8th Jan 2019
Tuesday

CAPE
Lecture 2

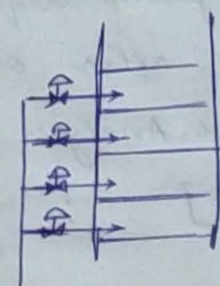
I/P $\longrightarrow$ Process $\longrightarrow$ O/P

Analyse
$\downarrow$
Math Equation

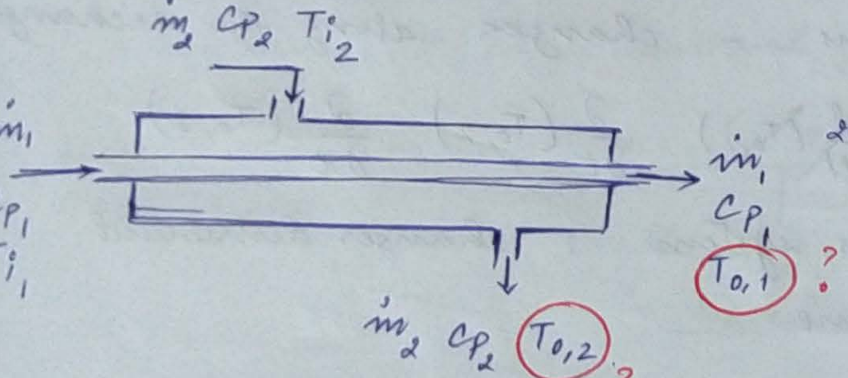
Variables ? Design
operating
IPC – control / manipulated
parameters
constants

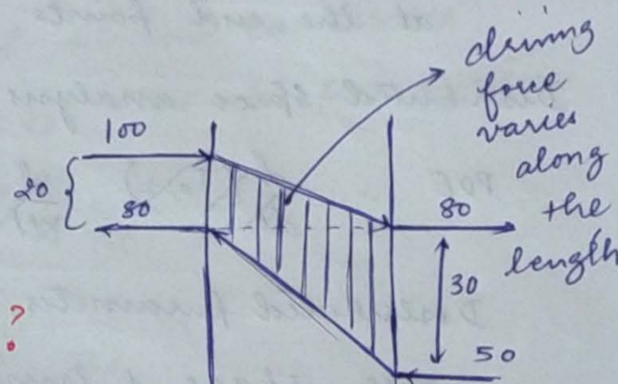
- Locating the feed tray – Parametric study
  [not truly variable]

- constants – physical properties



- Math Eqn $\rightarrow$ Algebric
  $\rightarrow$ ODE
  $\rightarrow$ PDE





$$Q = \dot{m}_1 Cp_1 (T_{i,1} - T_{0,1}) = \dot{m}_2 Cp_2 (T_{i,2} - T_{0,2}) \quad \ldots (1)$$

Science
$\downarrow$
Area – Engg.

Cost of a shell & tube exchanger $= K_1 (A)^{0.7}$

Area dictates the cost of the equipment

$$Q = UA(LMTD) \quad \ldots (2)$$

S.S model

$\hookrightarrow$ driving force changes along the length
[not const]

9th Jan 2019
Thursday

CAPE
Lecture 2

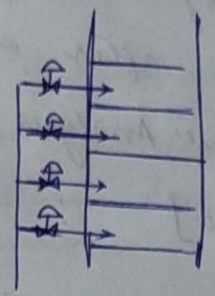
I/P → Process → O/P

Analyse
↓
Math Equation

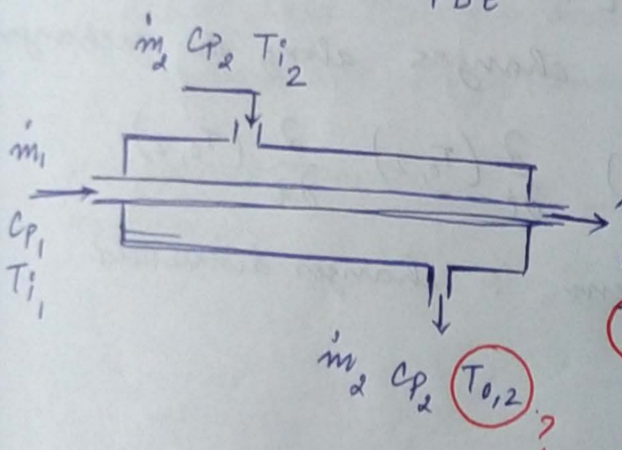
Variables ? Design
Operating
IPC – control / manipulated parameters
Constants

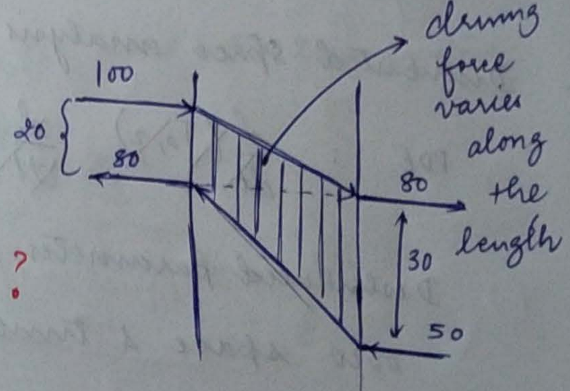
- Locating the feed tray – Parametric study
  [not truly variable]

- Constants – physical properties



- Math Eqn → Algebric
  → ODE
  → PDE



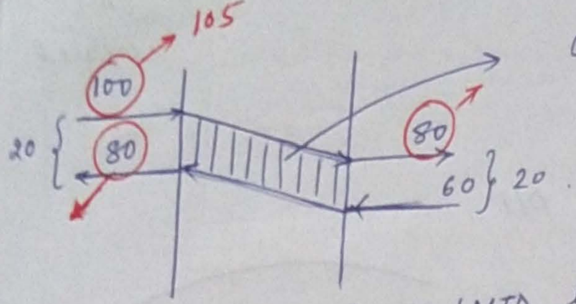


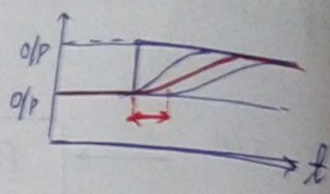
$$Q = \dot{m}_1 C_{P_1} (T_{i,1} - T_{0,1}) = \dot{m}_2 C_{P_2} (T_{i,2} - T_{0,2}) \quad \ldots (1)$$ Science
↓
Cost of a shell & tube exchanger $= k_1 (A)^{0.7}$ ← Area – Engg.
dictates the cost of the equipment

$$Q = UA(LMTD) \quad \ldots (2)$$

$\boxed{\text{S.S model}}$

↳ driving force changes along the length [not const]





- here, we donot use LMTD to calculate the temp diff.
- We proceed by guessing one variable & the converging the other variable.
- Two initial guess - w time (?)
- IFD - Information flow diagram
- The system requires some time to achieve steady state after one of the variable is changed.
- Dynamic Analysis - changes w.r.t time [we require a ODE] : $\frac{d}{dt}(T_{0,2})$, $\frac{d}{dt}(T_{0,1})$

  at the end points. [Lumped Parameter].
- Distributed space analysis - changes along the exchanger

  PDE : $\cancel{\frac{d}{dt}(T_{0,2})}$. $\cancel{\frac{d}{dt}(T_{0,1})}$. $\frac{\partial}{\partial t}(T_{0,2})$. $\frac{\partial}{\partial x}(T_{0,2})$.

  Distributed parameter system : changes distributed over space & time

- Mathematical Eqn
  - ↳ Analytical
  - ↳ Numerical

- Discretization

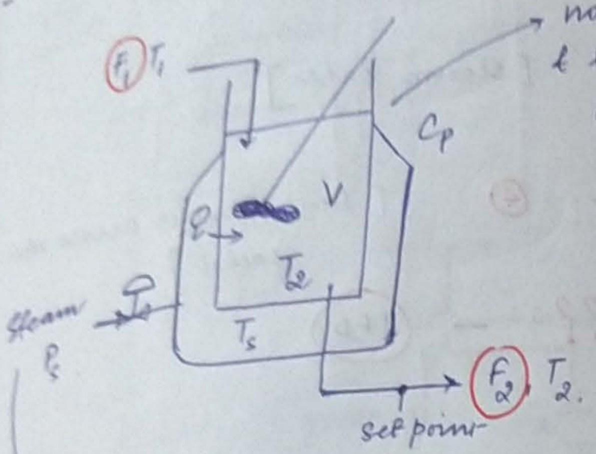
$$\underbrace{\frac{dx}{dt}}_{\text{derivative}} = \underbrace{\frac{x^{n+1} - x^{n}}{\Delta t}}_{\text{algebric}} + \underbrace{E}_{\text{error}}.$$

↳ can propogate with time

- Stability should of the solution should be considered

- After getting the numerical values we plot colorful contours of the solution

- Conversion of ODE ⇒ IFD



normal mixing & heating [no reaction]

can be saturated OR superheated

as heat transfer fluid ↓ saturated steam

T.P.P. [Thermal Power Plant] ↳ as W.f – Steam-Turbine

Thermodynamics

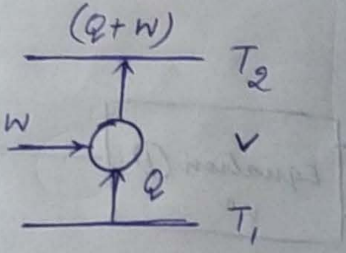
HT + Work

↓

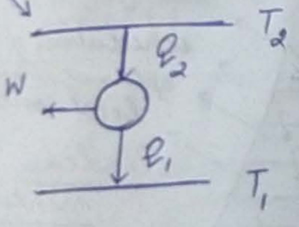
Superheated steam do not heat the turbine & steam does not condense.

Latent heat transfer occurs & steam condenses giving out large amount of heat to the system

Heat pump



Heat engine



Assumptions : ① uniform mixing

② No heat loss

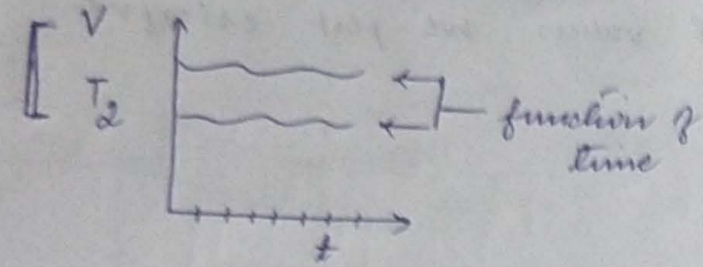
dynamic study : $F_1 - F_2 = \frac{dV}{dt}$ .... ①

[overall mass balance]

$$F_1 C_p T_1 - F_2 C_p T_2 + \frac{Q}{\rho} = \frac{d}{dt}(V C_p T_2) \quad \ldots \text{②}$$

[overall heat balance]

CV



$T_s = f(P_s)$ .... ③ [steam table]

$Q = (UA)[T_s - T_2]$ .... ④ [heat transfer across the jacket]

Algorithm to solve the eq^n ?? → IFD

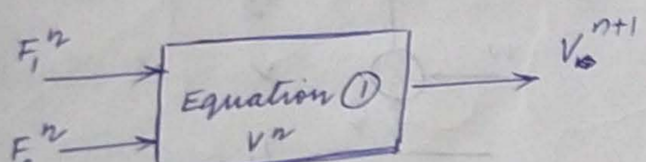
$\boxed{}$ → represents the eq

I/P: F_1, F_2 → $\boxed{1}$ → V (O/P) ⟶ the block contains derivative of V.

$$\frac{V^{n+1} - V^n}{\Delta t} = F_1^n - F_2^n$$

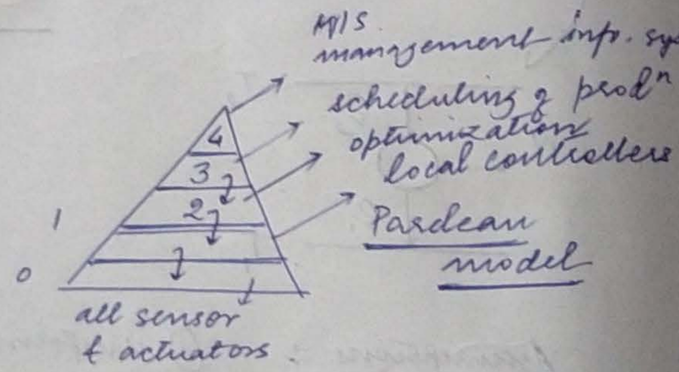
$$V^{n+1} = V^n + \Delta t\,(F_1^n - F_2^n) \quad \text{(explicit)}$$

①



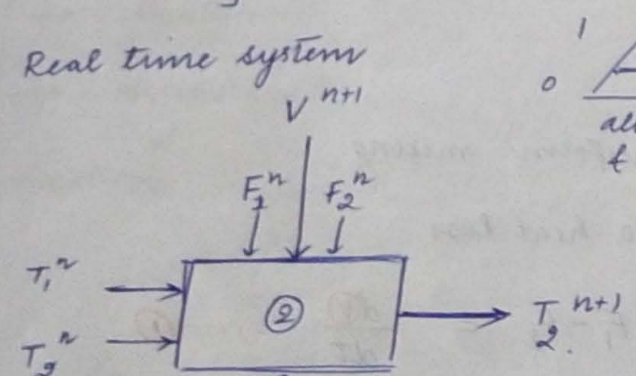
[n - time step]

- Real time system

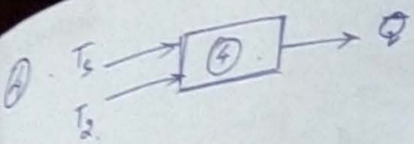


Pardean model

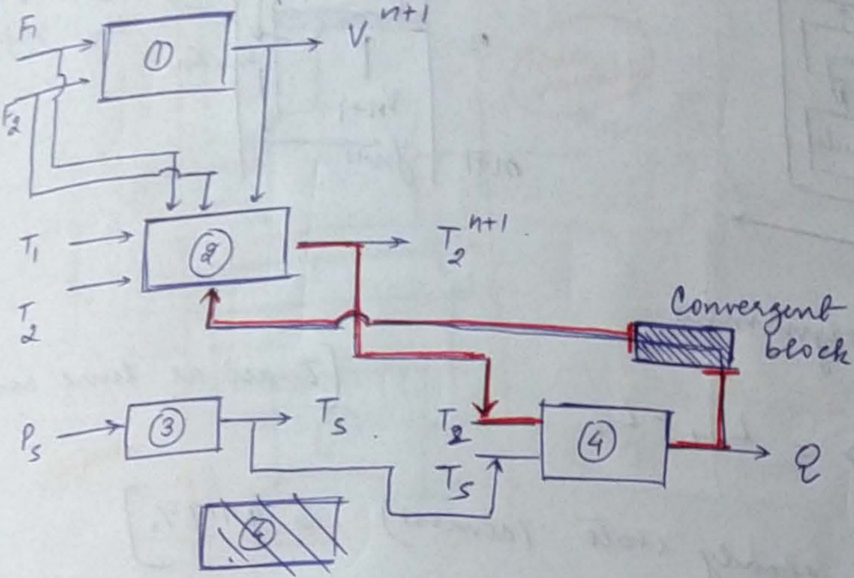
②



③ $P_s \rightarrow \boxed{3} \rightarrow T_s$.



IFD



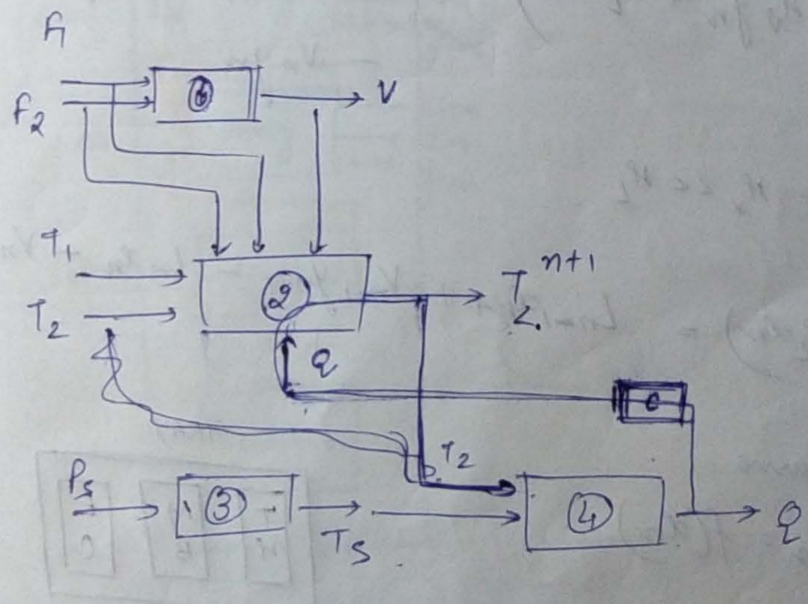
→ to close the gap b/w Q_{guess} & Q_{actual} (calculated).

Implicit eqn: $ax^3 + bx^2 + cx + d = 0$.

$$x = \frac{-(ax^3 + bx^2 + d)}{c}$$

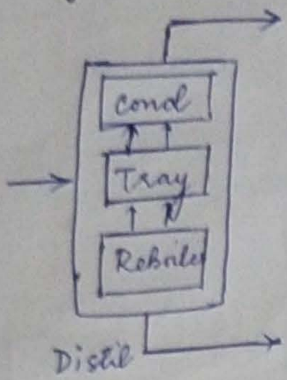
x_{n+1} $\quad$ x_n

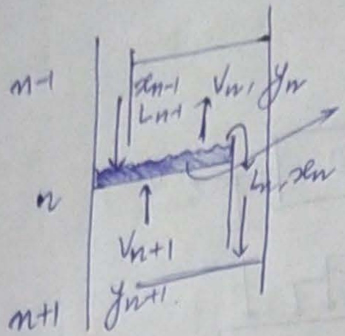
$$\underset{x_{n+1}}{x} = f(\underset{x_n}{x})$$



14th Jan 19
Monday

Binary Distillation Column





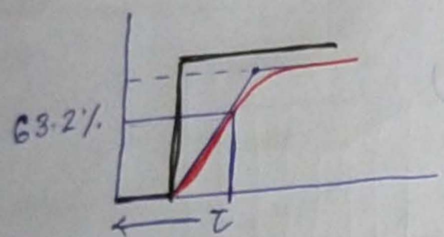
H_L - liq holdup
H_V - vap holdup

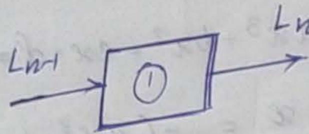
① Tray hydrodynamics

[τ act as time constant]

$$\tau \frac{dL_n}{dt} = L_{n-1} - L_n$$

[$t = 5\tau$ gives steady state (almost) ~ 99.9%]





② Mass balance of n^{th} tray.

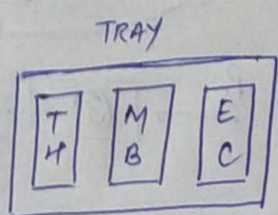
$$\frac{d}{dt}\left(H_V y_n + H_L x_n\right) = L_{n-1} x_{n-1} + V_{n+1} y_{n+1} - L_n x_n - V_n y_n$$

Assumption $H_V << H_L$.

$$\frac{d}{dt}(H_L x_n) = L_{n+1} x_{n+1} + V_{n+1} y_{n+1} - L_n x_n - V_n y_n$$

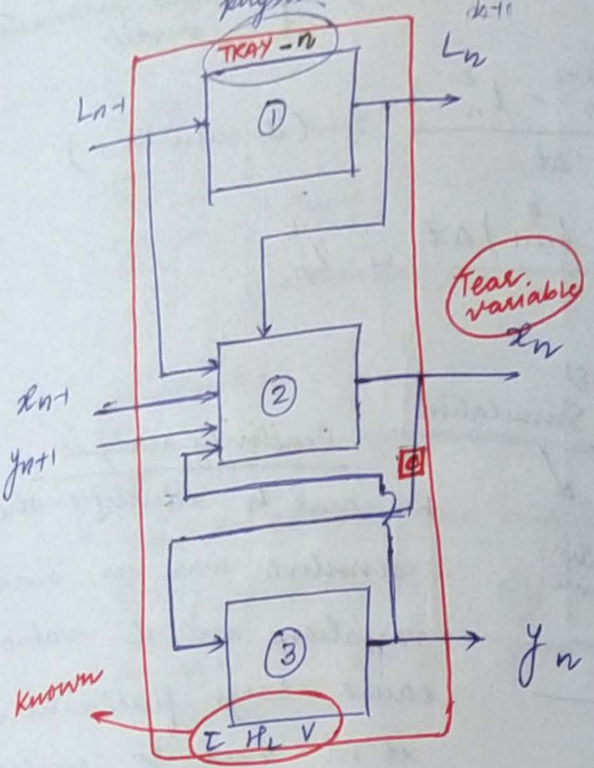
③ Eq^n curve

$$y_n = f(x_n)$$



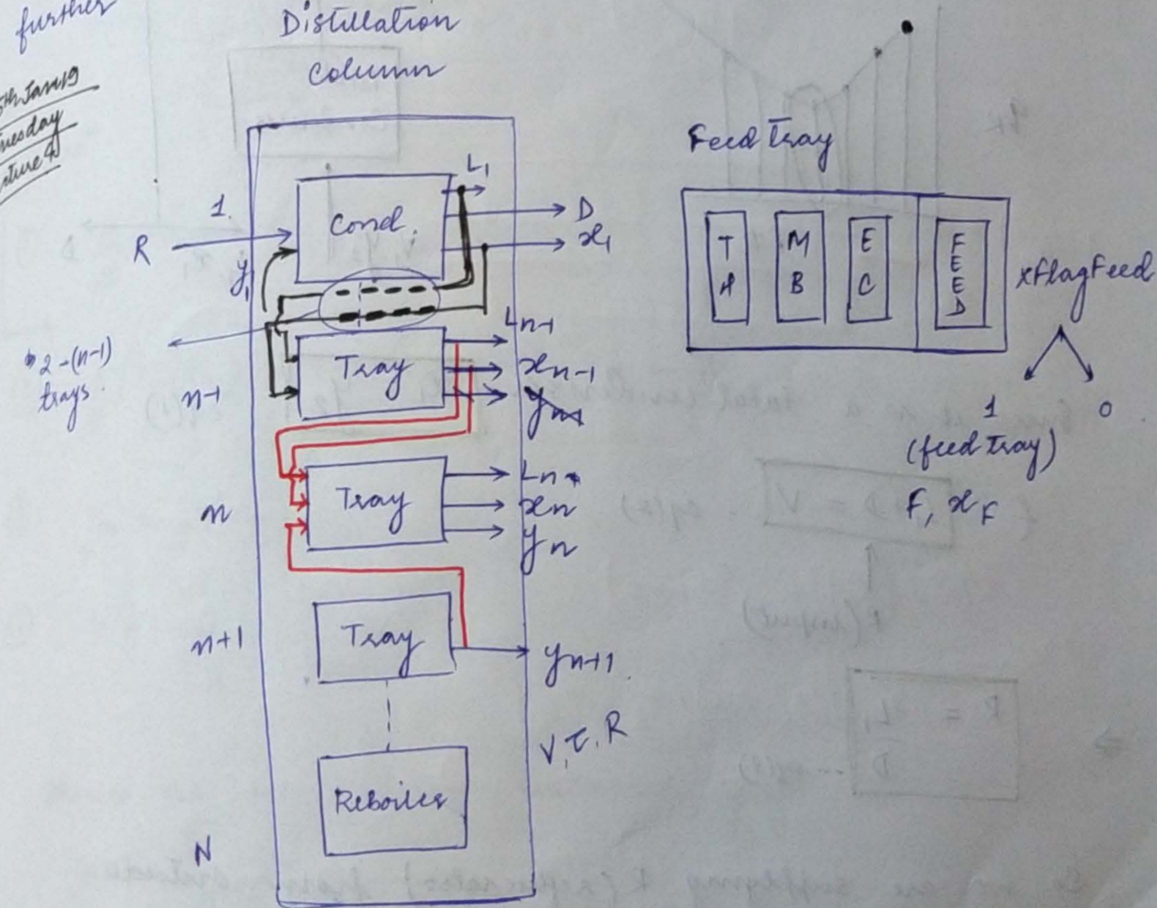
Similar to the physical model.

IFD



here, we can guess x_n then can calculate y_n & move further

15th Jan 19 Tuesday Lecture 4

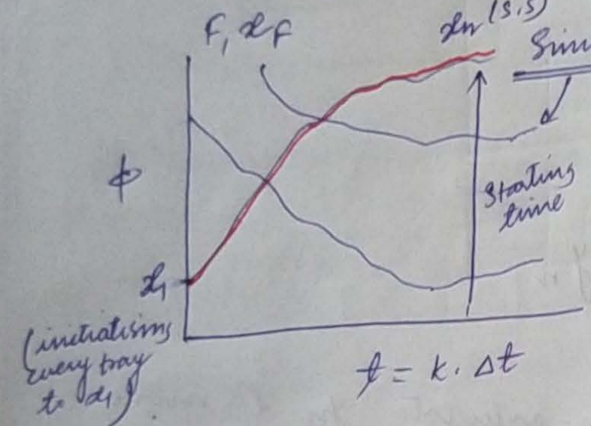


All calculations are inside the boundary but F & x_F are from outside & connect the system to other equipments. Reflux ratio is also from outside.

$$L_n - L_{n-1} = \tau \frac{dL_n}{dt}$$ (explicit) [Lumped parameter model]

$$L_n^k - L_{n-1}^k = \tau \frac{L_n^{k+1} - L_n^k}{\Delta t}$$ (discretization)

$$L_n^{k+1} = \frac{(L_n^k - L_{n-1}^k)\Delta t}{\tau} + L_n^k$$

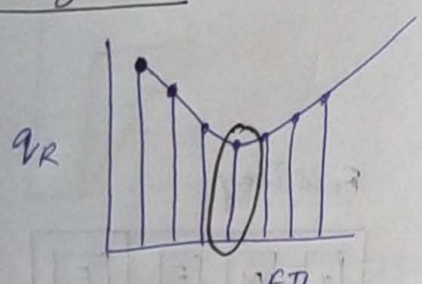


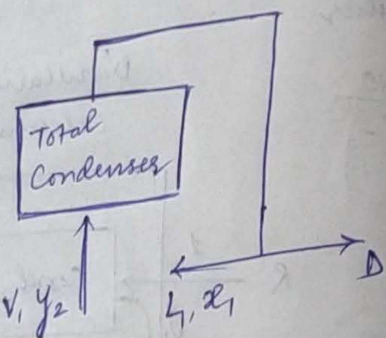
Simulation

Sensitivity analysis

We need to identify the most sensitive var. as small variations in its value can cause large fluctuation so it we need to control it more.

Optimization





Since it is a total condenser $\boxed{x_1 = y_2}$ ... eq(1)

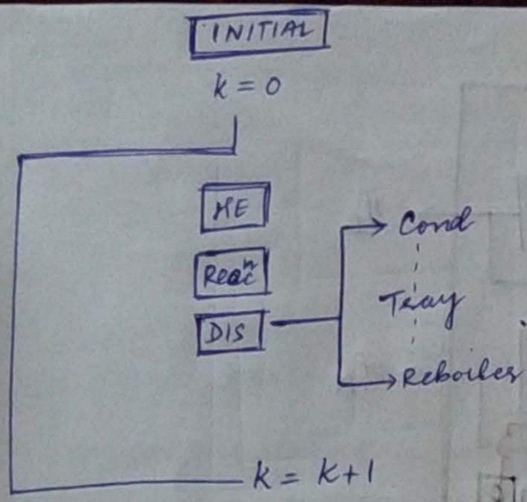
& $\boxed{L_1 + D = V}$ ... eq(2)

R(input)

$\Rightarrow$ $\boxed{R = \frac{L_1}{D}}$ ... eq(3)

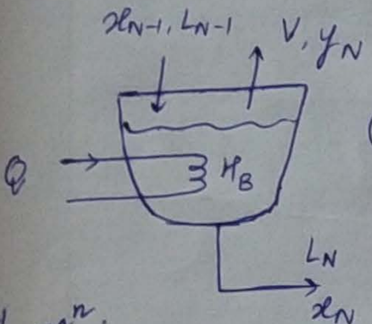
So we are supplying R (reflux ratio) from outside.

- Lumped Parameter Model (ODE - $\frac{d}{dt}$)
- Distributed Parameter Model. [PDE]
  acc. for spatial changes as well.
  ($\frac{\partial}{\partial t}$, $\frac{\partial}{\partial x}$, $\frac{\partial}{\partial y}$ & $\frac{\partial}{\partial z}$)



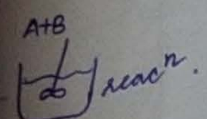
Outside time loop.

There are nested convergence block & are solved step by step. After solving for $(k+1)^{th}$ step then we can solve for $(k+2)^{th}$ step and so on.



N

Reboiler



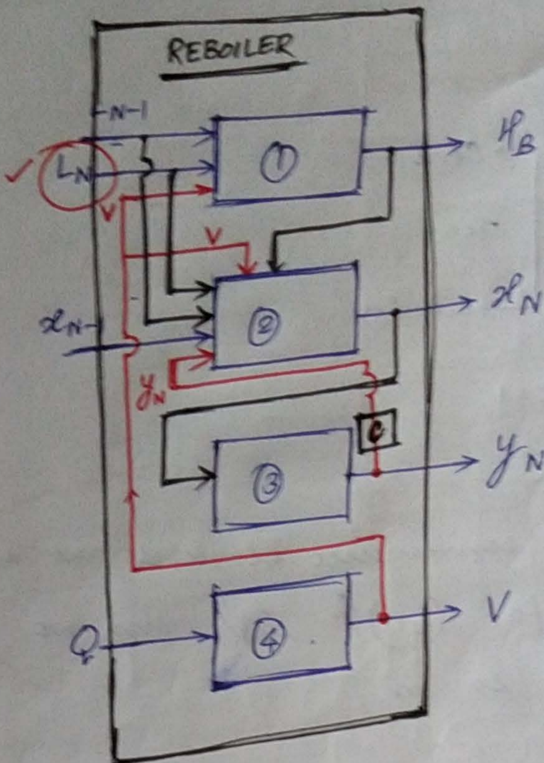
① $$\frac{d}{dt}(H_B) = L_{N-1} - L_N - V$$

② $$\frac{d}{dt}(H_B \cdot x_N) = L_{N-1}x_{N-1} - L_N x_N - V y_N$$

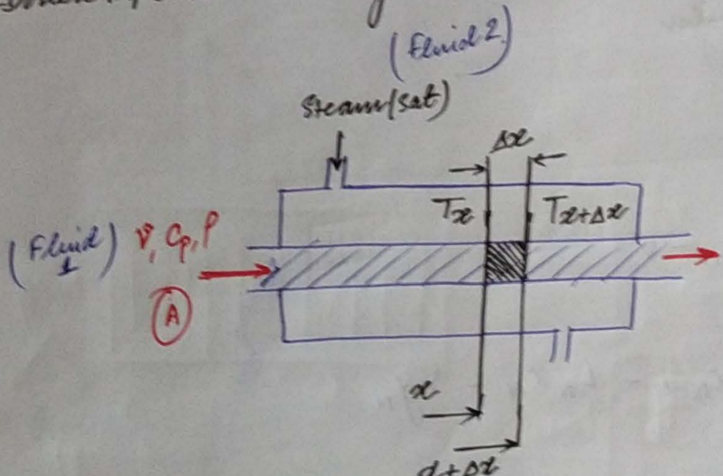
③ $$y_N = f(x_N)$$

④ $$V = \frac{Q}{\lambda}$$

There's no total heat balance, just for the vapourization part.



Double Pipe Heat Exchanger



$$(v A \rho) C_p (T_x - T_{x+\Delta x}) + h(A_s \cdot \Delta x)(T_s - T_x) = \frac{\partial}{\partial t}(A \cdot \Delta x \cdot \rho\, C_p \cdot T)$$

$$\Rightarrow \quad (v A \rho) C_p \frac{\partial T}{\partial x} + h(A_s)(T_s - T) = \frac{\partial}{\partial t}(A \rho C_p T)$$

→ Split ~~value~~ Boundary value Problem [SBVP]

PINCH TECHNOLOGY

MER – Maximum Heat Recovery

Stream → hot $T_i > T_f$
$\dot{m}C_p = CP$ → cold $T_f > T_i$

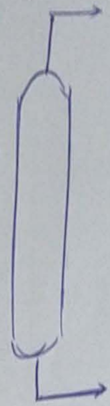
Heat exchanger (stream + stream)
Cooler (hot stream + external cold utility)
Heater (cold stream + external hot utility)

utility → Hot
utility → cold

Crude pre-heat train CDU

A typical flow is a follows –

30°C ⟶ Heat exchanger network (through preheat) $\xrightarrow{270^\circ C}$ Furnace $\xrightarrow{360^\circ}$

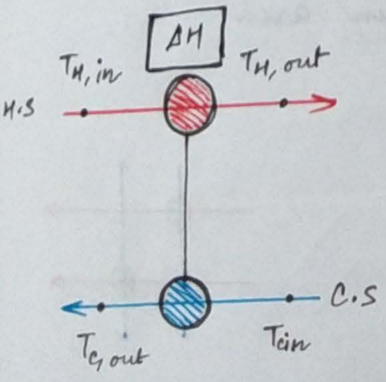


→ Consider 2 streams

	IN	OUT	
I	400	440	CP = 2
II	100	20	CP = 1

can stream I cool stream II

No, because the quality of stream is different. Such a heat exchange is non-spontaneous and violates the second law of thermodynamics.



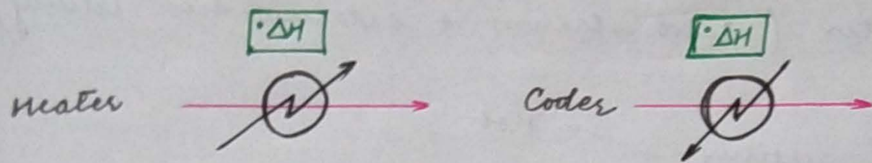
ΔH - heat duty

⟶ Grid representation of the heat exchanger network

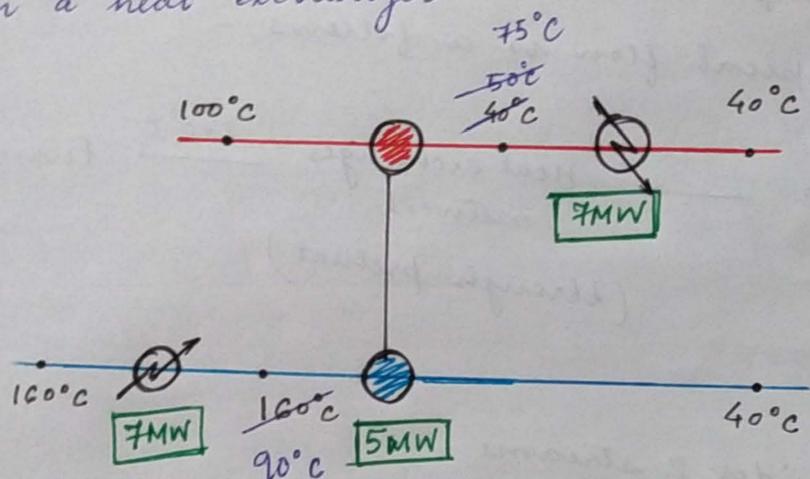
	(°C) T_i	(°C) T_f	(KW/°C) CP	(MW) ΔH
H1	100	40	200	+ 12
C1	40	160	100	− 12

→ Stream table

$\Delta T_{min} = 10°C$



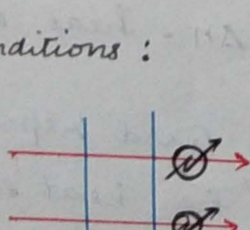
Approach temp – The temp (closest) b/w HS & CS in a heat exchanger



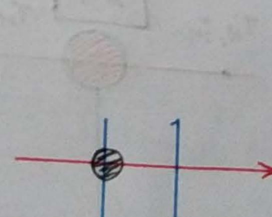
The temperatures have been scratched out to honour the ΔT_{min} (the minimum approach temp)

*Note: Lesser the min approach temp, greater the area of HE network. Capital cost increases due to increase in area.

Extreme Conditions :



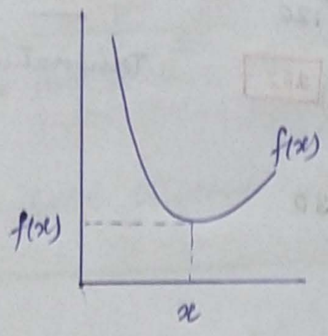
No heat exchanger



No utility - only H.E.

Cost of H.E. is a trade-off b/w the quality of heat exchanger and its extent (ΔT_{min}) and the area

As ΔT_{min} increases, quality ↓ and area ↓ and costs ↓. Optimisation from graph theory & Euler's network theory.



f(x) such that PE is minimum

Q.

	T_i	T_f	CP	ΔH
H1	180	80	1.0	+100
C1	30	120	1.8	−162
H2	130	40	2.0	+180
C2	60	100	4.0	−160
				−42

−42 → Defficit

If $HU = 42 + x$

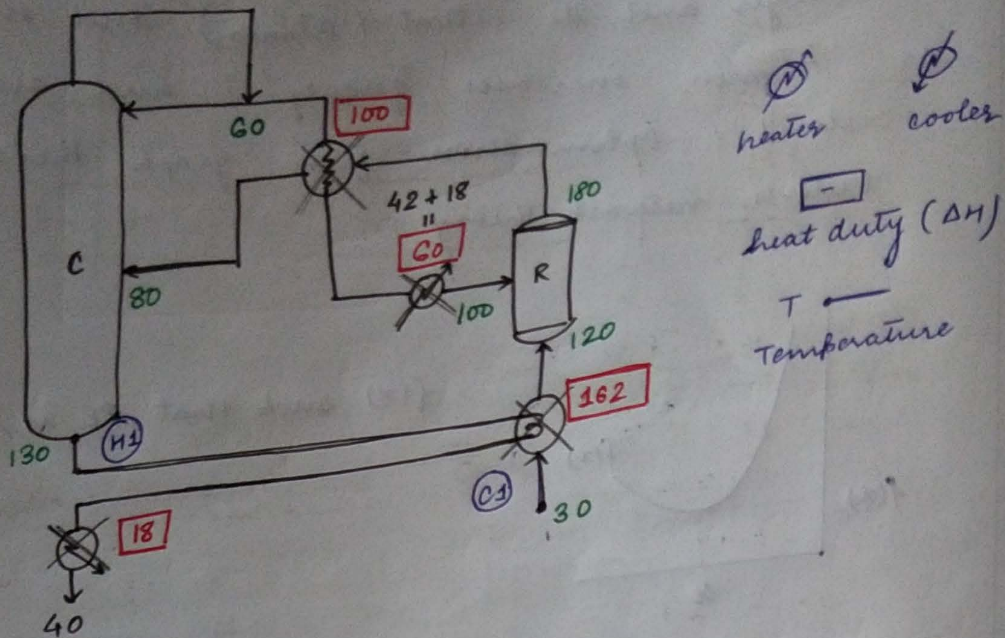
$CU = x$

Case (i) : Extreme condition − No HE.

$CU = 280$

$HU = 322$

29·01·2019



Stream Table ①

St.no.	T_i	T_f	C_p	$\Delta H = C_p \times \Delta T$
C1	30	120	1·8	−162
H1	130	40	2·0	+(162+18) = +180
C2	60	100	4·0	−(100+60) = −160
H2	180	80	1·0	+ 100
				−~~+~~42

$(+180) + (+100) = +280$

$-(162 + 160) = -~~+~~322$

~~+~~−42

Enw +42 +x H.U

x C.U

Endothermic process

We need to supply heat to the process.

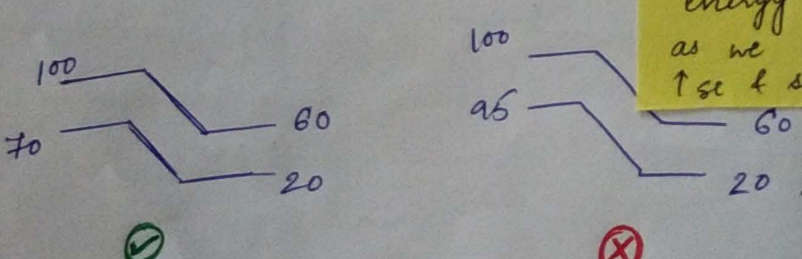
We need to optimize x with Pinch Technology.

– Here we need to optimize x with Pinch Technology. We will remove the existing h.e. & re-design the process but we cannot change values in the stream table, changing stream table values will change the process.

$\Delta T_{min} = 10$

Difference b/w cold stream & hot stream should be greater than or equal to ΔT_{min}

ΔT_{min} is a trade-off b/w energy and capital. Coz as we ↓se ΔT_{min} the area ↑se & so does the cost.



Stream Table ②

	Cp	T_i	T_f	ΔH
C1	2	20	135	-230
H1	3	170	60	330
C2	4	80	140	-240
H2	1.5	150	30	180

Exothermic process

$+510 - 470 = +40$

We need to supply C.U.

$C.U = -(40 + x)$

$\Delta T_{min} = 10$

* Hot stream Temp $- \dfrac{\Delta T_{min}}{2}$
* Cold stream Temp $+ \dfrac{\Delta T_{min}}{2}$

Temp : 20, 135, 170, 60, 80, 140, 150, 30 ← Original

(±) 25, 140, 165, 55, 85, 145, 145, 25 ← Modified

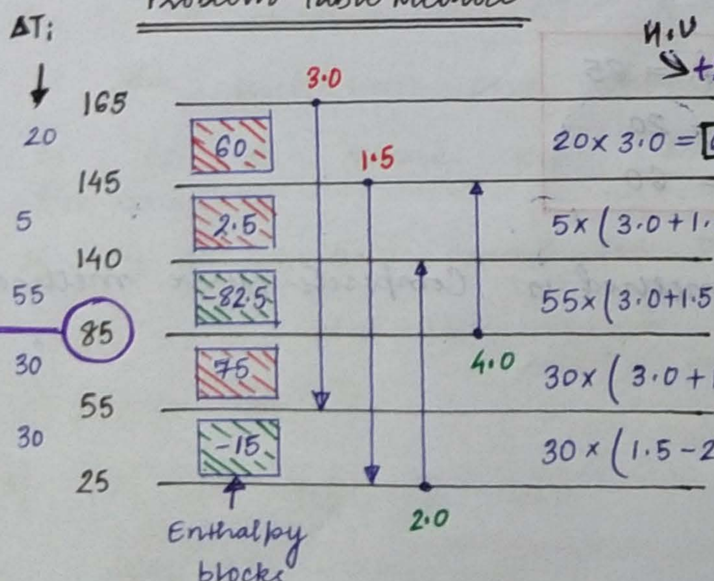
- We are changing the quality of stream but difference b/w T_i & T_f remains same

Sort : 165, 145, 145, 140, 85, 55, 25, 25 ← Descending

165, 145, 140, 85, 55, 25 ← Repeated no.s are removed

Problem Table Method

- Surplus of heat
- Deficient of heat



Cummulative heat is zero. ⇓ T_{pinch}

H.U $= Cp \times \Delta T$

$\Delta H_i = \Sigma Cp_i \times \Delta T_i$

$\Sigma Cp_i = \Sigma Cp_H - \Sigma Cp_C$

+20+x

$20 \times 3.0 = \boxed{60}$ → +20+x

$5 \times (3.0 + 1.5 - 4.0) = 2.5$ → $\boxed{62.5}$ → 82.5 + x

$55 \times (3.0 + 1.5 - 2.0 - 4.0) = -82.5$ → $\boxed{-20}$ → 0 + x PINCH

$30 \times (3.0 + 1.5 - 2.0) = 75$ → $\boxed{55}$ → 75 + x

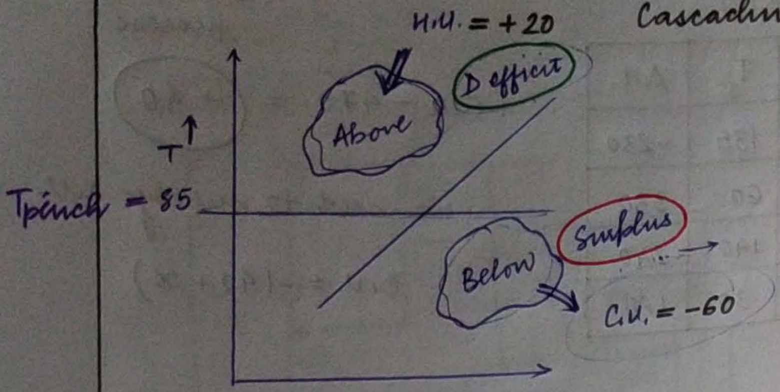
$30 \times (1.5 - 2.0) = -15$ → $\boxed{40}$ → 60 + x.

⇓

$\boxed{C.U. = \cancel{40}}$ 60

Here, we have only a single -ve enthalpy term so we can +20 at the top & now take a cummulative sum ⇒ Cummulative cascading

Cascading of Heat



Surplus
↓
Defficit

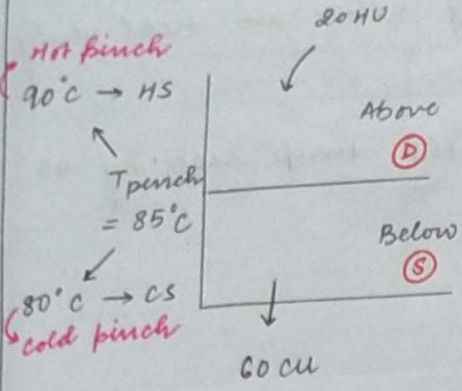
- If surplus is at higher temp then we DONOT need any utility as it is sufficient to provide the defficit.
- But here surplus is at lower temp so we need utilities.
- If we add x amt of heat it gets add to every cummulatively heat which means we can optimize the process further.
- If there ≥ 1 −ve cum heat flow then we need to add the highest −ve cum heat flow.

  e.g. −20, −30, −12

Pinch Temp = 85
Min. HU = 20
Min CU = 60

— Alternative method is Composite curve method.

05.02.2019

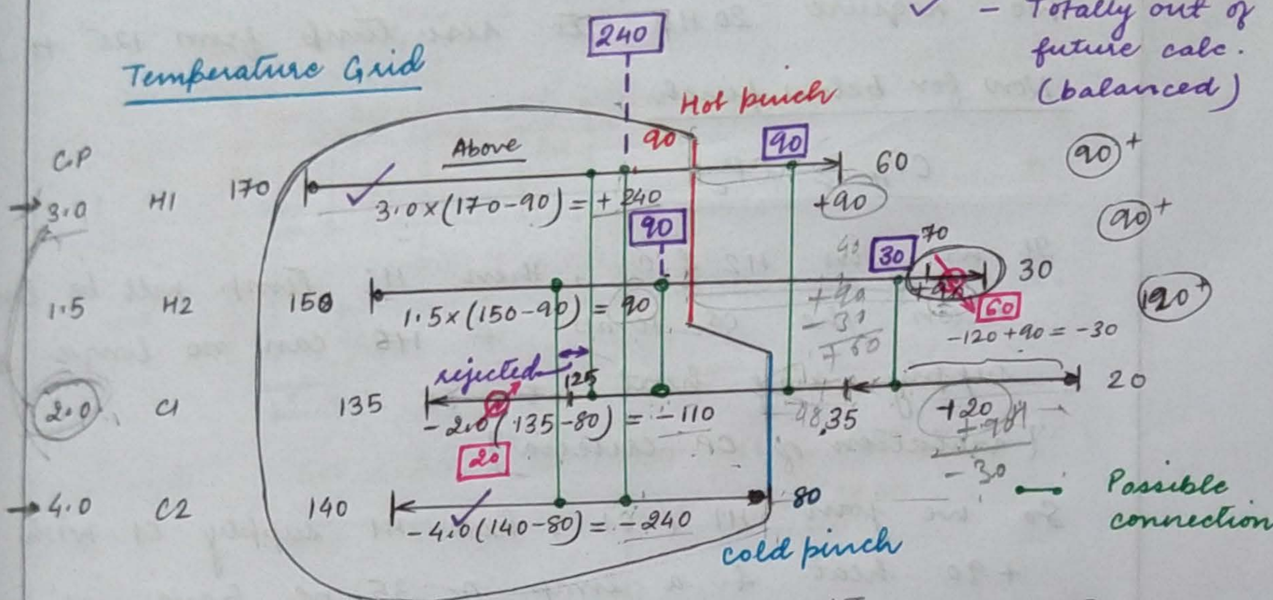


← Heater required [difficient]

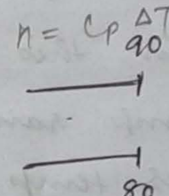
← Only cooler required as it is already surplus

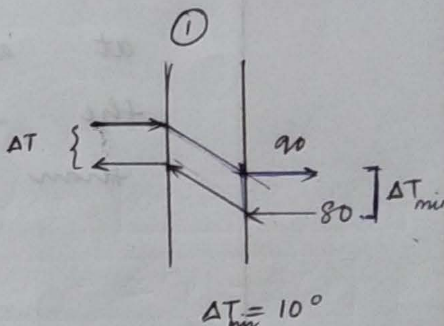
Temperature Grid

✓ – Totally out of future calc. (balanced)



• CP Criteria

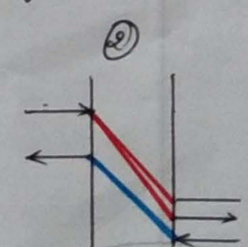




We have 4 possibilities.

Acc to CP criteria the ΔT at the unknown end should be 10° or more than 10° for above.

If CP_s & ΔH are equal for both CS & HS then ΔT will also be equal so we get a temp profile in ①



If CP_s are different then

$$\boxed{CP_H \cdot \Delta T_H = CP_c \cdot \Delta T_c}$$

$$CP_H \downarrow \cdot \Delta T_H \uparrow = CP_c \uparrow \Delta T_c \downarrow$$ ← $CP_c \geq CP_H$

We have one end known to be $\Delta T_{min} = 10$

So we search for highest CP_H and then find CP_c higher than this CP_H & join these

streams
Mention the smaller enthalpy value in heat duty box b/w the 2 streams.

C1 gets 90 (heat) so the temp rise by 45°

$$\Delta T = \frac{90}{2} = 45°$$

$$80 \xrightarrow{+45°} 125$$

We require 20 HU to rise temp from 125° to 135.

Now for below pinch

$$CP_H \geq CP_c$$

If we join H2 & C1, then HS temp will be lower than the CS temp & HS can no longer supply any heat to CS.
[violation of CP criteria]

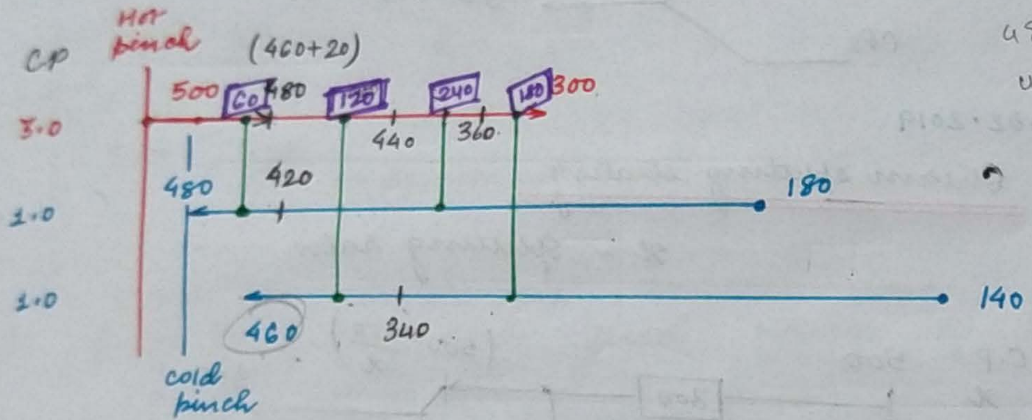
So we join H1 & C1, here H1 supply C1 with +90 heat & a temp of 35 we have arrived at after this we can join H2 & C1 as the temp range does not give HS temp lower than CS temp.

05.02.2019

	T_i	T_f	CP	ΔH
H1	500	300	3	+600
C1	180	480	1	-300
C2	160	460	1	-300

$\Delta T_{min} = 20°C$

480 HS] 20
460 CS



Temp 500, 300, 180, 480, 160, 460

490 290 190 490 170 470

Sort : 490, 470, 290, 190, 170

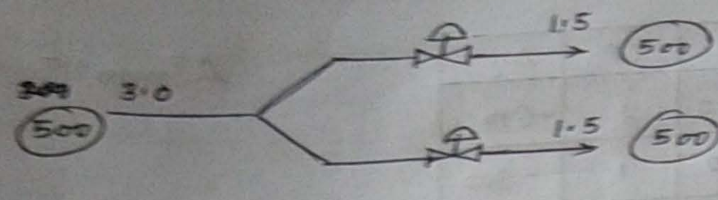
490

470

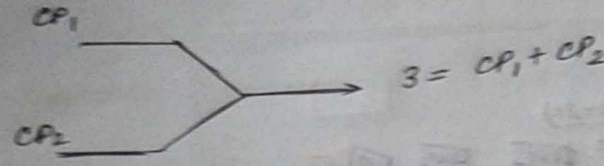
290

190

170



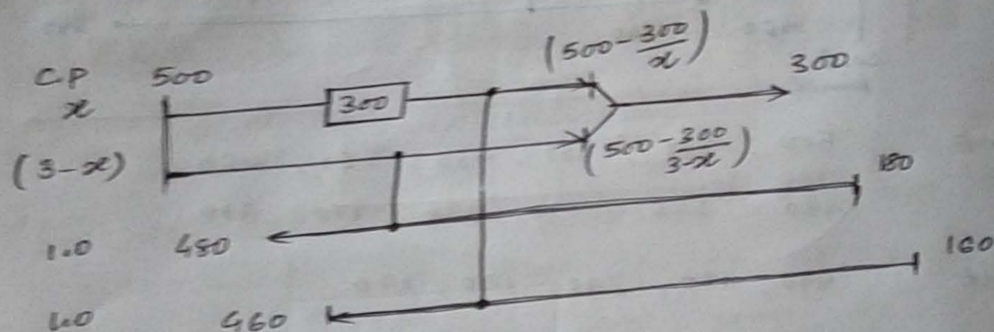
Splitter



08-02-2019

Stream splitting strategy

x - splitting ratio



$$\Delta H = CP \times \Delta T \qquad \Delta T_{min} = 20^\circ C$$

$$C = R \cdot \left(A(m^2)\right)^{0.6}$$

$$Q = UA(LMTD)$$

$$LMTD_1 = \frac{(500-460) - \left[\left(500 - \frac{300}{x}\right) - 160\right]}{\ln\left(\frac{40}{340 - \frac{300}{x}}\right)}$$

$$(UA)_1 = \frac{300}{(LMTD)_1}$$

$$(UA)_2 = \frac{300}{(LMTD)_2}$$

$$\frac{\partial}{\partial x}(\Sigma A) = 0 \qquad [\text{area minimisation}]$$

$$\Sigma C = \alpha \left[A_1^{0.6} + A_2^{0.6} \right]$$

$$\frac{\partial}{\partial x}(\Sigma C) = 0 \qquad [\text{cost minimisation}]$$

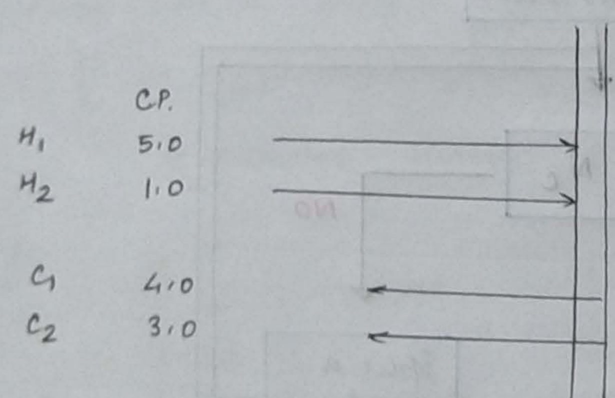
constrainted

$$\begin{cases} 500 - \dfrac{300}{x} \geq 160 + 20 \\[2ex] 500 - \dfrac{300}{3-x} \geq 180 + 20 \end{cases} \qquad [\Delta T_{min} = 20\,°C]$$

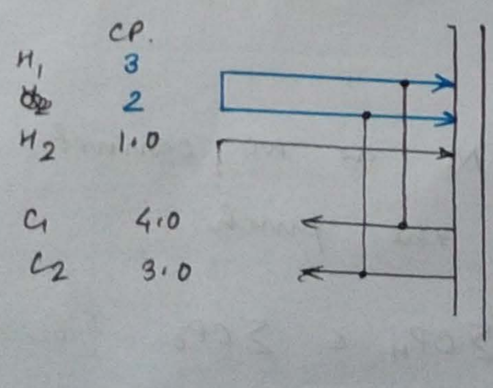
So from here we can find range of x

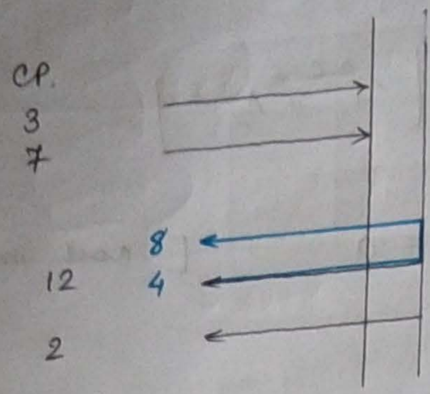
CP criteria

$CP_H \leq CP_C$ (above)



Since, we do not have any cold stream having CP greater than 5.0 (CP of H_1), we need to split H_1

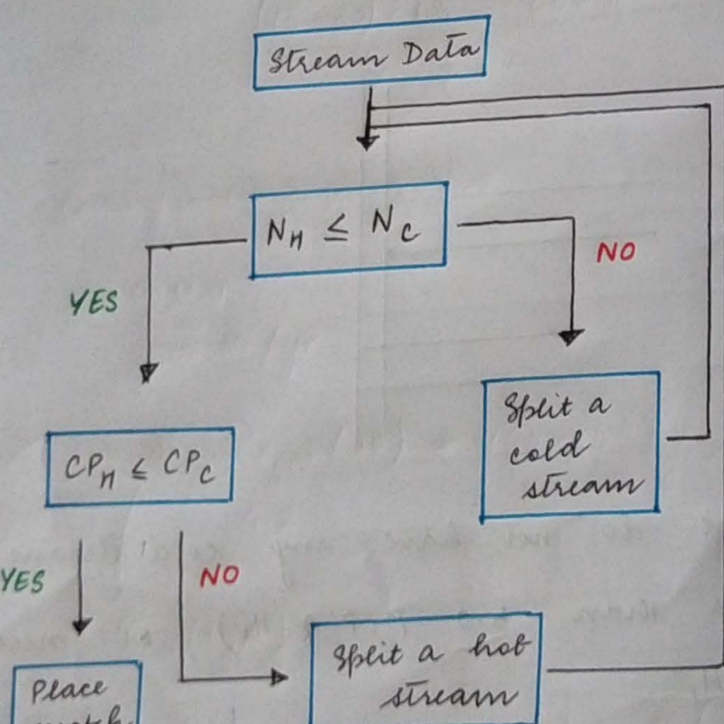




Here, we will split C1 as there will no stream to compensate for H_1.

- A single stream can be split and can be combined later but we CANNOT combine two different streams.

Above Pinch cases : [Algorithm]

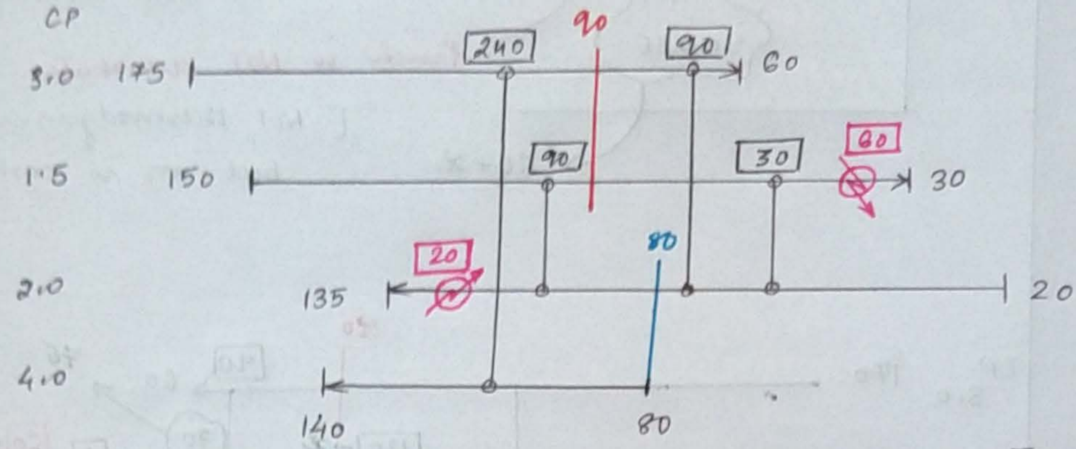


We need $N_H \leq N_C$ as we cannot use a cold utility above the pinch.

Above pinch $\sum CP_H \leq \sum CP_C$ [always true]

So even if split a CS and CP_c goes down we will still have a solution

LOOP & PATH



the concept of path comes when loop is across the pinch

N - no. of stream

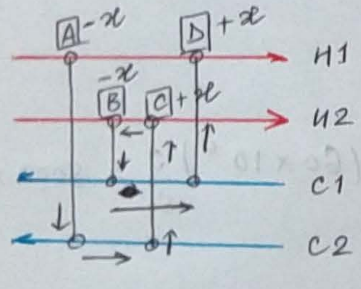
L - no. of loop

$$U_{min} = N + L - 1$$

So we same two streams exchanging heat in two steps but here desire to reduce cost by reducing the no. of heat exchanger & letting them exchange heat in a single step.

[$(A_1 + A_2)^{0.6} < A_1^{0.6} + A_2^{0.6}$ so 1 bigger h.e is better than 2 smaller h.e]

E.g.

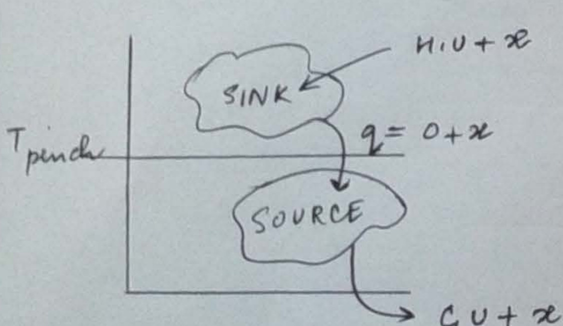


A, B, C, D are heat duties

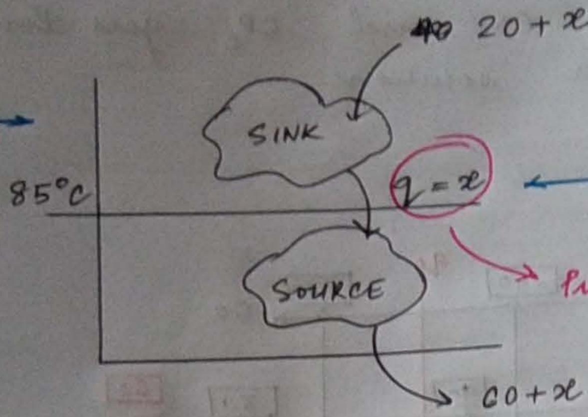
Knowing the least ~~between~~ among them & putting x equal to ~~equal~~ it

Suppose if D is the smallest then $x = -D$

So the heat duties will be $(A+D)$, $(B+D)$, $(C-D)$ & 0



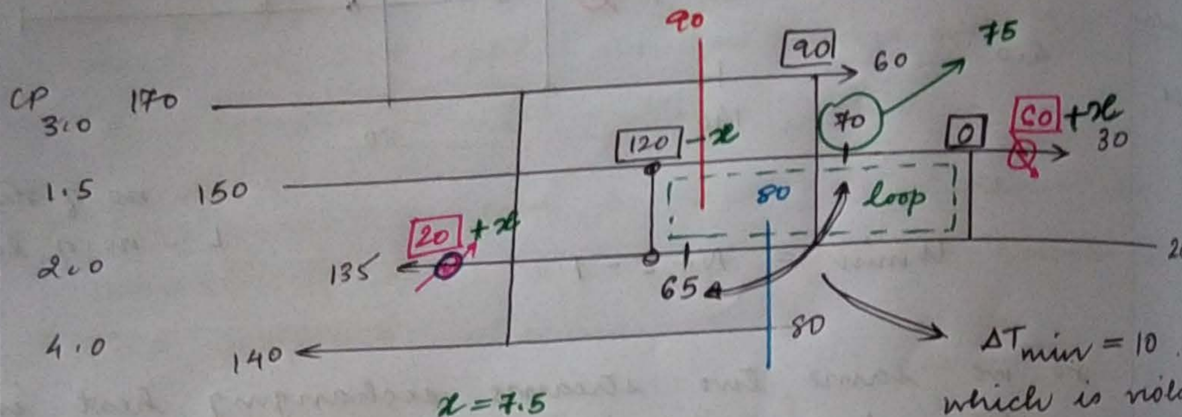
For our ques →



← Path [connection b/w sink and source]

Pinch is NOT adiabatic

[Not thermodynamically optimal but is cost optimal]



$\Delta T_{min} = 10$ which is violated here so we need to make it 10° diff.

$$(75 - 30) \times 1.5 = 60 + x$$

$$x = 7.5$$

cooling water requirement

60 MW

8000 Hr/yr

$$m_{cw} \underset{\overset{\shortparallel}{4.2}}{Cp_{cw}} (10) = (60 \times 10^6) \frac{J}{s} \times 8000 \times 60 \times 60$$

m_{cw} (kg) =

Total Cost (₹) = m_{cw} (kg) × r (₹/kg)