Programming Series

“Material and Energy Balance Simulation of Multiple Effect Evaporator”

Just using python!

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Overview

An evaporator is an equipment where evaporation take place. Evaporation is the process of turning liquid form of chemical substance to gaseous form is carried out. A different kind of evaporation can be used for heating and possibly boiling a product containing a liquid to cause the liquid separate by evaporate from the product.

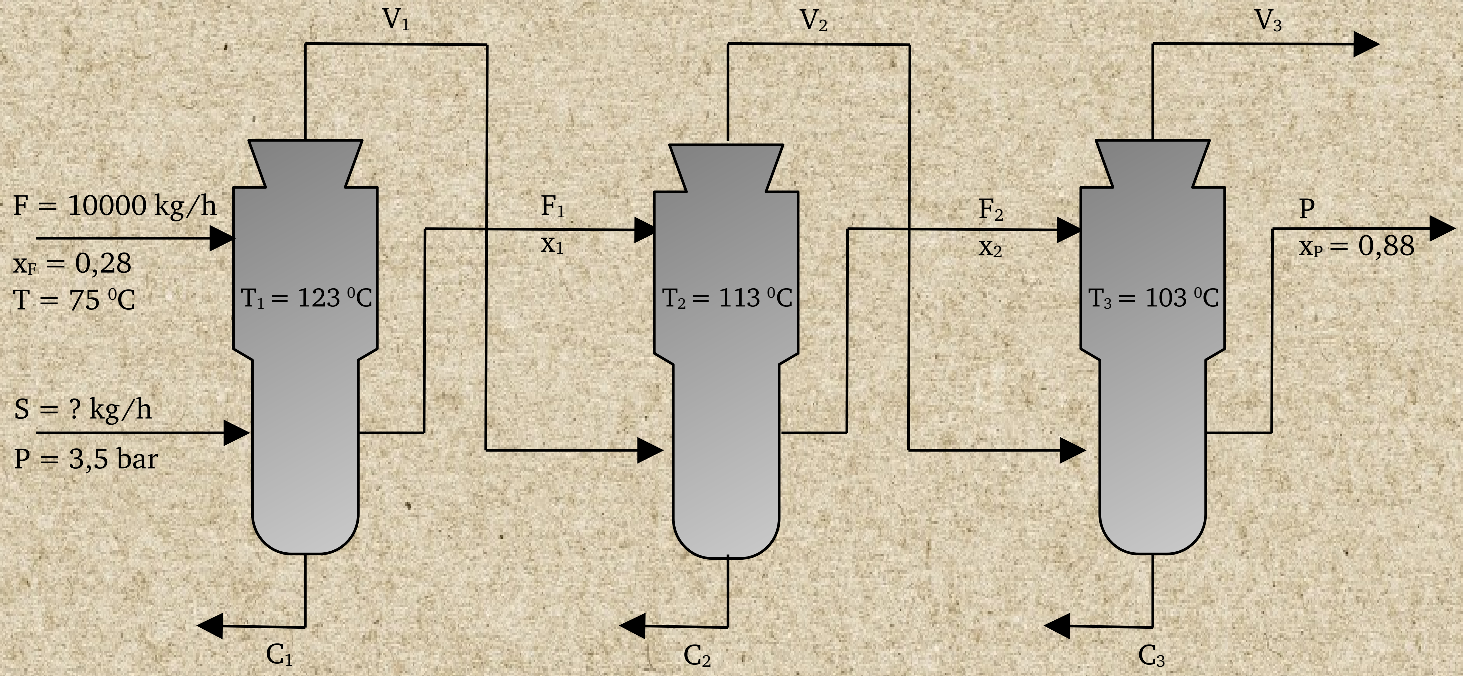
Multiple effect evaporator are consist of sequence evaporator that arrange together for more efficient heating in order to obtain desired concentration. The water vapor from the first effect can be introduced into heating source of next effect. The concentrate of first effect is feed to the next to achieve further evaporation. The boiling point in each effect is lower than the last due to decrease water contain.

The Problem >>>

The Problem

A triple-effect evaporator is being used to concentrate glycerine-water mixture at 10000 kg/h. The mixture is 28% of weight percent at 75°C. The mixture must be concentrated to 88% of weight percent. Saturated steam at 3,5 bar is available. Assume the heat transfer areas in each effect are equal and the evaporation temperature inside the each effect is 123°C, 113°C, 103°C. Using steam table for steam properties and additional data, calculate :

a. all unknown stream (S, V_1, V_2, V_3, F_1, F_2, and P)
b. all unknown concentration (x_1 and x_2)
c. steam economy



Steam properties :

P = 3,5 bar	T = 133 ^{0}C	H_V = 2731,63 kJ/kg	H_L = 559,93 kJ/kg
P = 2,2 bar	T = 123 ^{0}C	H_V = 2705,9 kJ/kg	H_L = 516,41 kJ/kg
P = 1,6 bar	T = 113 ^{0}C	H_V = 2695,77 kJ/kg	H_L = 475,2 kJ/kg
P = 1,15 bar	T = 103 ^{0}C	H_V = 2592,11 kJ/kg	H_L = 410,44 kJ/kg

Specific heat :

c_F = 3,70 kJ/kg ^{0}C
c_{F1} = 3,39 kJ/kg ^{0}C
c_{F2} = 2,82 kJ/kg ^{0}C
c_P = 2,64 kJ/kg ^{0}C

Overall heat transfer coefficient :

U_1 = 1230 W/ m^2 ^{0}C
U_2 = 895 W/ m^2 ^{0}C
U_3 = 895 W/ m^2 ^{0}C

Solution >>>

WARNING !

Why didn't you try to solve on your own ?

Ok just kidding, ☺
here's the solution for you

Solution >>>

Solution

The solution are start by deriving material and energy balance each effect and solve unknown variable using matrix operation.

overall material balance :

$$F = V_1 + V_2 + V_3 + P$$

from glycerine balance :

$$x_F\, F = x_P\, P$$

$$\boxed{P = \frac{x_F\, F}{x_P}}$$

from water balance :

$$\boxed{V_1 + V_2 + V_3 = F - P} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\boxed{V = F - P} \quad \textit{(total water removed)}$$

enthalpy balance :

enthalphy balance from 1st effect :

$$F\, H_F + S\, H_{VS} = F_1\, H_{F1} + V_1\, H_{V1} + C\, H_{LS}$$

$$F\, H_F + S\, H_{VS} - C\, H_{LS} = F_1\, H_{F1} + V_1\, H_{V1}$$

$$F\, H_F + S\, (H_{VS} - H_{LS}) = F_1\, H_{F1} + V_1\, H_{V1}$$

$$F\, H_F + S\, \lambda_S = F_1\, H_{F1} + V_1\, H_{V1}$$

$$\boxed{- S\, \lambda_S + V_1\, H_{V1} + F_1\, H_{F1} = F\, H_F} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

which H is enthalpy of liquid (assuming constant specific heat) and λ is latent heat of vaporization of steam (from steam table)

$$\boxed{H = c\,(T - T_{reff})} \qquad \text{and} \qquad \boxed{\lambda = H_V - H_L}$$

repeat the process for 2nd and 3rd effect, yield :

$$\boxed{V_1\, H_{V1} - V_2\, H_{V2} + F_1\, H_{F1} - F_2\, H_{F2} = 0} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\boxed{V_2\,H_{V2} - V_3\,H_{V3} + F_2\,H_{F2} = P\,H_P} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

now calculate heat exchanger duty inside evaporator

$$Q = U\,A\,(T_{hot} - T_{cold}) = m\,\lambda$$

for 1st effect :

rearranging

$$A_1 = \frac{S\,\lambda_S}{U_1(T_s - T_1)}$$

$$\boxed{A_1 = \frac{S\,\lambda_S}{q_s}} \qquad \text{which} \quad U_1\,(T_s - T_1) = q_s$$

for 2nd and 3rd effect :

$$\boxed{A_2 = \frac{V_1\,\lambda_1}{q_1}} \qquad \text{and} \qquad \boxed{A_3 = \frac{V_2\,\lambda_2}{q_2}}$$

because heat transfer area each effect are equal, we get :

from 1st and 2nd effect :

because heat transfer area each effect are equal, we get :

$$A_1 = A_2$$

$$\frac{S\,\lambda_S}{q_s} = \frac{V_1\,\lambda_1}{q_1}$$

$$\boxed{S\,\lambda_S\,q_1 - V_1\,\lambda_1\,q_s = 0} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

repeat for 2nd and 3rd effect :

$$\boxed{V_1\,\lambda_1\,q_2 - V_2\,\lambda_2\,q_1 = 0} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Finally we have six equations with six unknown variables (S, V_1, V_2, V_3, F_1, and F_2). Now we have to assembling all those equations and solve it. We can easily solve those equations using matrix since this is linear algebra problem.

$$0S + V_1 + V_2 + V_3 + 0F_1 + 0F_2 = V \qquad \ldots\ldots\ldots\ldots (1)$$

$$\lambda_S\, q_1\, S - \lambda_1\, q_s V_1 + 0V_2 + 0V_3 + 0F_1 + 0F_2 = 0 \qquad \ldots\ldots\ldots\ldots (5)$$

$$0S + \lambda_1\, q_2 V_1 - \lambda_2\, q_1 V_2 + 0V_3 + 0F_1 + 0F_2 = 0 \qquad \ldots\ldots\ldots\ldots (6)$$

$$- S\,\lambda_S + V_1 H_{V1} + 0V_2 + 0V_3 + H_{F1} F_1 + 0F_2 = F H_F \qquad \ldots\ldots\ldots\ldots (2)$$

$$0S + H_{V1} V_1 - H_{V2} V_2 + 0V_3 + H_{F1} F_1 - H_{F2} F_2 = 0 \qquad \ldots\ldots\ldots\ldots (3)$$

$$0S + 0V_1 + H_{V2} V_2 - H_{V3} V_3 + 0F_1 + H_{F2} F_2 = P H_P \qquad \ldots\ldots\ldots\ldots (4)$$

in matrix form :

$$\begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 \\ \lambda_S q_1 & -\lambda_1 q_S & 0 & 0 & 0 & 0 \\ 0 & \lambda_1 q_2 & -\lambda_2 q_1 & 0 & 0 & 0 \\ -\lambda_S & H_{V1} & 0 & 0 & H_{F1} & 0 \\ 0 & H_{V1} & -H_{V2} & 0 & H_{F1} & -H_{F2} \\ 0 & 0 & H_{V2} & -H_{V3} & 0 & H_{F2} \end{bmatrix} \begin{bmatrix} S \\ V_1 \\ V_2 \\ V_3 \\ F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} V \\ 0 \\ 0 \\ H_F \\ 0 \\ H_P \end{bmatrix}$$

now calculate other things :

concentration leaving 1st and 2nd effect, (x_1 and x_2) :

$$\boxed{x_1 = \frac{x_F F}{F_1}} \qquad \boxed{x_2 = \frac{x_1 F_1}{F_2}}$$

steam economy

$$Steam\,economy = \frac{V_1 + V_2 + V_3}{S}$$

The Code >>>

The Code

evaporator.py

```python
"""
Created on Sun May 30 20:54:10 2021
@author: Naufal Hadi
"""
# This python file are compute material and energy balance on
# triple effect evaporator

# import necessary modules
import numpy as np
import scipy.linalg

# define feed and product condition
F = 10000 # feed flow, kg/h
xf = 0.28 # feed concentration, mass fraction
xp = 0.88 # product concentration, mass fraction

# define steam properties
P = 3.5 # steam pressure, bar
Ts = 133 # steam temperature, deg celsius

# temperature of feed and each effect
T = np.array([75, 123, 113, 103]) # deg celcius

# define enthalpy of saturated vapor and saturated liquid from steam tables
# enthalpy of saturated vapor at 133, 123, 113, 98, and 50 deg C
Hv = np.array([2731.63, 2705.9, 2695.77, 2672.8]) # kJ/kg

# enthalpy of saturated liquid at 133, 123, 113, 98, and 50 deg C
Hl = np.array ([559.93, 516.41, 475.2, 410.44]) # kJ/kg

# specific heat (respectively to F, F1, F2, F3, and P)
cp = np.array([3.70, 3.39, 2.82, 2.64]) #kJ/kg C

# overall heat transfer coefficient each effect
U = np.array([1230, 895, 895]) # W/(m2 C)
#---------This is computation section---------------------
# solving material balance for glycerine and water
P = F*xf/xp # final product flow, kg/h
V = F-P # overall vapor flow, kg/h

# calculate enthalpy of feed and intermediate product
Tref = np.ones(4)*25 #set reference temperature, deg C
H = cp*(T-Tref)
```

The Code (cont.)

```
# calculate heat duty on heat exchanger region
qs = U[0]* (Ts - T[1])
q1 = U[1]* (T[1] - T[2])
q2 = U[2]* (T[2] - T[3])
q = np.array([qs, q1, q2])

# calculate latent heat of vaporization of steam (Hv - Hl) for heat exchanger
lamda = Hv - Hl # kJ/kg

# construct the matrix
eq1 = np.array([0, 1, 1, 1, 0, 0])
eq2 = np.array([lamda[0]*q[1], lamda[1]*q[0]*(-1), 0, 0, 0, 0])
eq3 = np.array([0, lamda[1]*q[2], lamda[2]*q[1]*(-1), 0, 0, 0])
eq4 = np.array([lamda[0]*(-1), Hv[1], 0, 0, H[1], 0])
eq5 = np.array([0, lamda[1], Hv[2]*(-1), 0, H[1], H[2]*(-1)])
eq6 = np.array([0, 0, lamda[2], Hv[3]*(-1), 0, H[2]])

#now make it matrix form
A = np.array([eq1, eq2, eq3, eq4, eq5, eq6])
B = np.array([V, 0, 0, F*H[0], 0, P*H[3]])

# start computing
C = flows =scipy.linalg.solve(A,B) # solver for linear algebra

# store all solution
S, V1, V2, V3, F1, F2 = C[0], C[1], C[2], C[3], C[4], C[5]

# calculate other parameters
x1 = F*xf/F1 # concentration in 1st effect, mass fraction
x2 = F1*x1/F2 # concentration in 2nd effect, mass fraction
Se = (V1 + V2 + V3)/S # steam economy
C = S + V1 + V2

# print all solutions
print("Simulation Report :")
print("----------------------------------------------------------------")
print("Steam consumption, S                  :" , S, "kg/h")
print("Vapor flow in 1st effect, V1          :" , V1, "kg/h")
print("Vapor flow in 2nd effect, V2          :" , V2, "kg/h")
print("Vapor flow in 3rd effect, V3          :" , V3, "kg/h")
print("Total water removed, V                :" , V, "kg/h")
print("Intermediate flow in 1st effect, F1   :" , F1, "kg/h")
print("Intermediate flow in 2nd effect, F2   :" , F2, "kg/h")
print("Final product flow, P                 :" , P, "kg/h")
print("Total condensate recovery, C          :" , C, "kg/h")
print("Concentration leaving 1st effect, x1 :" , x1)
print("Concentration leaving 2nd effect, x2 :" , x2)
print("Steam economy                         :" , Se, "kg water/ kg steam")
```

This code are available in my github page. You can download or pull the code for free. To run the code just simply type in terminal :

```
python evaporator.py
```

Then we get :

```
Out
Simulation Report :
-----------------------------------------------------------------
Steam consumption, S                   : 3217.9022193322226 kg/h
Vapor flow in 1st effect, V1           : 2322.4567363156557 kg/h
Vapor flow in 2nd effect, V2           : 2289.9506881547377 kg/h
Vapor flow in 3rd effect, V3           : 2205.7743937114224 kg/h
Total water removed, V                 : 6818.181818181818 kg/h
Intermediate flow in 1st effect, F1    : 7687.624366164756 kg/h
Intermediate flow in 2nd effect, F     : 5906.66505446536 kg/h
Final product flow, P                  : 3181.8181818181824 kg/h
Total condensate recovery, C           : 7830.309643802616 kg/h
Concentration leaving 1st effect, x1   : 0.36422175000166923
Concentration leaving 2nd effect, x2   : 0.4740407614417272
Steam economy                          : 2.1188281537021725 kg water/ kg steam
```

Simulation result :

Steam consumption, S	: 3217.9022193322226 kg/h
Vapor flow in 1st effect, V_1	: 2322.4567363156557 kg/h
Vapor flow in 2nd effect, V_2	: 2289.9506881547377 kg/h
Vapor flow in 3rd effect, V_3	: 2205.7743937114224 kg/h
Total water removed, V	: 6818.181818181818 kg/h
Intermediate flow in 1st effect, F_1	: 7687.624366164756 kg/h
Intermediate flow in 2nd effect, F_2	: 5906.66505446536 kg/h
Final product flow, P	: 3181.8181818181824 kg/h
Total condensate recovery, C	: 7830.309643802616 kg/h
Concentration leaving 1st effect, x_1	: 0.36422175000166923
Concentration leaving 2nd effect, x_2	: 0.4740407614417272
Steam economy	: 2.1188281537021725 kg water/ kg steam

Thanks for your time !

Enjoy this post and feel free to like and comment.

End