Assignment 2

Design of a plate heat exchanger system

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1 Introduction

In plate heat exchangers, heat is transferred over metal plates between fluids. The plates are stacked and hot and cold fluids alternate between them. This makes for a large heat exchange surface compared to shell and tube heat exchangers. The plates are connected by gaskets and in smaller heat exchangers or high pressure applications they are brazed together. Gaskets are seals that prevent leakages between the plates and are made of rubber or a polymer. Gaskets are the most critical part in plate heat exhangers in terms of material characteristics. Gasketed heat exchangers typically have a maximum operating pressure of 16 bar and a maximum temperature of 180 C.

In contrast with shell and tube heat exchangers, plate heat exchangers are compact. Moreover they have a better thermal performance. This means they have a higher efficiency and a closer approach temperature. Compared to shell and tube heat exchangers, plate heat exchangers are easy to clean. Besides that they suffer less from fouling than their shell and tube counterparts.

Industries where plate heat exchangers are often applied are the food and pharmaceutical industry. They are easy to take apart and inspection is straightforward as a result. Smaller plate heat exchangers are also used in domestic heating and the provision of hot water.

In this assignment the plate heat exchanger system in a distillation column will be dimensioned.

2 Design

The first step in the design procedure of the plate heat exchanger is to calculate the duty. The duty is the amount of heat to be transferred from one fluid to another per second. In this case the fluids flowing through the heat exchanger are propane (fluid 1) and propylene (fluid 2).

	$\dot{m}$ [kg/s]	$T_{in}[K]$	T_{out} [K]	$h_{in}[KJ/kg]$	$h_{out}[KJ/kg]$
propane (1)	20	328.15	328.15	352.23	624.77
propylene (2)	-	333.15	333.15	615.18	365.49

Table 1: Mass flux, temperature and enthalpy at in- and outlet

The duty can be calculated by setting up an energy balance.

$$\dot{Q} = \dot{m}_1(h_{1,out} - h_{1,in}) = \dot{m}_2(h_{2,in} - h_{2,out}) \tag{1}$$

This results in a duty of $\dot{Q} = 5.45MW$. The mass flow rate of the propylene stream can be determined with formula (1) as well and $\dot{m}_2 = 21.83$ kg/s. There is a temperature difference of five degrees between the flows, driving heat transport from the propylene stream to the propane stream.

The next step in the design process is to estimate an overall heat transfer coefficient. We have estimated it as $U_{assumed} = 3000$ $[W/m^2K]$. This is a reasonable estimate for a plate heat exchanger with corrugated plates and both streams consisting of light organic fluids.

The plates of the heat exchanger have chevron type corrugations. These corrugations cause the flows to become turbulent and thus enhance heat transfer. The corrugations are in an angle of 40 degrees with the horizon. The smaller the angle of the corrugations, the smaller the pressure drop over the heat exchanger. The fact that the plates in the heat exchanger are not flat demand for a correction factor to the surface area of the plates.
The required heat transfer surface can be translated with the following formula:

$$A = \frac{\dot{Q}}{U\Delta T} \tag{2}$$

The total heat transfer area is 363.39 m^2. This is not a great heat exchange surface for a single plate heat exchanger. Therefore we assume that we can design a system with only one heat exchanger without exceeding the limit set on the pressure drop of 0.3 bar over the heat exchanger. To find the number of plates in one heat exchanger the effective surface of one plate has to be computed.

$$A_p = \phi B_p L_p \tag{3}$$

In the equation above Φ is the ratio between the area of the plate surface with its corrugations and the area of the projection of the plate surface. Typically the value of this ratios is $\Phi = 1.22$. L_p and B_p are the dimensions of the area of the projection for height and width respectively. The dimensions chosen for the plates are $L_p = 1$ m and $B_p = 0.5$ m.

Dividing the required total heat transfer area by the effective area of one plate gives the required number of plates. The number of effective plates is 596. Both ends have a plate to close the system which means the heat exchanger will have 598 plates. The flow arrangement is countercurrent and the number of passes 1:1.

3 Heat transfer coefficients

The next step is to calculate the film heat-transfer coefficients for each stream. For the propane which is evaporating, the heat transfer coefficient can be computed with the following relation:

$$\alpha_1 = 19.26 Re_L^{0.5} Pr_L^{\frac{1}{3}} Bo_{eq}^{0.3} \frac{\lambda_L}{d_e}[(1-x) + x(\frac{\rho_L}{\rho_V})^{0.5}] \tag{4}$$

The average heat transfer coefficient for propane is $\alpha_1 = 8678.02 W/(m^2K)$.

For the propylene, which is condensing, the average heat transfer coefficient is determined with the relations below. The first relation is the Nusselt number for $G < 20[kg/sm^2]$.

$$Nu_{gc} = 0.943\phi[\frac{g\rho_L(\rho_L - \rho_G)L_p^3 \Delta h_{LG}}{\mu_L \lambda_L \Delta T_m}]^{0.25} \tag{5}$$

Multiplying the Nusselt number by the thermal conductivity of propylene and dividing by the characteristic dimension d_e will give the heat transfer coefficient for propylene:

$$\alpha_2 = \frac{Nu_{gc}\lambda_2}{d_e} \tag{6}$$

The average heat transfer for propylene is $\alpha_2 = 24769.26 W/(m^2K)$.

Now both the average heat transfer coefficient for the propane and propylene streams have been computed, the next step is to calculate the overall heat transfer coefficient. The following formula can be used to find the overall heat transfer coefficient.

$$U_o = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{1}{F_1} + \frac{1}{F_2} + \frac{t}{K_{st}}} \tag{7}$$

The overall heat transfer coefficient is dependent on the average heat transfer coefficients by convection in the propane and propylene streams, the thickness

(t) and conductivity of the plates (k_{st}), and the fouling factors. The values for the fouling factors are taken from table 19.8 in Sinnot and Towler. For light organics a value of $10000 (W/m^2K)$ is written in the table.

To verify the result for the overall heat transfer coefficient it has to be compared to the estimated overall heat transfer coefficient. There should be a deviation no greater than 30%. This can be done with the following formula:

$$Error = \frac{U_o - U_{assumed}}{U_{assumed}} * 100 \tag{8}$$

Filling in the above formula we find an error of 20.13%. In the table below the values computed in this section have been denoted.

Overall heat transfer coefficient $[W/m^2K]$	2396.158
Average heat transfer coefficient propane $[W/m^2K]$	8678.02
Average heat transfer coefficient propylene $[W/m^2K]$	24769.26
Fouling factor propane $[W/m^2K]$	10000
Fouling factor propylene $[W/m^2K]$	10000
Plate thickness [m]	$1 * 10^-3$
Conductivity Type 304 stainless steel plates $[W/mK]$	16.2

Table 2: Values found in the calculation of the overall heat transfer coefficient

4 Pressure drop

Finally the pressure drops for both the propane and propylene streams will be computed. Below the general formula for the pressure drop over the plate heat exchanger is denoted.

$$\Delta p = 2f\rho w^2 \frac{L_p}{d_e} \tag{9}$$

The variable d_e equals two times the channel spacing divided by the surface area factor ϕ. First the pressure drop for the propane stream will be calculated. For the propane stream the following relation for the friction factor holds:

$$f = 2.99Re^{-0.137}(-1.89 + 6.56(\frac{\theta}{30}) - 3.69(\frac{\theta}{30})^2 \tag{10}$$

By substituting (9) into (8) a pressure drop for the propane can be calculated. The value for the pressure drop is 0.00059 bar. For the propylene stream the next relation for the friction factor holds:

$$f = (4.207 - 2.673\theta^{-0.46})(4200 - 5.14b_d^{1.2})(Re_{eq}^{-0.95})pr^{0.3} \tag{11}$$

Chevron angle $\theta[deg]$	40
factor propane	0.32343632130587263
Re propane	1578.2783071730944
factor propylene	2.2231038323988797
Re propylene	6393.805438561879
Pr propylene	0.55506
b_d propylene	97.73758557744665
w1 [m/s]	0.05573606493000752
w2 [m/s]	0.06083666600994934
pressure drop propane [bar]	0.0005914090143766805
pressure propylene [bar]	0.0049459196286846556

Table 3: Values of the variables in the calculation of the pressure drop

By substituting (10) into (8) a pressure drop for the propylene stream can be found. The pressure drop for the propylene stream is 0.0049 bar.
With the overall heat transfer coefficient and the pressure drops being in the required range, we can accept the design for the plate heat exchanger.

5 Material selection gaskets

The material selected for the gaskets depends on the type of fluids flowing through the heat exchanger. Propane and propylene are both aliphatic hydrocarbons. Acrylonitrile-butane rubber is an especially suitable gasket material for a system processing aliphatic hydrocarbons.

6 Cost estimation

When designing a system of heat exhangers the following formula can be used to estimate the cost a single heat exchanger:

$$Cost = (a + bS^n) * 1.29 * 0.82 \tag{12}$$

S is the heat exchange area of a heat exchanger. The parameters a,b, and n depend on the type of heat exchanger. As the chosen type of heat exchanger is the Uplate and frame heat exchanger, $a = 1350$, $b = 180$ and $n = 0.95$. By multiplying the cost of one heat exchanger with the number of heat exchangers in the system -1 one can find the total costs of the heat exchanger system for the evaporator. As the original formula gives a value in dollars in 2007, it has been inflation adjusted (times 1.29) and converted to euros (times 0.82). The total cost is found to be: **52,954 Euros**

References

[1] Towler, G.(2013). *Chemical Engineering Design - Principles, Practise and Economics of Plant and Process Design*. Butterworth-Heinemann.

Appendix

```
import numpy as np
import matplotlib.pyplot as plt
import math as m
#1a
#Fluid 1 propane (saturated)
# (T in C) +273.15 K
T1=T1_out=T1_in=55+273.15
p1=19.072*10**5
#liq props
K1i=80.485*10**-3 #thermal cond
Pr1i=2.7774#Prandtl
cp1i=3.2013 #Cp
sti=3.5486*10**-3 #surface tension
m1=20
h1_in=352.23 #h in kJ/kg x=0
h1_out=624.77 #saturated vapor x=1
#(Allowable del P (in bar)*10**5 Pa)
adp1=0.3*(10**5)
Q=m1*(h1_out-h1_in)
print("Duty: "+str(Q/1000)+" MW")
r1i=438.76
r1o=43.706
rho1=0.5*(r1i+r1o)
mu1i=69.828*10**-6
mu1o=9.6977*10**-6
mu1=(mu1i+mu1o)/2
#2
#Fluid 2 propylene
# (T in C) +273.15 K
T2=T2_out=T2_in=60+273.15
P2=25.283*(10**5)
cp2i=2.9817
cp2o=3.4036
K2i=28.778*10**-3
mu2i=11.506*10**-6
Pr2i=1.1922

#(Allowable del P (in bar)*10**5 Pa)
```

```
adp2=0.3*(10**5)
h2_in=615.18
h2_out=365.49
m2=Q/(h2_in-h2_out)
print("Propylene mass flow: "+str(m2))
r2i=58.986
r2o=433.73
rho2=0.5*(r2i+r2o) #avg density
K2o=93.413*10**-3
K2=0.5*(K2i+K2o)
mu2o=66.919*10**-6
mu2=0.5*(mu2i+mu2o)
Pr2o=2.4383
st2=2.5271*10**-3
#3
U_a = 3000 #Assumed overall heat transfer co-efficient (corrugated plate liq-liq)
print("Assumed U: "+str(U_a))
#4
del_Tm = T2-T1
print("Temperature difference driving heat flow: "+str(del_Tm))

A=Q*1000/(U_a*del_Tm)
print("Total heat transfer area: " +str(A))
num=1
print("Number of heat exchangers: "+str(num))
#6
#subject to change
Lp=1
Bp=0.5
Aref=Lp*Bp
ang=40 #degrees (low pressure drop for lower angles)
tp=1*10*-3
sp=5*10**-3
phi=1.22
Ap=Aref*phi
Np=m.ceil(A/(Ap*num))
print("Number of effective plates: "+str(Np))
ANp=Np+2
print("Number of actual plates: "+str(ANp))
#1-1 pass parallel flow
#Heat transfer co-efficient
de=2*(sp)/phi
Ac=sp*Bp
nc=m.ceil((Np-1))
print("Number of channels per pass: "+str(nc))
```

```
x=np.linspace(0,1,11)

#propane heat transfer
G=(m1/num)/(Ac*nc)
Re=G*de/(mu1i)
Rea=Re
Geq=G*((1-x)+x*(r1i/r1o)**0.5)
qw=(Q/num)/(Ac*nc)
Bo=qw/(Geq*(h1_out-h1_in))
Reeq=Geq*de/(mu1)
print("Equivalent Re num: "+str(Reeq))
hem=19.26*((Re)**0.5)*(Pr1i**(1/3))*(Bo**0.3)*(K1i/de)
he=np.mean(hem)
print("Average heat transfer co-efficient(propane): "+str(he))
#propylene heat transfer
G=(m2/num)/(Ac*nc)
x=0.5
Geq=G*((1-x)+x*(r1i/r1o)**0.5)
Reeq=Geq*de/(mu2)
Re=G*de/(mu2o)
pr=0.55506
Nu=0.943*phi*(9.81*r2o*(r2o-r2i)*(Lp**3)*(h2_in-h2_out)/(mu2o*K2o*del_Tm))**0.25 #slides G<
hcm=Nu*(K2o)/de
hc=np.mean(hcm)
print("Average heat transfer co-efficient (Propylene): "+str(hc))
Fseaw=10000
Fam=10000
Kst=16.2 #ss304
t=1*10**-3
U=1/((1/hc)+(1/he)+(1/Fseaw)+(1/Fam)+(t/Kst))
print("Error: "+str(100*abs(U-U_a)/U_a)+" %")
print("Overall heat transfer co-efficient: "+str(U))

#delP propane
w1=(m1/num)/(Ac*nc*rho1)
fa=(2.99*Rea**(-0.137))*(-1.89+6.56*(ang/30)-3.69*(ang/30)**2) #Ayub
delPa=2*fa*rho1*(w1**2)*(Lp/de)
print("Total delP Propane(bar): "+str(delPa*10**-5))

#delP propylene
w2=(m2/num)/(Ac*nc*rho1)
bd=(r2o-r2i)*9.81*(de**2)/st2
f=(4.207-2.673*(ang**-0.46))*(4200-5.14*(bd**1.2))*(Reeq**-0.95)*(pr**0.3)
delPa=2*f*rho2*(w2**2)*(Lp/de)
print("Total delP Propylene(bar): "+str(delPa*10**-5))
```

```python
#cost

S=A/num
a=1350
b=180
n=0.95
Cost=a+(b*S**n)
Cost=Cost*1.29 #Inflationtool.com
Cost=Cost*0.82 #Euro
print("Cost per heat exchanger:  "+str(Cost)+" Euros")
print("Total cost:  "+str(Cost*num)+" Euros")
```