Process Heat Group Major Challenges

Lecture 2
22.033/22.33 – Nuclear Engineering Design Project
September 14, 2011

The Three Challenge Problems

- Heat exchanger (Hx) design
- Heat transport
- Heat storage (if necessary)

First, Some Nomenclature

Sensible heating – temperature change

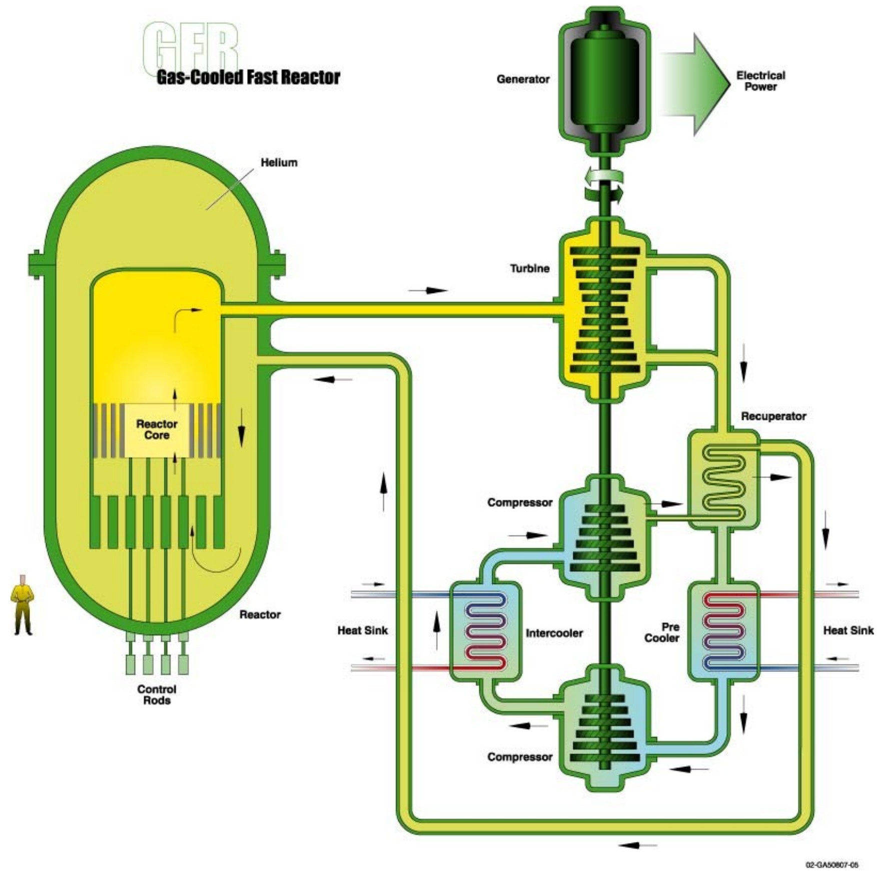
$$Q = \dot{m} c_p \Delta T$$

Latent heating – phase change

$$Q = \dot{m} h_{fg}$$

Bond energy storage – enthalpy of chemical reactions

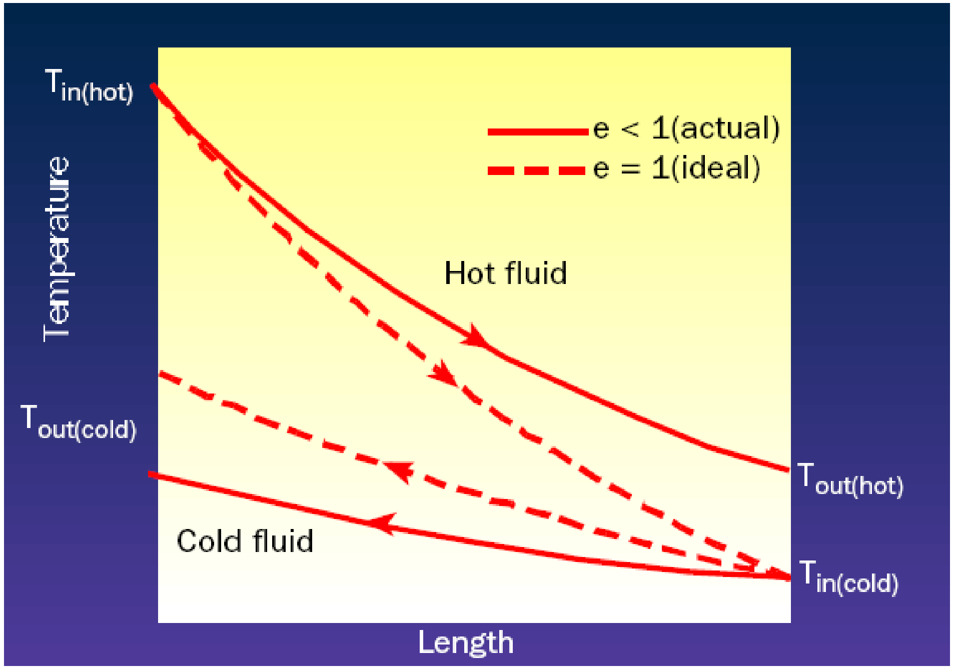
Where Do We Find Them?



Courtesy of the Generation IV International Forum. Used with permission.

Source: http://www.gen-4.org/Technology/systems/gfr.htm

Heat Exchangers – Fundamental Parameters



Source: Dean Bartlett. "The Fundamentals of Heat Exchangers" *The Industrial Physicist*, AIP, p. 20 (1996)

Hx <u>effectiveness</u> (ε)

- Measures how much heat is transferred compared to how much is possible

ε=1 is ideal, but practically impossible (big Hx)

Heat Exchangers – Fundamental Parameters

Diagram of heat exchanger removed due to copyright restrictions. See lecture video for details.

***Source: Ramesh K. Shah, Dusan P. Sekulic. Fundamentals of Heat Exchanger Design. John Wiley & Sons, Inc. p. 102 (2003).

Heat Exchangers – Fundamental Parameters

$$Q = U \cdot A \cdot F \cdot \Delta T_{lm}$$

Q = Heat transfer rate (W)

U = Thermal conductance (W/m^2K)

A = Heat transfer area (m^2)

ΔT_{lm} = Log mean temperature difference (K)

F = Factor (for flow configuration)

Heat Exchangers – Log Mean Temperature Difference (LMTD)

$$\Delta T_{lm} = \frac{(\Delta T_H - \Delta T_C)}{\ln\left(\frac{\Delta T_H}{\Delta T_C}\right)}$$

LMTD is a good measure of the effectiveness of simlar heat exchangers of different designs

Often, LMTD (counter flow) > LMTD (parallel flow)

Heat Exchangers – Finding Key Parameters

Figure 1 – A big, complicated heat exchanger chart

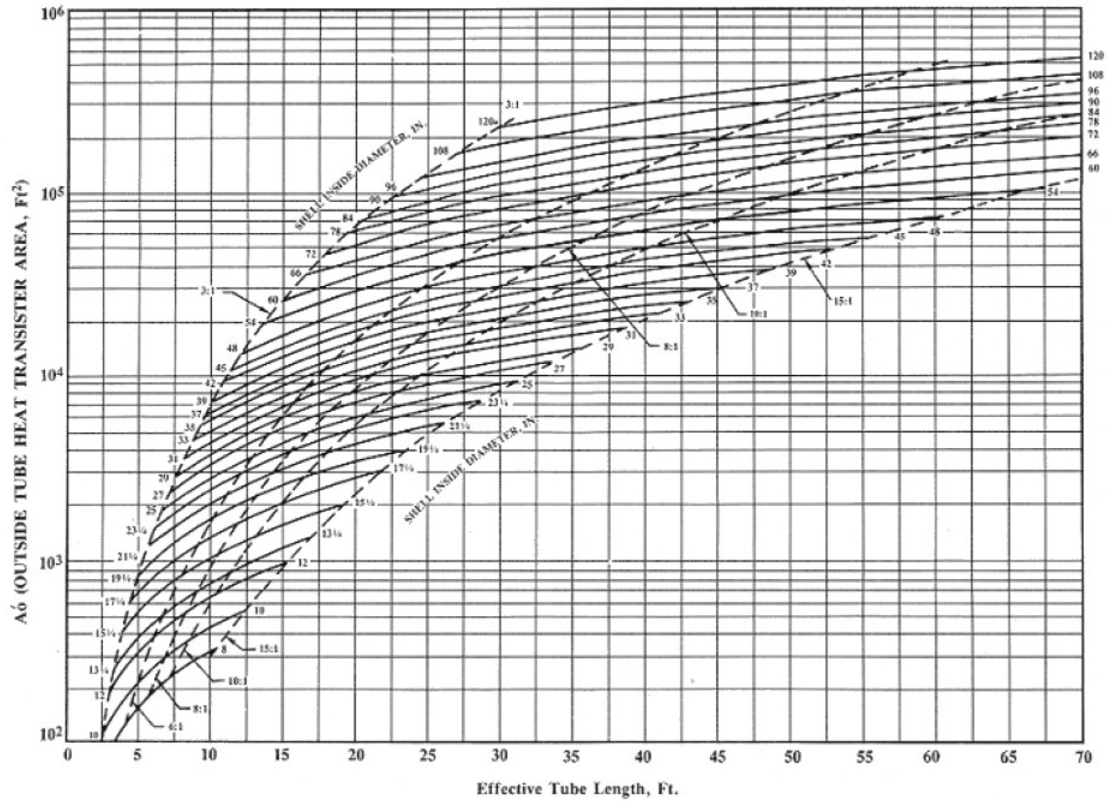


Fig. 2.26 Area as a Function of Shell Inside Diameter and Effective Tube Length for 3/4 in. O.D. S/T Trufin 19 Fins/In. on 15/16 in. Equilateral Triangular Tube Layout Fixed Tube Sheet, One Tubeside Pass, Fully Tubed Shell.

Source: Wolverine Tube Heat Transfer Data Book, p. 93 (2001), accessed at http://www.wlv.com/products/databook/ch2_5.pdf

Heat Exchangers – Fundamental Parameters

$$\varepsilon = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})}$$

For all flow configurations

$$C^* = \frac{C_{min}}{C_{max}} = \frac{(\dot{m}c_p)_{min}}{(\dot{m}c_p)_{max}} = \begin{cases} (T_{c,o} - T_{c,i})/(T_{h,i} - T_{h,o}) & \text{for } C_h = C_{min} \\ (T_{h,i} - T_{h,o})/(T_{c,o} - T_{c,i}) & \text{for } C_c = C_{min} \end{cases}$$

Hx is “balanced” when C* = 1

$$\text{NTU} = \frac{UA}{C_{min}} = \frac{1}{C_{min}} \int_A U\,dA$$

NTU = Number of Transfer Units

***Source: Ramesh K. Shah, Dusan P. Sekulic. Fundamentals of Heat Exchanger Design. John Wiley & Sons, Inc. p. 116, 118-119 (2003).

Hx Flow Types

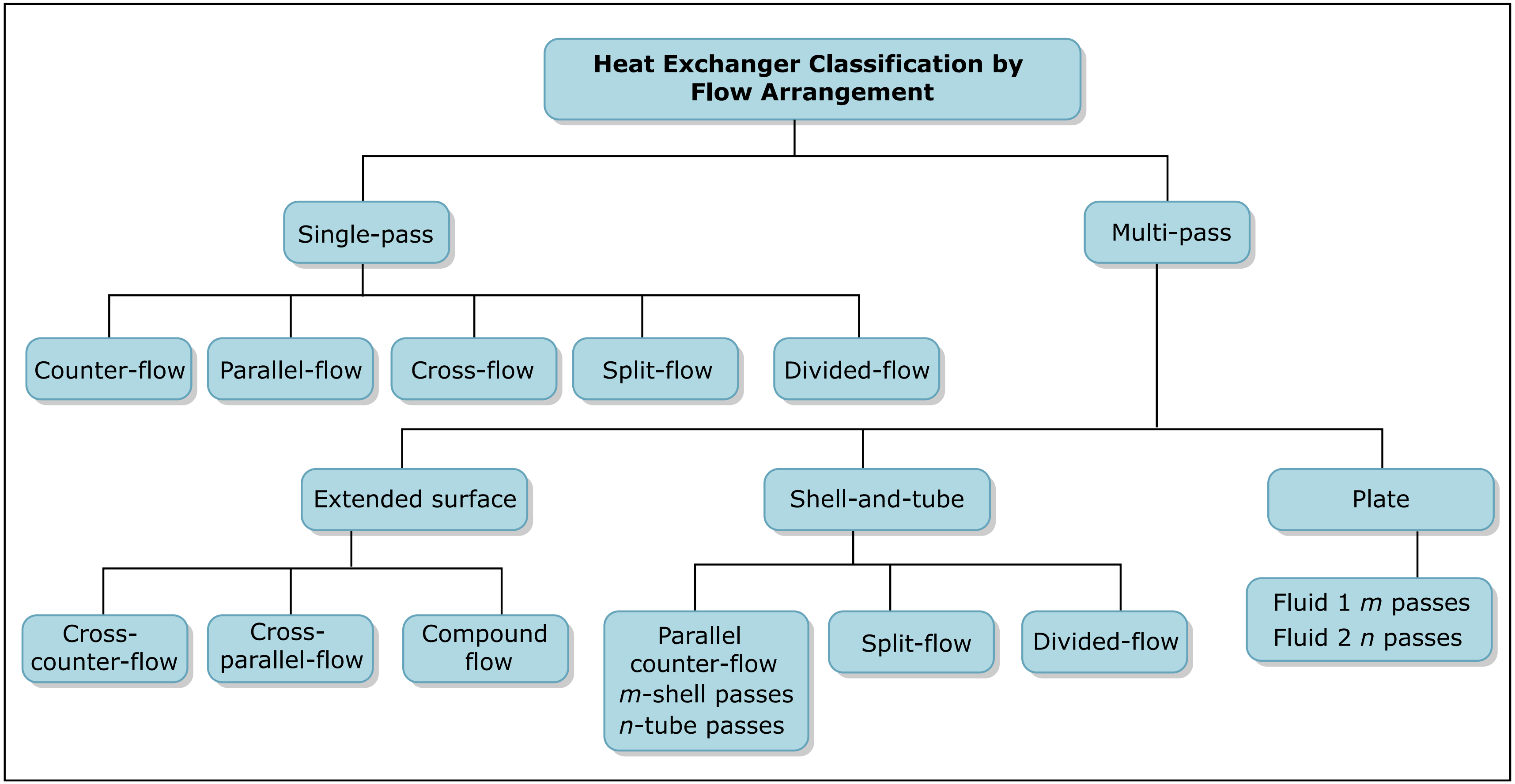


Image by MIT OpenCourseWare.

***After Ramesh K. Shah & Dusan P. Sekulic. Fundamentals of Heat Exchanger Design. John Wiley & Sons, Inc. (2003).

Parallel Flow vs. Counterflow

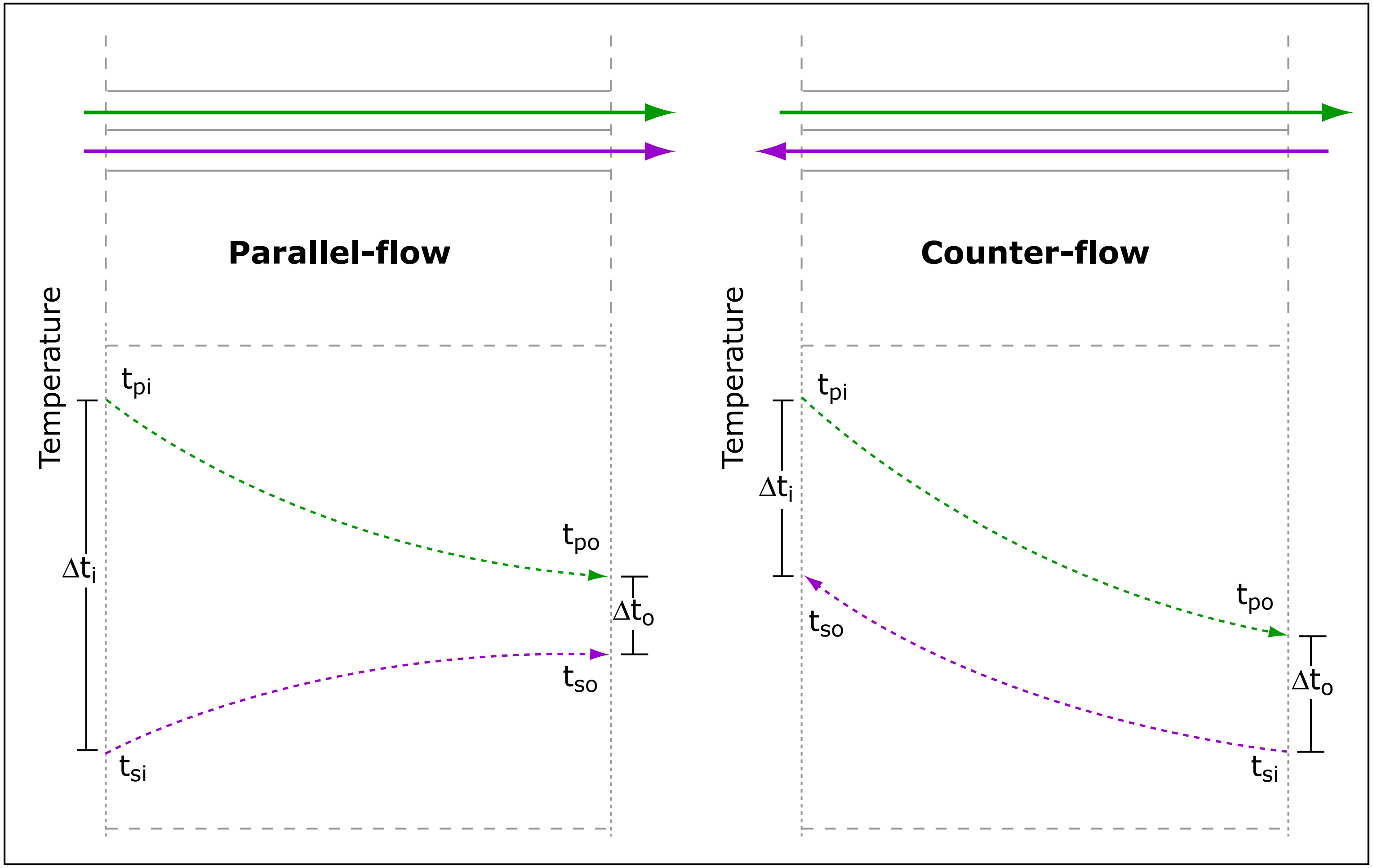
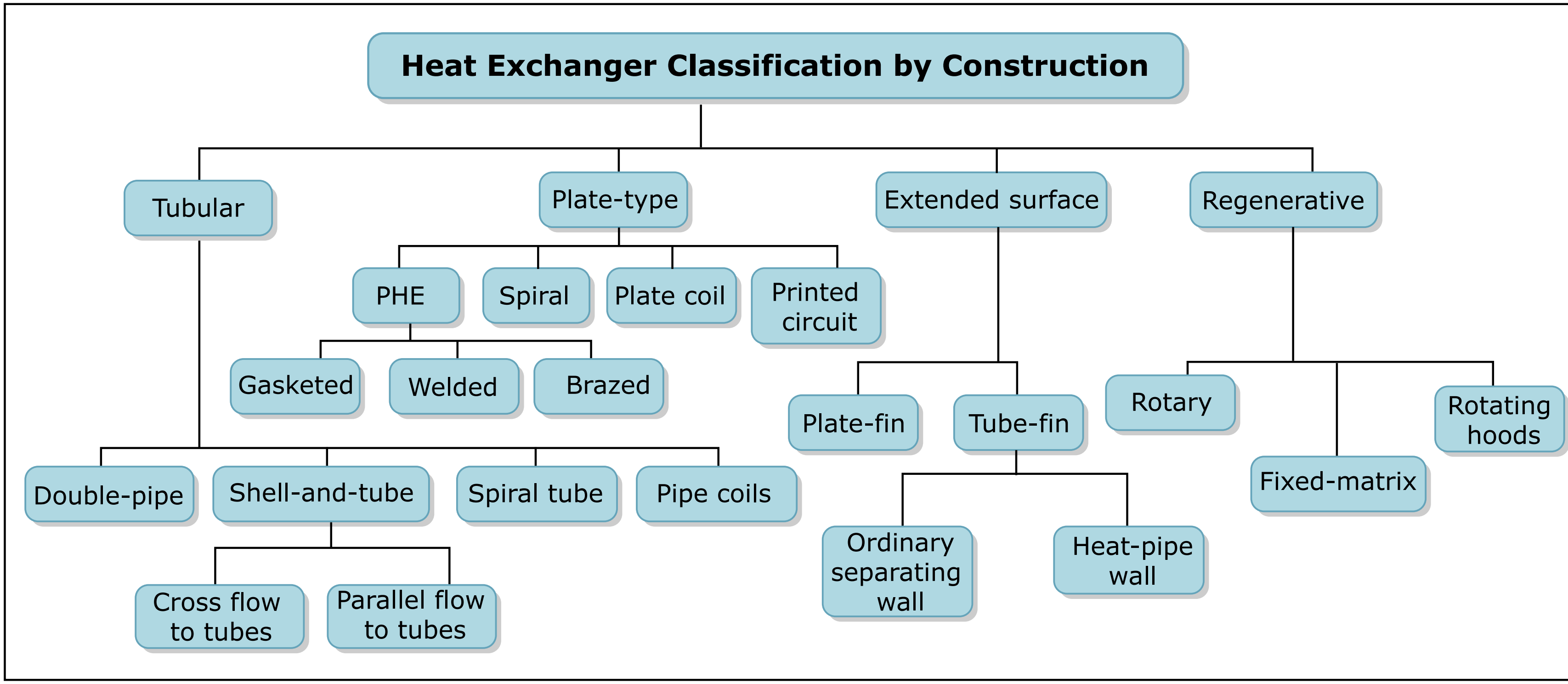


Image by MIT OpenCourseWare.

See http://www.engineeringtoolbox.com/arithmetic-logarithmic-mean-temperature-d_436.html

Hx Flow Configurations



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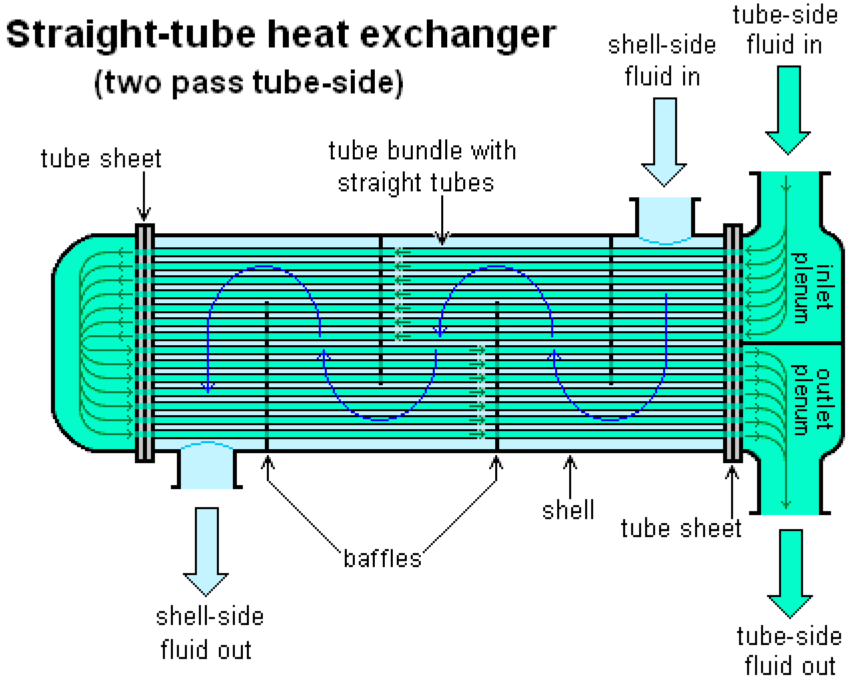
After Ramesh K. Shah, Dusan P. Sekulic. Fundamentals of Heat Exchanger Design. John Wiley & Sons, Inc. (2003).

Hx Flow Configurations - Tubular



Courtesy of Wikipedia User:H Padleckas. Used with permission.

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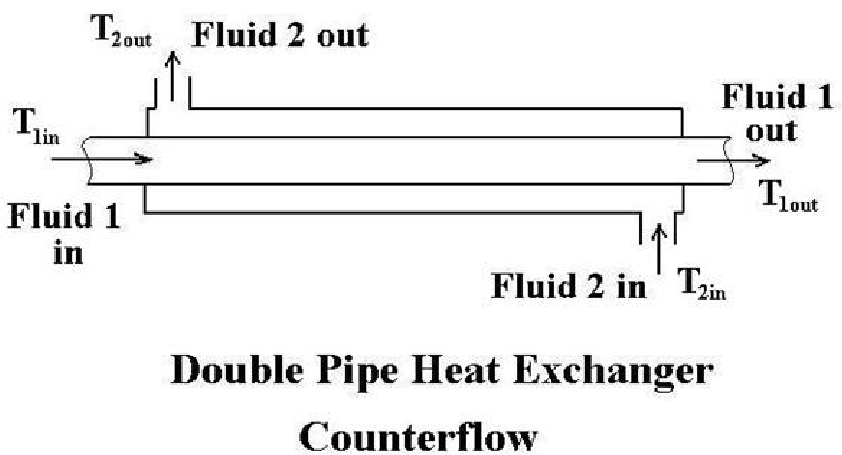
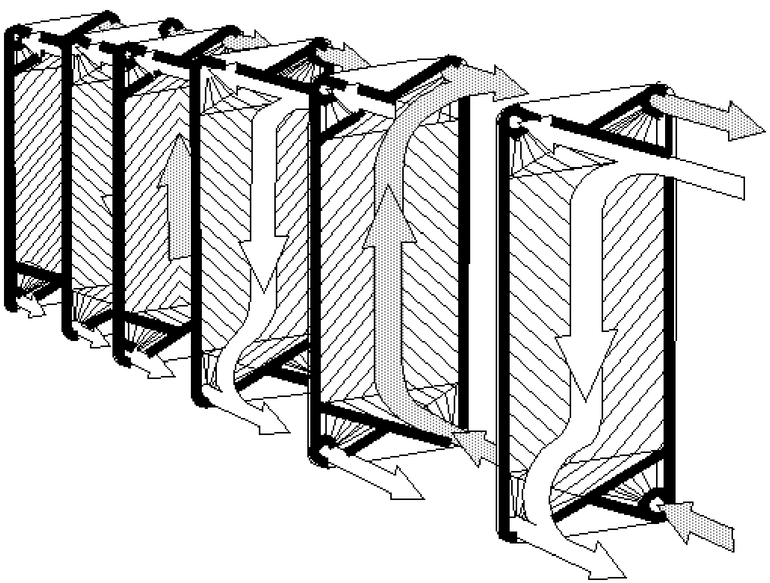


Courtesy of Harlan Bengtson. Used with permission.

Hx Flow Configurations – Plate

Plate (brazed) type



Source: http://www.alfa-biz.com/Gasketed-Plate-Heat-Exchanger.asp

Spiral type

Source: http://www.hiwtc.com/photo/products/16/02/14/21470.jpg

Hx Heat Transfer Mechanisms

Other design parameters should largely determine this choice

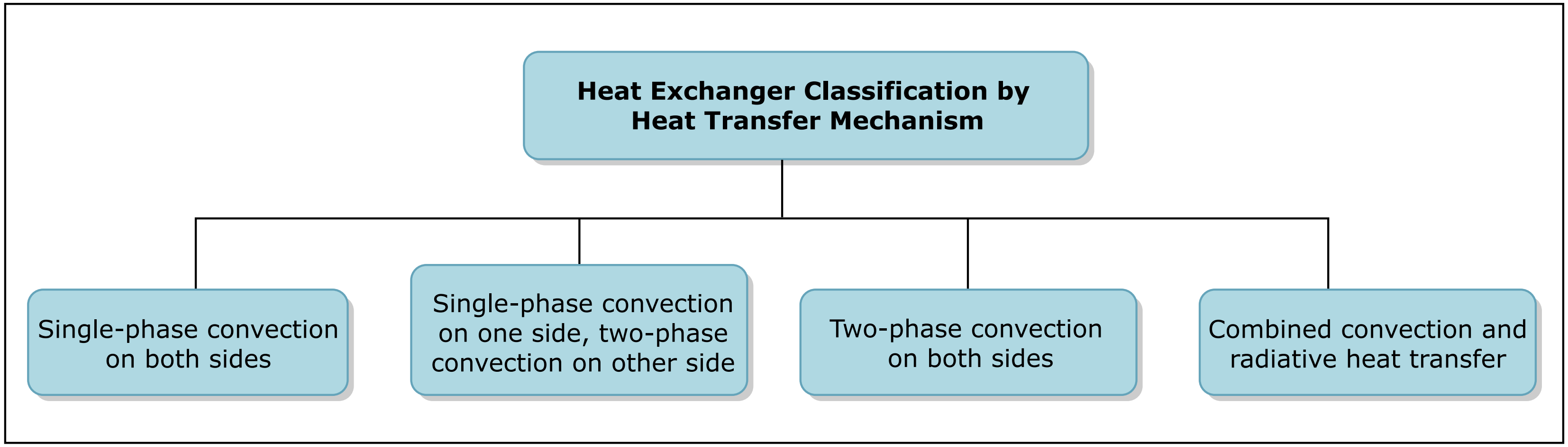


Image by MIT OpenCourseWare.

After Ramesh K. Shah, Dusan P. Sekulic. Fundamentals of Heat Exchanger Design. John Wiley & Sons, Inc. (2003).

Heat Exchangers - Questions

What type to use?

What working fluids?

What geometry? Flow considerations? Laminar or turbulent?

Where is the tradeoff between cost & performance?

Materials concerns?

See also: T. Kuppan. "Heat exchanger design handbook." and Som, "Introduction To Heat Transfer.

Heat Transport

Main problem: Get process heat from the reactor to the hydrogen & biofuels plants

How? Must consider:

- Temperatures
- Losses
- Flow rates
- Flow transients

Heat Transport – Long Distance

How to model it?

- Thermal resistances
- FEM
- Loop analysis

How to pump it? Forced? Gravity?

Distance from Rx to H_2, biofuel plant is one of the most important parameters

Heat Transport - Questions

What are the constraints? ($T_{H\text{-}Rx}$, $T_{C\text{-}H2}$, $T_{C\text{-}bio}$)

How far does the heat have to go?

Where to take the heat from?

How to transport it?

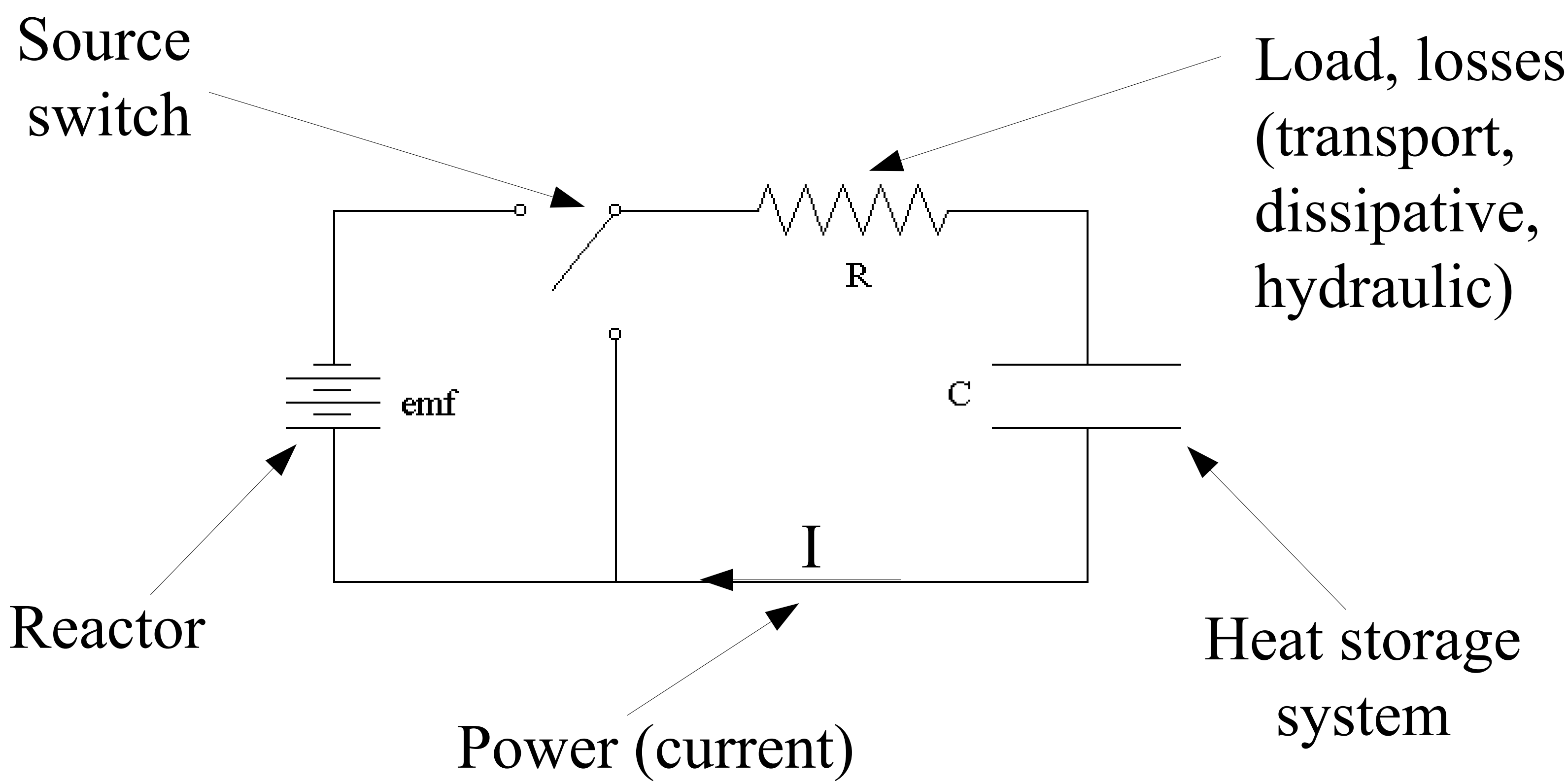
How to model it? What/where are losses?

Should some of it be stored...

Heat Storage

- Heat storage is a way to balance out load instabilities (<u>capacitive effect</u>)
  - Store some heat to run turbines and/or product factories during transients
  - Can help avoid or delay plants load-dumping or load-following
- Must balance benefits gained vs. heat lost by storage

Heat Storage – Electrical Analogy



Courtesy of Prof. Eric C. Toolson. Used with permission.

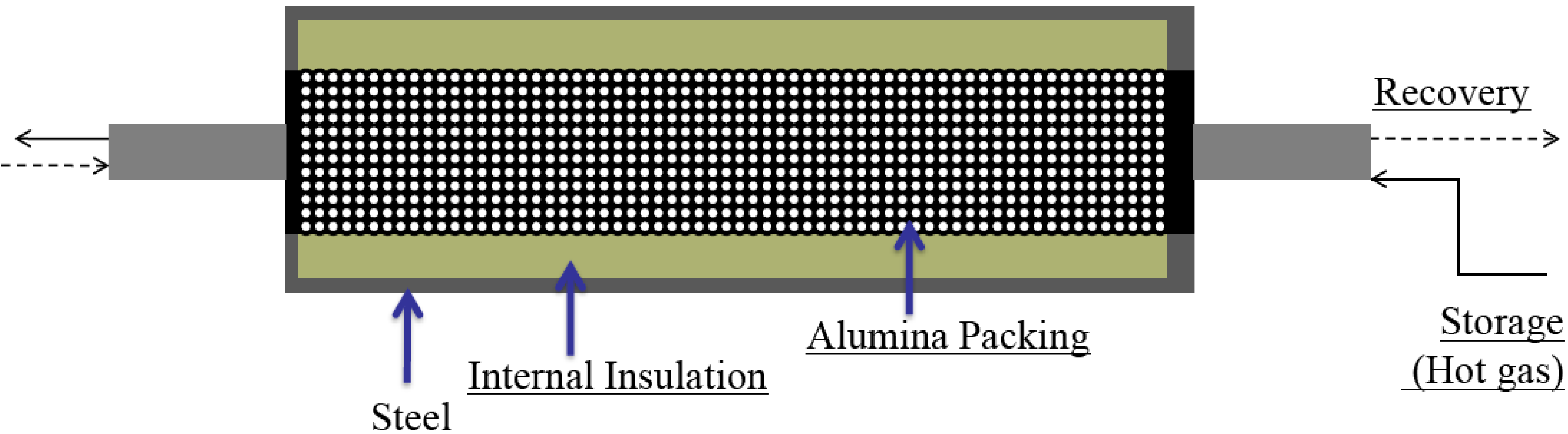
Image source: http://www.unm.edu/~toolson/rc_circuit.html

Heat Storage Technologies

- Sensible heat storage
  - Simply apply hot fluid to a material, reverse flow when required
- Latent heat storage
  - Uses phase change materials (PCMs)
  - Dependent on melting point, heat of fusion
- Bond energy storage
  - Dependent on reaction temperature, enthalpy

Heat Storage – Sensible Heat

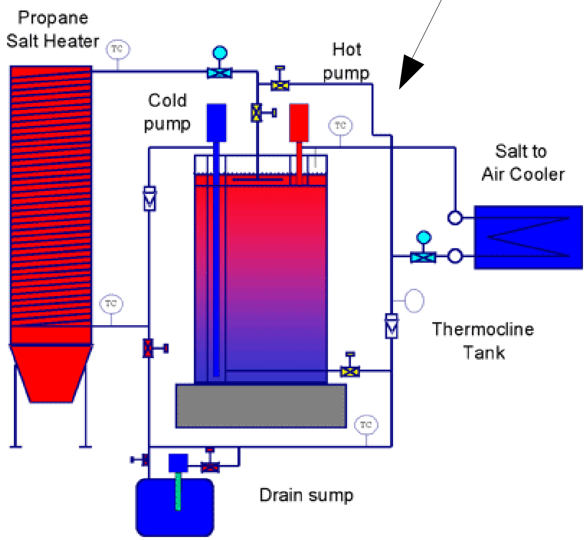
Example: Hot gas on alumina fluidized bed



Source: R. Shinnar et al. "A novel storage method for concentrating solar power plants allowing operation at high temperature." DoE Presentation, Boulder, CO (2011).

Heat Storage – Sensible Heat

Other proposed & demonstrated storage media: Molten salt, concrete



Thermocline test at Sandia National Laboratories

Concrete TES at U. Stuttgart

See http://www.nrel.gov/csp/troughnet/thermal_energy_storage.html

Heat Storage – Phase Change Materials

Melting temperature and heat of fusion of inorganic substances with potential use as a PCM

Compound	Melting temperature (K)	Heat of fusion (kJ/kg)
H_2O	273.2	333
$LiClO_3{\cdot}3H_2O$	281.3	253
$KF{\cdot}4H_2O$	291.7	231
$Mn(NO_3)_2{\cdot}6H_2O$	299.0	125.9
$CaCl_2{\cdot}6H_2O$	302.2	190.8
$LiNO_3{\cdot}3H_2O$	303.2	296
$Na_2SO_4{\cdot}10H_2O$	305.6	254
$Zn(NO_3)_2{\cdot}6H_2O$	309.2	246.5
$Na_2CO_3{\cdot}10H_2O$	307.2	146.9
$CaBr_2{\cdot}6H_2O$	303.2	115.5
$Na_2HPO_4{\cdot}12H_2O$	308.7	265
$Na_2S_2O_3{\cdot}5H_2O$	321.2	201
$Na(CH_3COO){\cdot}3H_2O$	331.2	264
$Na_2P_2O_7{\cdot}10H_2O$	343.2	184
$Ba(OH)_2{\cdot}8H_2O$	351.2	265.7
$Mg(NO_3)_2{\cdot}6H_2O$	362.2	162.8
$(NH_4)Al(SO_4){\cdot}6H_2O$	368.2	269
$MgCl_2{\cdot}6H_2O$	390.2	168.6
$NaNO_3$	580.2	172
KNO_3	606.2	266
KOH	653.2	149.7
$MgCl_2$	987.2	452
NaCl	1073.2	492
Na_2CO_3	1127.2	275.7
KF	1130.2	452
K_2CO_3	1170.2	235.8

Source: M. Demirbas. "Thermal Energy Storage and Phase Change Materials: An Overview." *Energy Sources, Part B*, 1:85–95, 2006.

- More compact
- Layout can be more complicated
- Salts can be corrosive
- Graphite foils have been used to improve heat spreading

Heat Storage – Bond Energy

Absorb/Release chemical energy by shifting chemical equilibrium reactions

- Change temperature, pressure
- Examples: hydration, hydriding, ammonia/salt reactions
- Chemical reaction should be reversible

Heat Storage – Questions

What temperature(s) is/are required?

What materials to use?

What capacity to use? (kWh, MWh, Gwh)

How does cost scale with size?

What are loss rates & pathways?

When would it be used, if at all?

Where would it be located?