054402 Design and Analysis

LECTURE 7: INTRODUCTION TO HEAT EXCHANGER NETWORK (HEN) SYNTHESIS

Daniel R. Lewin
Department of Chemical Engineering
Technion, Haifa, Israel

Schedule – Introduction to HEN Synthesis

- **Unit 1**. Introduction: Capital vs. Energy
  - What is an optimal HEN design
  - A Simple Example (Class Exercise 1)
  - Setting Energy Targets
- **Unit 2**. The Pinch and MER Design
  - The Heat Recovery Pinch
  - HEN Representation
  - Class Exercise 2
- **Unit 3**. The Problem Table
  - Class Exercises 3 and 4

Schedule – Advanced HEN Synthesis

- **Unit 4**. Loops and Splits
  - Minimum Number of Units by Loop Breaking
  - Class Exercise 5
  - Stream Split Designs
  - Class Exercise 6
- **Unit 5.** Threshold Problems
  - Class Exercise 7

Schedule – Heat and Power Integration

- **Unit 6.** Data Extraction
  - Class Exercise 8
- **Unit 7.** Heat Integration in Design
  - Grand Composite Curve
  - Heat-integrated Distillation
  - Heat Engines
  - Heat Pumps

Part One: Objectives

- The first part of this three-part Unit on HEN synthesis serves as an introduction to the subject, and covers:
  - The "pinch"
  - The design of HEN to meet Maximum Energy Recovery (MER) targets
  - The use of the Problem Table to systematically compute MER targets
- Instructional Objectives:

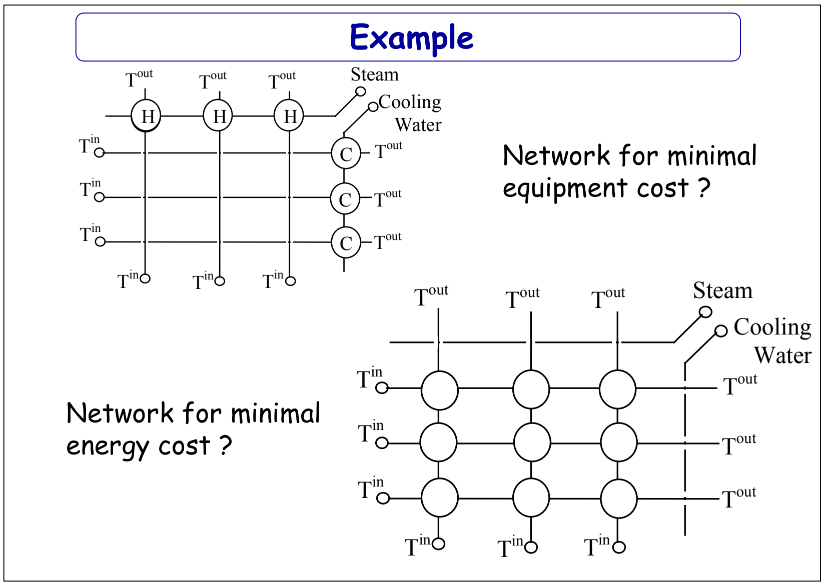
  Given data on hot and cold streams, you should be able to:
  - Compute the pinch temperatures
  - Compute MER targets
  - Design a simple HEN to meet the MER targets

UNIT 1: Introduction - Capital vs. Energy

- The design of Heat Exchanger Networks deals with the following problem:
- <u>Given:</u>
  - N_H hot streams, with given heat capacity flowrate, each having to be cooled from supply temperature T_H^S to targets T_H^T.
  - N_C cold streams, with given heat capacity flowrate, each having to be heated from supply temperature T_C^S to targets T_C^T.
- <u>Design:</u>

  An optimum network of heat exchangers, connecting between the hot and cold streams and between the streams and cold/hot utilities (furnace, hot-oil, steam, cooling water or refrigerant, depending on the required duty temperature).
- What is optimal?

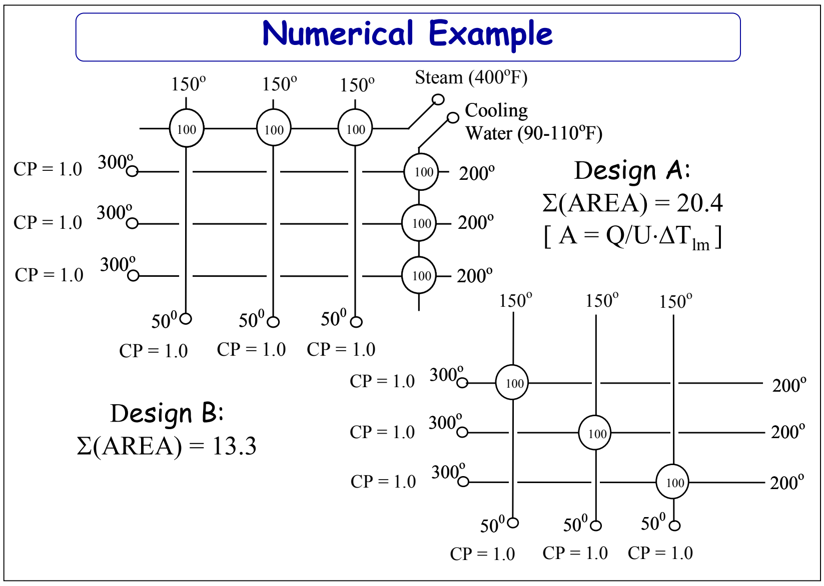
  Implies a trade-off between CAPITAL COSTS (Cost of equipment) and ENERGY COSTS (Cost of utilities).



Example

Network for minimal equipment cost ?

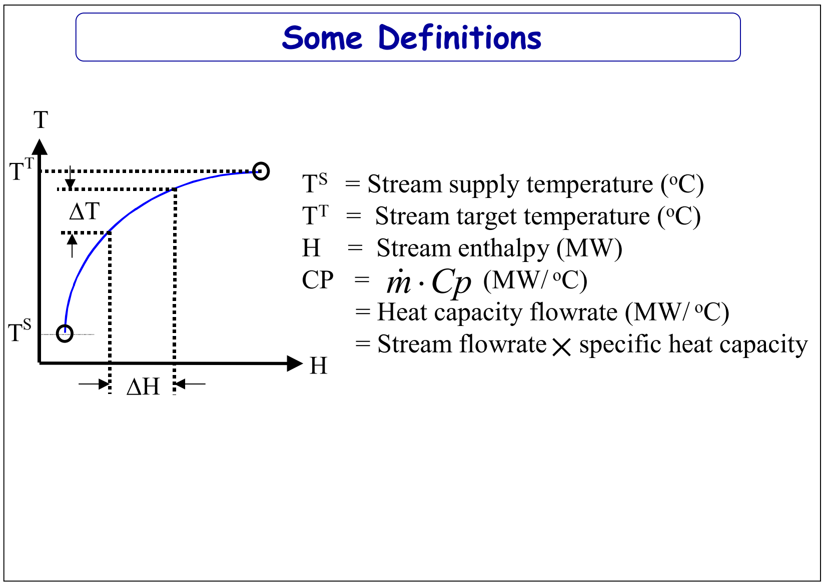
Network for minimal energy cost ?



Numerical Example

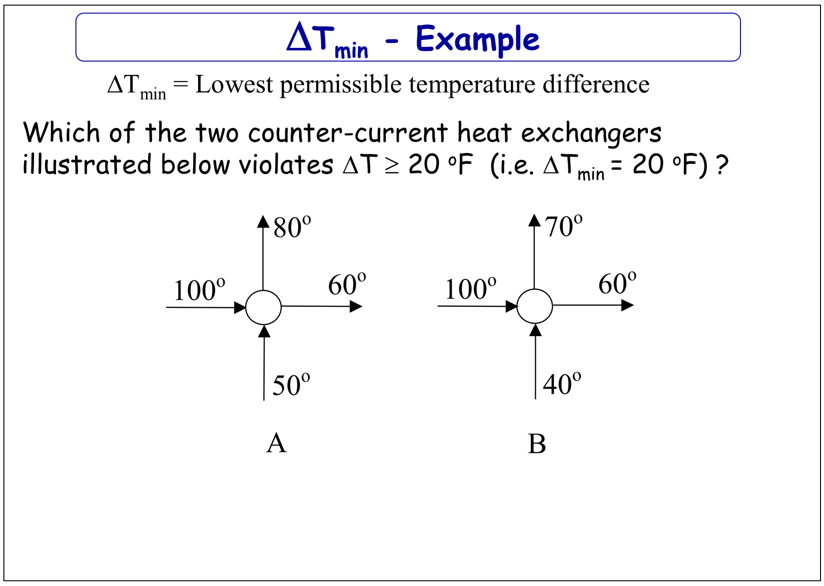
Design A:
Σ(AREA) = 20.4
[$A = Q/U \cdot \Delta T_{lm}$]

Design B:
Σ(AREA) = 13.3



Some Definitions

T^S = Stream supply temperature (°C)
T^T = Stream target temperature (°C)
H = Stream enthalpy (MW)
CP = $\dot{m} \cdot Cp$ (MW/°C)
= Heat capacity flowrate (MW/°C)
= Stream flowrate × specific heat capacity

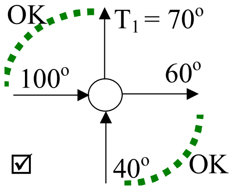


ΔT_{min} - Example

ΔT_{min} = Lowest permissible temperature difference

Which of the two counter-current heat exchangers illustrated below violates $\Delta T \geq 20$ °F (i.e. $\Delta T_{min} = 20$ °F) ?

Definitions (Cont'd)



Exchanger Duty.

Data: Hot stream CP = 0.3 MW/ °C
Cold stream CP = 0.4 MW/ °C

Check: $T_1 = 40 + (100 - 60)(0.3/0.4) = 70°C$ ☑

$$Q = 0.4(70 - 40) = 0.3(100 - 60) = 12 \text{ MW}$$

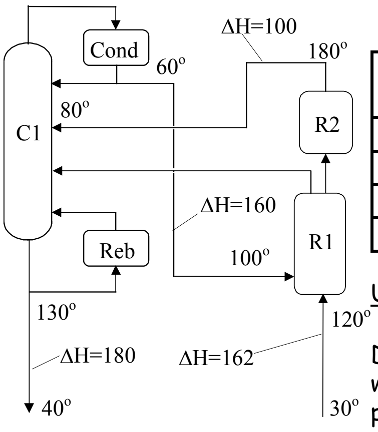
Heat Transfer Area (A): $A = Q/(U \cdot \Delta T_{lm})$

Data: Overall heat transfer coefficient, U=1.7 kW/m² °C
(Alternative formulation in terms of film coefficients)

$$\Delta T_{lm} = (30 - 20)/\log_e(30/20) = 24.66$$

So, $A = Q/(U \cdot \Delta T_{lm}) = 12000/(1.7 \times 24.66) = 286.2 \text{ m}^2$

Class Exercise 1



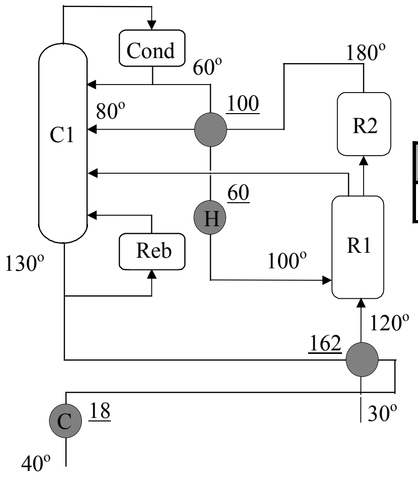
$\Delta T_{min} = 10$ °C

Stream	T^S (°C)	T^T (°C)	ΔH (kW)	CP (kW/°C)
H1	180	80	100	1.0
H2	130	40	180	2.0
C1	60	100	160	4.0
C2	30	120	162	1.8

Utilities. Steam@150 °C, CW@25°C

Design a network of steam heaters, water coolers and exchangers for the process streams. Where possible, use exchangers in preference to utilities.

Setting Energy Targets

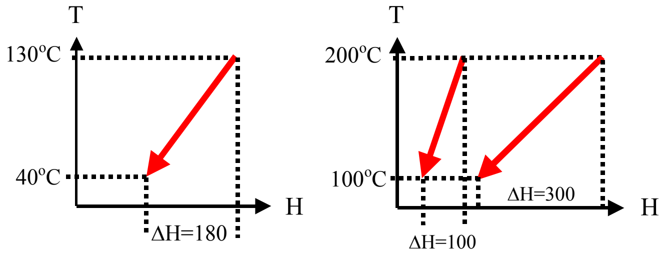


Summary of proposed design:

Steam	CW	Units
60 kW	18 kW	4

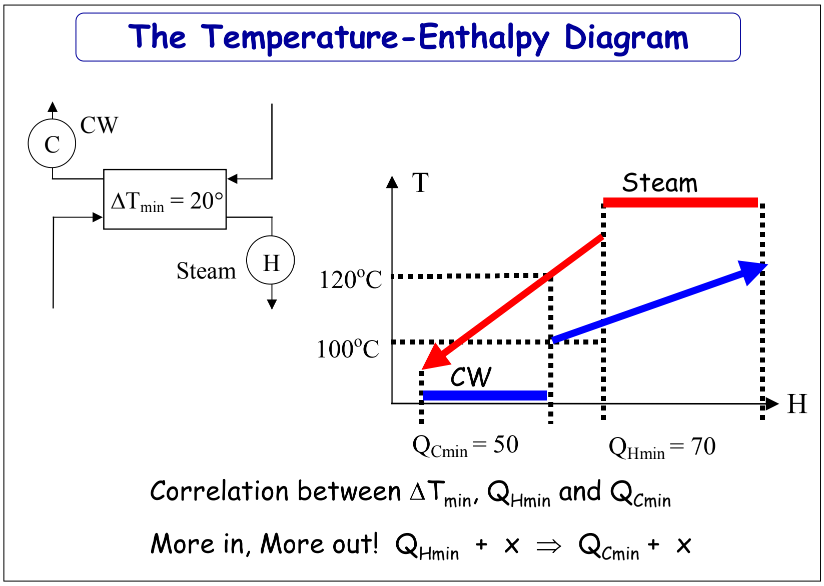
Are 60 kW of Steam Necessary?

The Temperature-Enthalpy Diagram



One hot stream

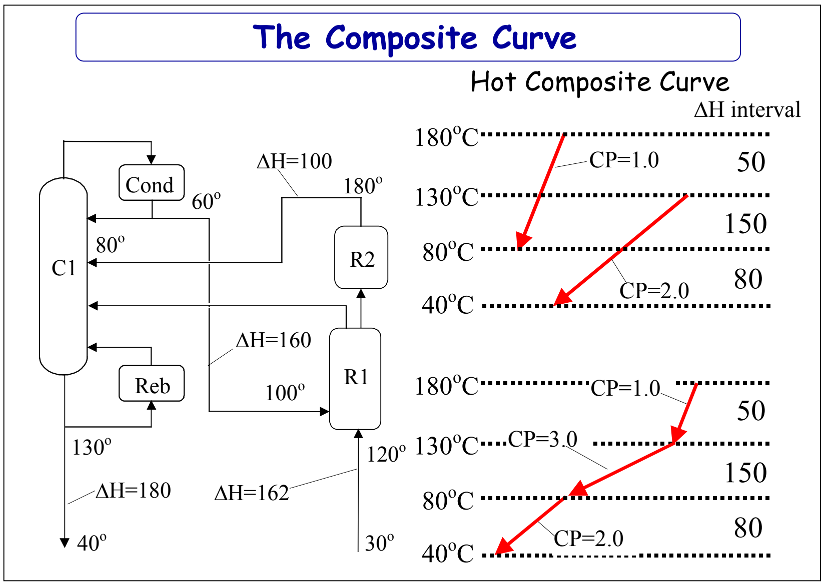
Two hot streams



The Temperature-Enthalpy Diagram

Correlation between ΔT_{min}, Q_{Hmin} and Q_{Cmin}

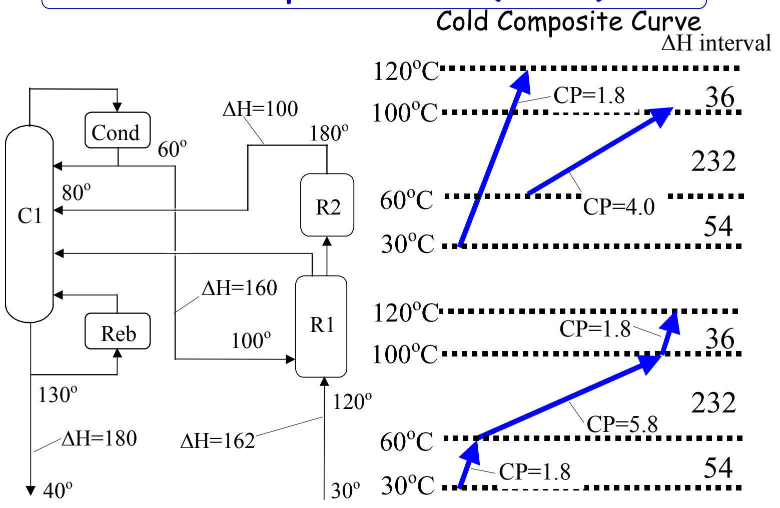
More in, More out! $Q_{Hmin} + x \Rightarrow Q_{Cmin} + x$



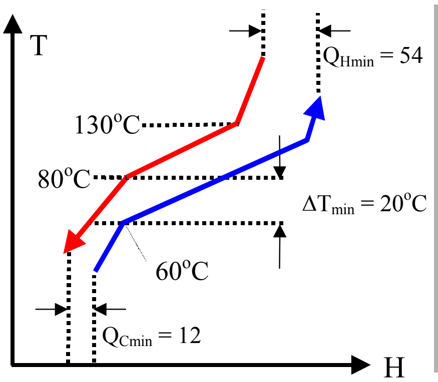
The Composite Curve

Hot Composite Curve

The Composite Curve (Cont'd)



The Composite Curve (Cont'd)



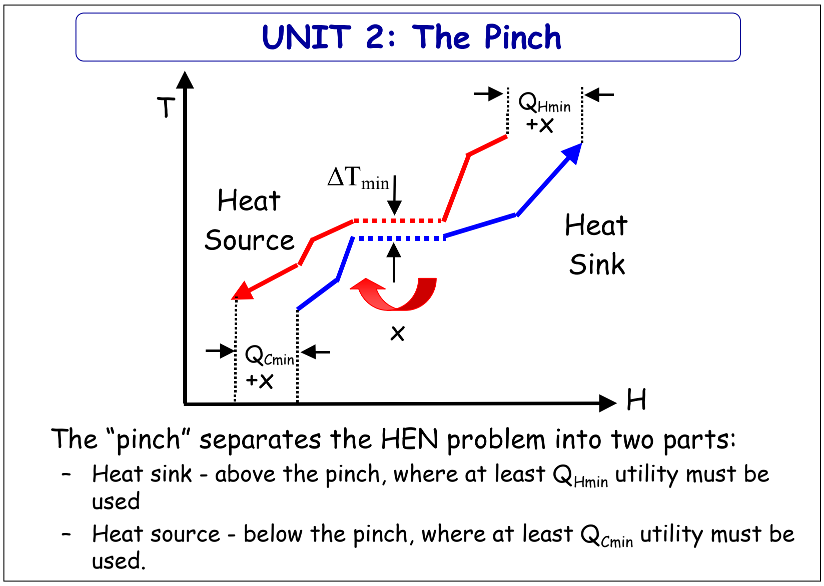
<ins>Result:</ins>
Q_{Cmin} and Q_{Hmin} for desired ΔT_{min}

MER Target

Here,
hot pinch is at 70 °C,
cold pinch is at 60 °C
Q_{Hmin} = 48 kW and
Q_{Cmin} = 6 kW

Method: manipulate hot and cold composite curves until required ΔT_{min} is satisfied.

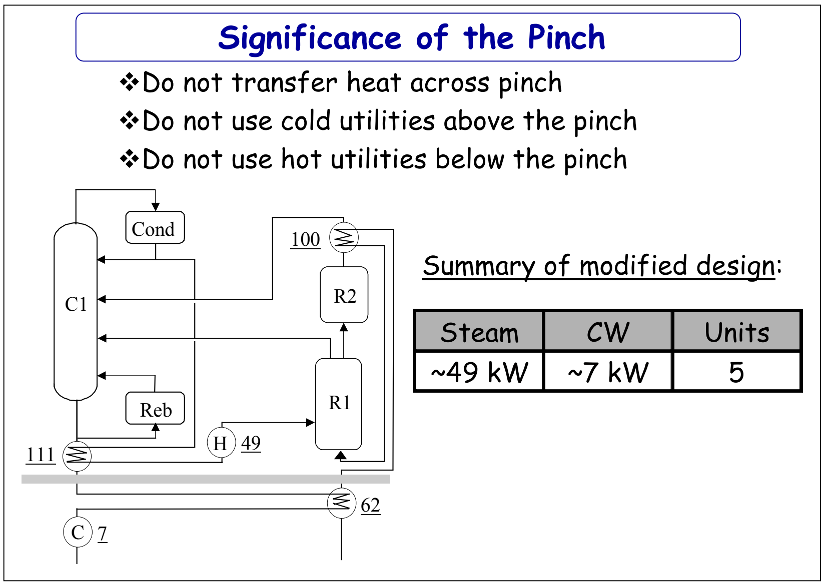
This defines hot and cold pinch temperatures.



UNIT 2: The Pinch

The "pinch" separates the HEN problem into two parts:

- Heat sink - above the pinch, where at least Q_{Hmin} utility must be used
- Heat source - below the pinch, where at least Q_{Cmin} utility must be used.

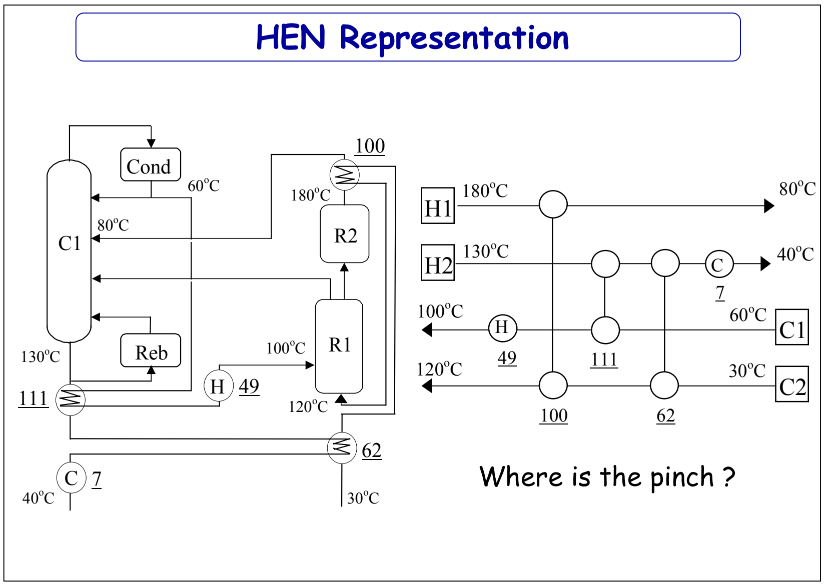


Significance of the Pinch

- ❖Do not transfer heat across pinch
- ❖Do not use cold utilities above the pinch
- ❖Do not use hot utilities below the pinch

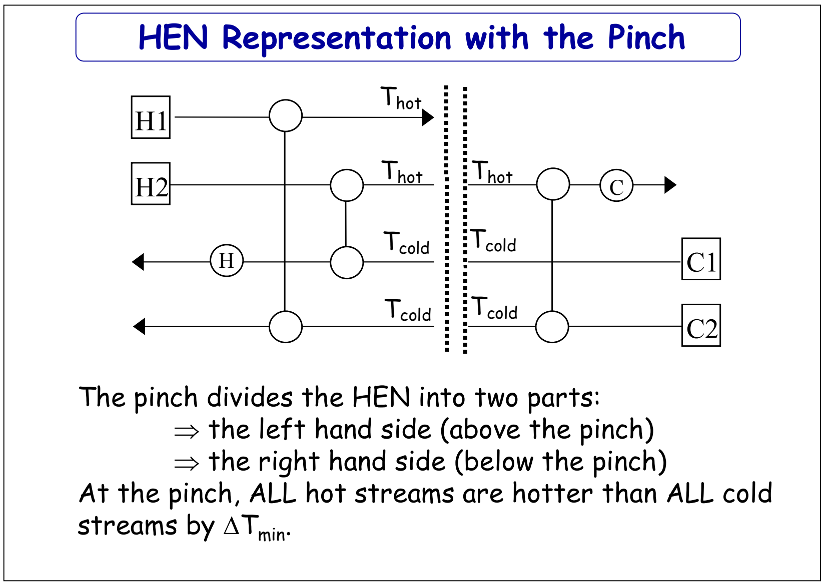
Summary of modified design:

Steam	CW	Units
~49 kW	~7 kW	5



HEN Representation

Where is the pinch ?



HEN Representation with the Pinch

The pinch divides the HEN into two parts:

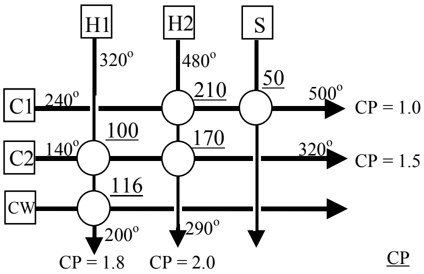
⇒ the left hand side (above the pinch)

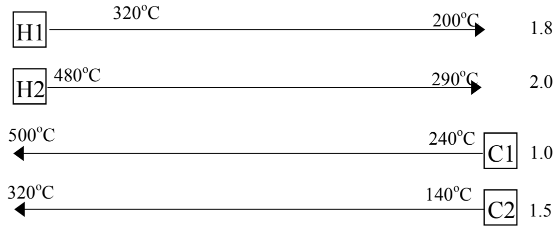
⇒ the right hand side (below the pinch)

At the pinch, ALL hot streams are hotter than ALL cold streams by ΔT_{min}.

Class Exercise 2

- For this network, draw the grid representation
- Given pinch temperatures at 480 °C /460 °C, and MER targets: Q_{Hmin}= 40, Q_{Cmin}= 106, redraw the network separating the sections above and below the pinch.
- Why is $Q_H > Q_{Hmin}$?





Class Exercise 2 - Solution

Design for Maximum Energy Recovery(MER)

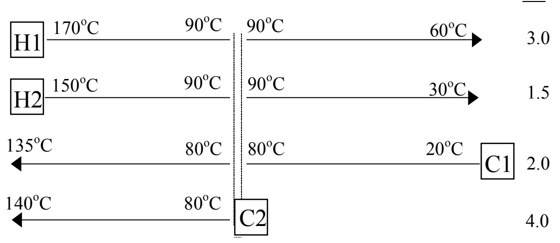
Example

Step 1: MER Targeting.

Pinch at 90° (Hot) and 80° (Cold)
Energy Targets:
Total Hot Utilities: 20 kW
Total Cold Utilities: 60 kW

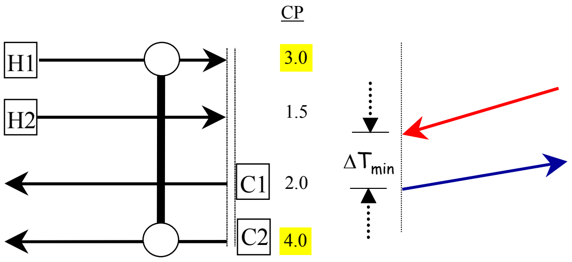
Design for MER (Cont'd)

Step 2: Divide the problem at the pinch



Design for MER (Cont'd)

Step 3: Design hot-end, starting at the pinch:
Pair up exchangers according to CP-constraints.
Immediately above the pinch, pair up streams such that: $CP_{HOT} \leq CP_{COLD}$
(This ensures that $T_H - T_C \geq \Delta T_{min}$)

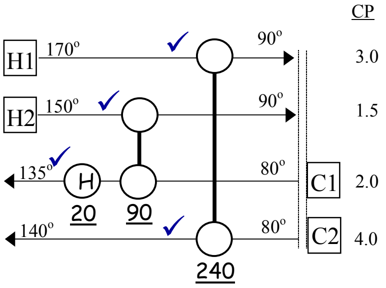


Meets ΔTmin constraint

Design for MER (Cont'd)

Step 3 (Cont'd): Complete hot-end design, by ticking-off streams.

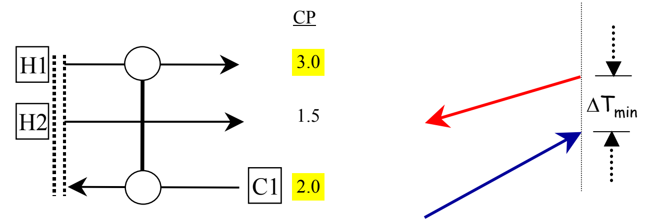
Q_{Hmin} = 20 kW ✓



Add heating utilities as needed (⇒MER target)

Design for MER (Cont'd)

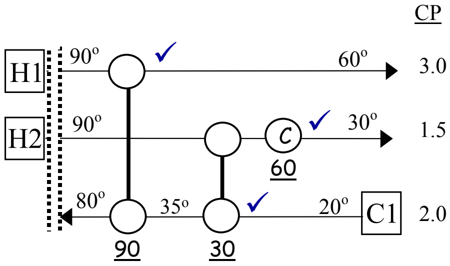
Step 4: Design cold-end, starting at the pinch:
Pair up exchangers according to CP-constraints.
Immediately below the pinch, pair up streams such that: $CP_{HOT} \geq CP_{COLD}$
(This ensures that $T_H - T_C \geq \Delta T_{min}$)



Meets ΔT_{min} constraint

Design for MER (Cont'd)

Step 4 (Cont'd): Complete cold-end design, by ticking-off streams.

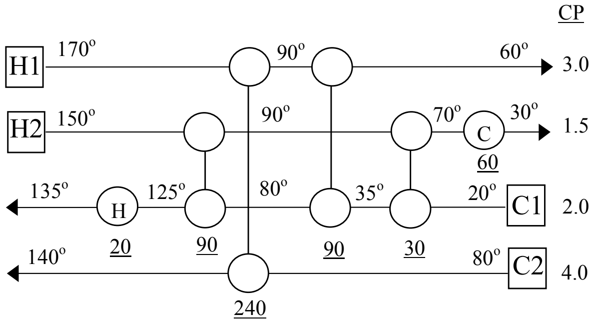


Q_{Cmin} = 60 kW ✓

Add cooling utilities as needed (⇒MER target)

Design for MER (Cont'd)

Completed Design:



Note that this design meets the MER targets:
Q_{Hmin} = 20 kW and Q_{Cmin} = 60 kW

Design for MER (Cont'd)

Design for MER - Summary:

❶ MER Targeting. Define pinch temperatures, Q_{hmin} and Q_{Cmin}

❷ Divide problem at the pinch

❸ Design hot-end, starting at the pinch: Pair up exchangers according to CP-constraints. Immediately above the pinch, pair up streams such that: $CP_{HOT} \leq CP_{COLD}$. "Tick off" streams in order to minimize costs. Add heating utilities as needed (up to Q_{Hmin}). Do not use cold utilities above the pinch.

❹ Design cold-end, starting at the pinch: Pair up exchangers according to CP-constraints. Immediately below the pinch, pair up streams such that: $CP_{HOT} \geq CP_{COLD}$. "Tick off" streams in order to minimize costs. Add cooling utilities as needed (up to Q_{Cmin}). Do not use hot utilities below the pinch.

❍ Done!

Class Exercise 3

Stream	T^S (°C)	T^T (°C)	ΔH (kW)	CP (kW/°C)
H1	180	80	100	1.0
H2	130	40	180	2.0
C1	60	100	160	4.0
C2	30	120	162	1.8

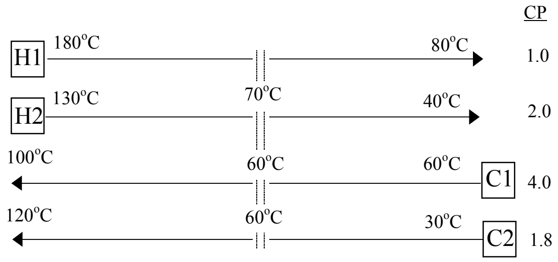
ΔT_{min} = 10 °C.

Utilities:

Steam@150 °C, CW@25°C

Design a network of steam heaters, water coolers and exchangers for the process streams. Where possible, use exchangers in preference to utilities.

Q_{Hmin}=48



Q_{Cmin}=6

UNIT 3: The Problem Table

Example:

Stream	T^S (°F)	T^T (°F)	ΔH (kBtu/h)	CP (kBtu/h °F)
H1	260	160	3000	30
H2	250	130	1800	15
C1	120	235	2300	20
C2	180	240	2400	40

ΔT_{min} = 10 °F.

Step 1: Temperature Intervals

(subtract ΔT_{min} from hot temperatures)

Temperature intervals:

250°F ⇒ 240°F ⇒ 235°F ⇒ 180°F ⇒ 150°F ⇒ 120°F

UNIT 3: The Problem Table (Cont'd)

Step 2: Interval heat balances

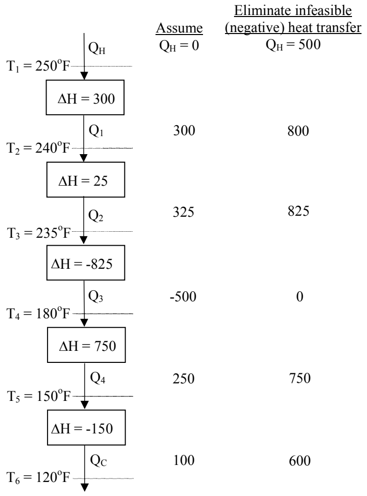
For each interval, compute:

$\Delta H_i = (T_i - T_{i+1}) \times (\Sigma CP_{Hot} - \Sigma CP_{Cold})$

Interval		H1	H2	C1	C2	$T_i - T_{i+1}$	ΣCP_{Hot} $-\Sigma CP_{Cold}$	ΔH_i
1	250	■				10	30	300
2	240	■	▓		░	5	5	25
3	235	■	▓	▒	░	55	–15	–825
4	180	■	▓	▒		30	25	750
5	150		▓	▒		30	–5	–150
6	120							

UNIT 3: The Problem Table (Cont'd)

Step 3: Form enthalpy cascade.



This defines:
Cold pinch temp. = 180 °F
Q_{Hmin} = 500 kBtu/h
Q_{Cmin} = 600 kBtu/h

Class Exercise 4 - Now try again!

Stream	T^S (°C)	T^T (°C)	ΔH (kW)	CP (kW/°C)
H1	180	80	100	1.0
H2	130	40	180	2.0
C1	60	100	160	4.0
C2	30	120	162	1.8

ΔT_{min} = 10 °C.

Calculate the Problem Table.
Predict Q_{Hmin} and Q_{Cmin}.
Draw the Enthalpy Cascade.

Step 1: Temperature Intervals
(subtract ΔT_{min} from hot temperatures)
Temperature intervals:

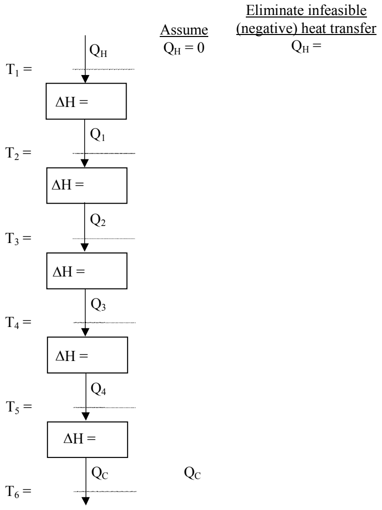
Class Exercise 4 (Cont'd)

Step 2: Interval heat balances
For each interval, compute:
$\Delta H_i = (T_i - T_{i+1}) \times (\Sigma CP_{Hot} - \Sigma CP_{Cold})$

Interval	T_i	$T_i - T_{i+1}$	ΣCP_{Hot} $-\Sigma CP_{Cold}$	ΔH_i
1				
2				
3				
4				
5				
6				

Class Exercise 4 (Cont'd)

Step 3: Form enthalpy cascade.



This defines:
Cold pinch temp. = °C
Q_{Hmin} = kW
Q_{Cmin} = kW

Introduction to HEN Synthesis - Summary

- **Unit 1**. Introduction: Capital vs. Energy
  - What is an optimal HEN design
  - Setting Energy Targets
- **Unit 2**. The Pinch and MER Design
  - The Heat Recovery Pinch
  - HEN Representation
  - MER Design: (a) MER Target; (b) Hot- and cold-side designs
- **Unit 3**. The Problem Table
  - for MER Targeting

Next week: Advanced HEN Synthesis