*rho_water_l*(velocity_water^2)*L_p/d_e % Pa
```

```
p_2 = 9.9458e+04
```

```
P_2 = p_2 + p_pt % Pa
```

```
P_2 = 1.0202e+05
```

3. Sinnott and Towler:

```
j_f = 0.6*(Reynolds_water^(-0.3));
p_3 = 4*j_f*(L_path/d_e)*rho_water_l*(velocity_water^2) % Pa
```

```
p_3 = 3.3715e+04
```

```
P_3 = p_3 + p_pt % Pa
```

```
P_3 = 3.6274e+04
```

4. VDI:

```
p_4 = xi*rho_water_l*w^2*L_p/d_e/2 % Pa
```

```
p_4 = 8.2977e+04
```

```
P_4 = p_4 + p_pt % Pa
```

```
P_4 = 8.5536e+04
```

It can be seen that the maximum pressure drop is below 1 bar. The obtained pressure drops are nominal for a flat plate heat exchanger connected in parallel.

13.1. Determination of Pressure Drop - Ammonia

A more calculated analysis is made to determine the equivalent Reynolds number and mass velocity by determining a more accurate value for the mean vapor quality. This is done by a simple loop as below.

```
X = 0.1:0.1:0.9;
req=zeros(length(X),1);
for i = 1:length(X)
    geq = G_amm*((1-X(i)) + X(i)*(rho_amm_l/rho_amm_g)^0.5);
    req(i) = geq*d_e_a/visc_amm_l;
end
```

Now, the pressure drop in the ammonia channel can be determined as below.

Port Pressure Drop

```
L_path = L_p*N_pass; % m
d_pt = 0.1; % m
A_pt = pi*(d_pt^2)/4; % m^2
velocity_amm_pt = m_amm/(rho_amm_l*A_pt*N_hex) % m/s
```

```
velocity_amm_pt = 0.3157
```

```
p_pt = 1.3*rho_amm_l*(velocity_amm_pt^2)*N_pass/2
```

```
p_pt = 39.1880
```

1. Yan and Lin

```
f_6 = (6.947e5)*(mean(req)^-1.109)*(Reynolds_amm_l^-0.5)
```

```
f_6 = 7.1617
```

```
p_6 = 2*f_6*rho_amm_l*(velocity_amm_in^2)*L_path/d_e_a % Pa
```

```
p_6 = 1.3670e+04
```

```
P_6 = p_6 + p_pt % Pa
```

```
P_6 = 1.3709e+04
```

The pressure drop is acceptable and not too low.

Cell Method to Verify Parameters

In order to accurately verify that the assumed vapor quality and hence, the assumed overall heat transfer coefficient as correct, a discrete cell method is used. A simple energy balance is made to determine cumulatively the values of heat transfer, overall heat transfer coefficient and the required length of the plate.

The values required for the iteration are initialised.

```
delta_x = 0.1; x0 = 0.05;
L = 0; Q_sum = 0;
T_in = T_in_water; T_a = T_in_amm;
m_a = m_channel_a; m_w = m_channel_w;
```

The overall heat transfer coefficient is reduced to exclude the heat transfer coefficient of ammonia which is computed inline for varying vapor qualities.

```
value =(fouling_ammonia^-1) + T_p/k_metal + 1/(fouling_water) +...
    (alpha_w_1^-1);
U_constant = value^-1;
```

Now, the equations are looped over 10 cells, with a vapor quality difference of 0.1 per cell.

```
for i=1:10

    G_eq = G_amm*((1-x0) + x0*(rho_amm_l/rho_amm_g)^0.5);
    R_eq = G_eq*d_e_a/visc_amm_l; Phi = phi/0.375;
    Bo_eq = Q_dot/A/(h_amm_g-h_amm_l)/G_eq;

    alpha_a = (k_amm_l/d_e_a)*19.26*R_eq*(Reynolds_amm_l^(-0.5))*...
        (Prandtl_amm_l^(1/3))*Bo_eq^0.3;

    val = (alpha_a^-1) + (U_constant^-1);
    U = 1/val;

    Q = m_a*delta_x*(h_amm_g - h_amm_l);
    Q_sum = Q_sum + Q*N_channels;
    delta_T = Q/(m_w*Cp_water);

    T_out = T_in - delta_T;
    T_lm = ((T_in - T_a) - (T_out - T_a))/log((T_in - T_a)/(T_out - T_a));

    L = L + Q/(U*B_p*Phi*T_lm);
    x0 = x0 + delta_x;
    T_in = T_out;
end
```

The determined values are displayed and it can be seen that they are accurate and aligns with the assumed design values.

```
Q_sum % W
```

```
Q_sum = 1.7581e+07
```

```
L % m
```

```
L = 2.7980
```

```
U % W/m^2K
```

```
U = 2.0171e+03
```

14. Cost Estimation

The 2010 model is used for estimating total costs. The coefficients are taken from the table in Sinnott and Towler. We get the following:

```
S = A/N_hex; % m^2
a = 1600; b = 210; n = 0.95;
```

The total cost per heat exchanger is proportional to the heat transfer area, and hence, a simple power law is employed.

```
C = a + b * S^n; % in $
C_T = C*N_hex; % in $
C_T = C_T*0.899; % in €
```

The obtained cost is multiplied by the inflation factor of 1.14 to obtain the cost of equipment in euros in 2020 as

```
C_T = C_T*1.14 % in €
```

```
C_T = 5.4864e+05
```

The total capital costs associated with the heat exchanger includes the installation and maintenance costs which have a multiplying factor of 3.5. Hence, the total cost is

```
Cost_total = C_T*3.5 % in €
```

```
Cost_total = 1.9202e+06
```

The above costs are nominal considering the heat exchangers are industrial grade and heavy duty.