Chemical Engineering 612

Reactor Design and Analysis

Lecture 16

Hydraulic Analysis – Natural Circulation

Spiritual Thought

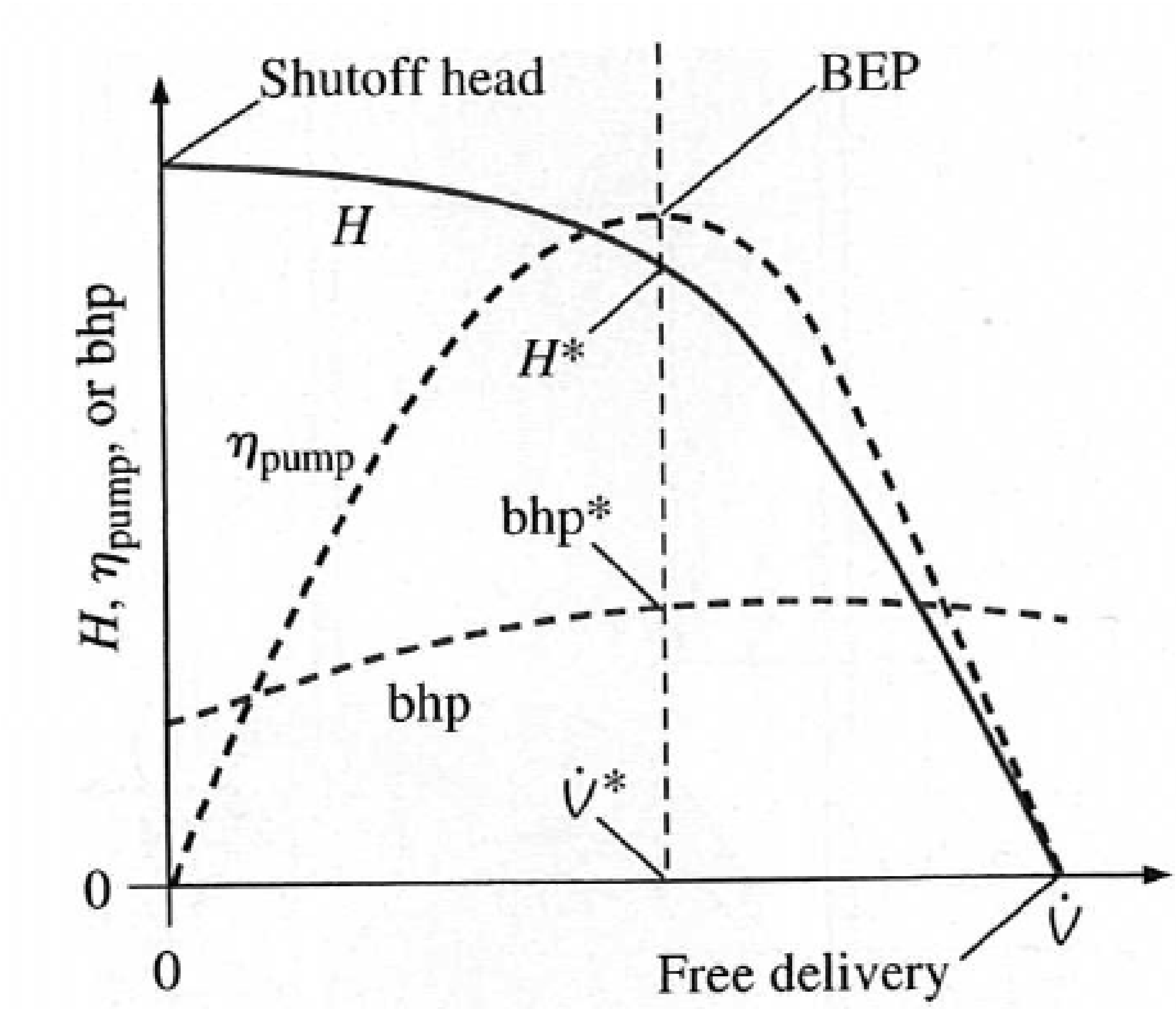
"I remember well the day [my son] passed away. As Jeanene and I drove from the hospital, we pulled over to the side of the road. I held her in my arms. Each of us cried some, but we realized that we would have him beyond the veil because of the covenants we had made in the temple. That made his loss somewhat easier to accept."

Elder Richard G. Scott

Sample Problem

- Calculate the pressure drop across a bare-rod core assembly (no spacer grids or mixing vanes) for a closed stainless steel square assembly with 264 tubes in square configuration, P/D = 1.13, D = 0.34 in, L = 10 ft, S = 6.531 in $\dot{m} = 100$ kg/s water.

Pump Curve Schematic

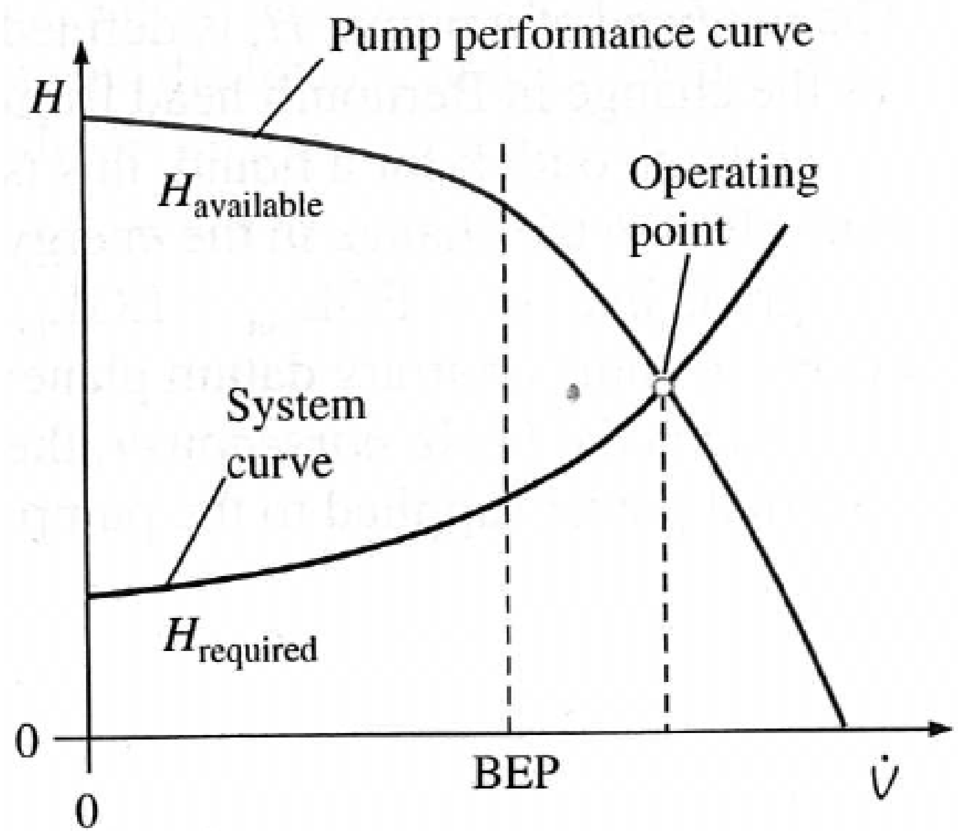


Pump Operation Curves

- Piping system requires a given **V** and a given H.

$$H_{req} = \frac{P_2 - P_1}{\rho g} + \frac{v_2^2 - v_1^2}{2g} + (z_2 - z_1) + H_{loss}$$

  - H_{loss} is friction and minor losses, etc.
- Pump has a corresponding **V** and H.
- These **must match**, forming the operating point.
  - This may not be the best efficiency.
- Select a pump so that the best efficiency point (BEP) occurs at the operating point.
- Generally oversize the pump a bit
  - higher flow for given H_{req}
  - or Higher H_{avail} for given flow
  - Add a valve after pump → raises H_{req} to match H_{avail} for given flow
  - Somewhat wasteful, but offers control.
  - Also may increase efficieny. (But higher efficieny may not compensate for extra work wasted in the valve (see example 14.2)

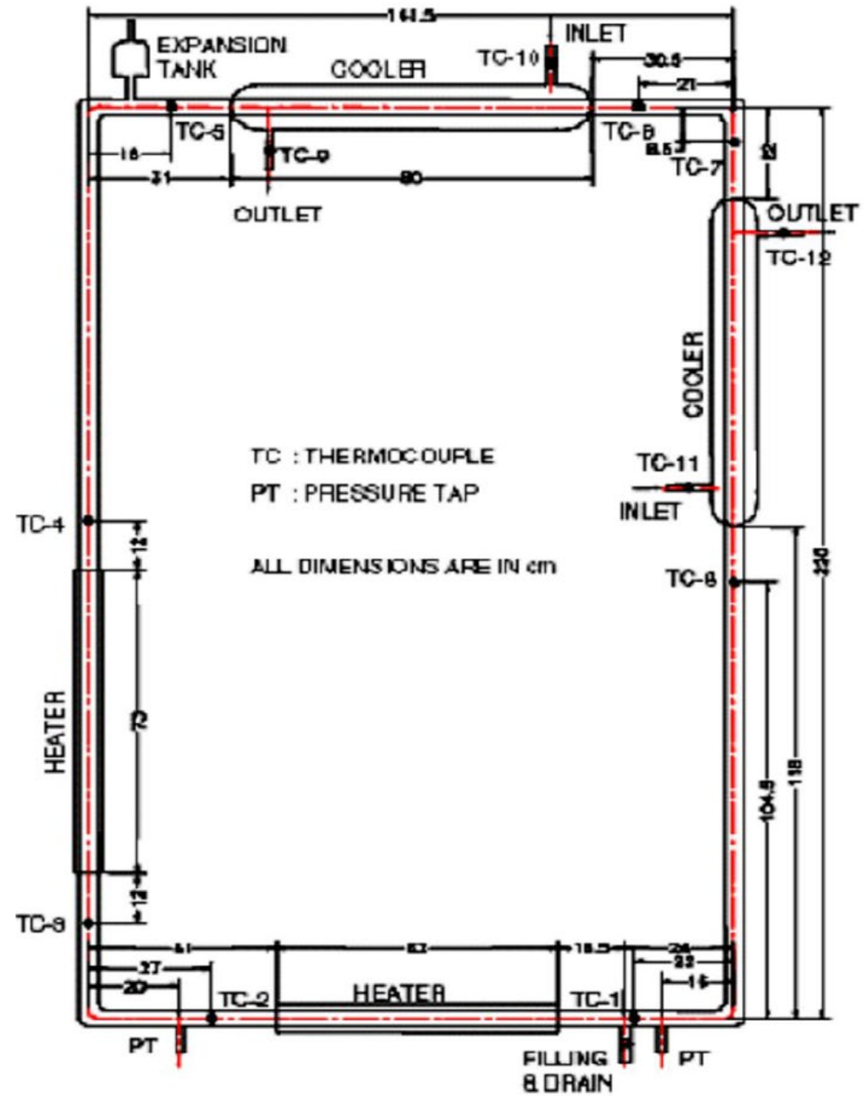


Passive Safety Systems

- Use natural forces and phenomena
  - Density Gradients
  - Gravity
  - Heat Conduction/Convection
  - Chemical Reactions
- Varying levels of passivity (A-D)
- Most passive systems require working fluid
- Natural circulation – No forced flows

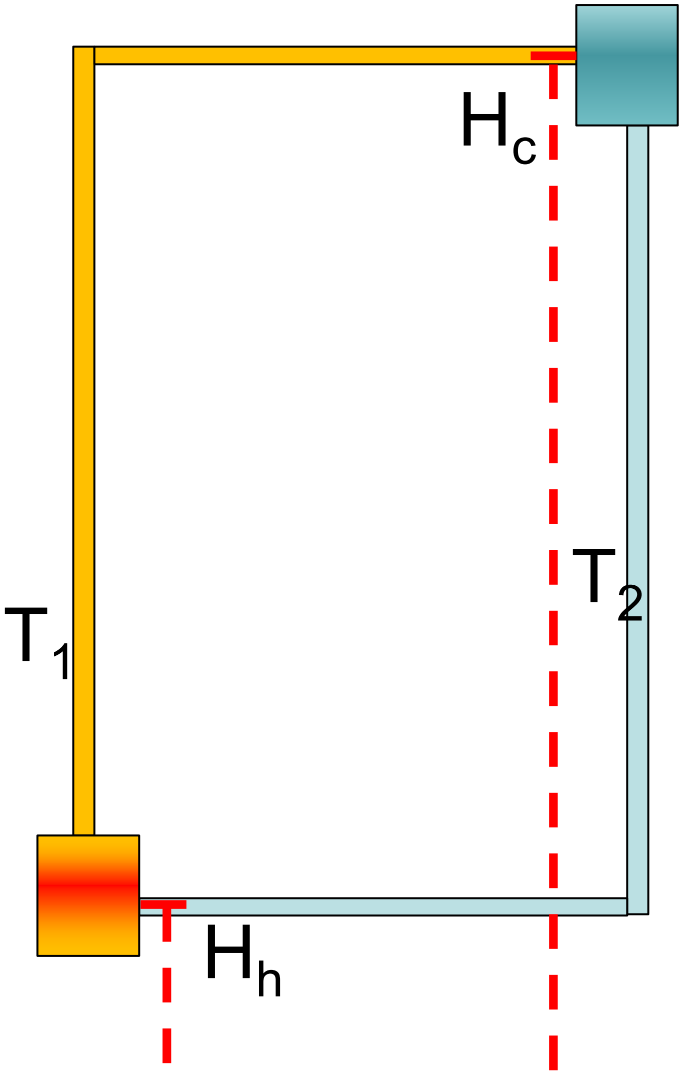
Natural Circulation Example

- Heater on bottom
- Cooler on top
- Expansion tank
- Complete Loop
- Minimized pressure drops
- Essentially isothermal in cold and hot legs



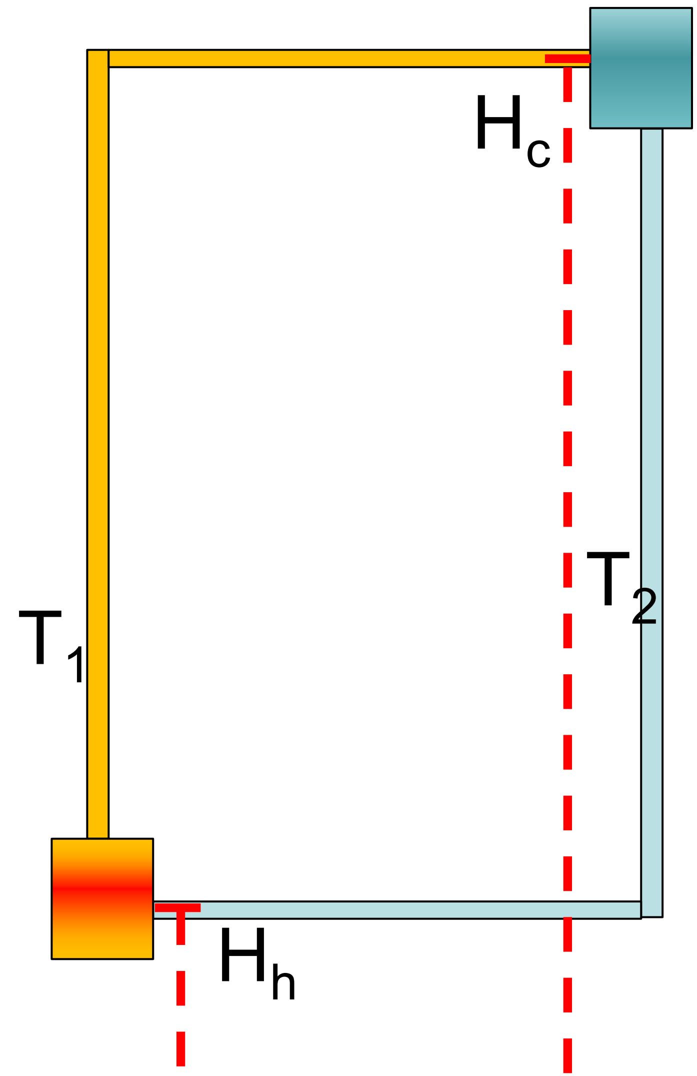
Natural Circulation Evaluation (I)

- *Force Balance*
  - *Hot Leg*
  - $F_{B,h} = \int_{\rho_{T1}}^{\rho_{T2}} gH_h A d\rho(T)$
  - Cold Leg
  - $F_{B,c} = \int_{\rho_{T2}}^{\rho_{T1}} gH_c A d\rho(T)$
  - Full Loop
  - $F_{B,c} = \int_{\rho_{T2}}^{\rho_{T1}} g\Delta H A d\rho(T)$



Natural Circulation Evaluation (II)

- Friction
- $F_f = \left(f\frac{L}{D} + K\right) A \frac{\rho(T)v^2}{2}$
- Flow velocity
- $\dot{V} = vA = A\sqrt{\frac{2\int_{\rho_{T2}}^{\rho_{T1}} g\Delta H d\rho}{\left(f\frac{L}{D}+K\right)\rho(T)}}$
- Balance of Friction and buoyance forces defines v



1 Phase Governing Equations (I)

- Loop Momentum Balance
- $\sum_{i=1}^{N}\left(\frac{l_i}{a_i}\right)\frac{d\dot{m}}{dt} = \beta g\rho(T_H - T_C)L_{th} - \frac{\dot{m}^2}{\rho a_c^2}\sum_{i=1}^{N}\left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]$

Where: N = number of segments

l = segment length

a = flow area

$\dot{m}$= mass flow rate

β = thermal expansion coefficient

L_{th} = Length between heat source and sink

g = gravitational constant

ρ = fluid density

T_H, T_C = hot and cold temperatures, respectively

d_h = hydraulic diameter

K = minor loss coefficient

f = coefficient of friction

1 Phase Governing Equations (II)

- Loop Energy Balance
- $C_{vl} M_{sys} \frac{d(T_M - T_C)}{dt} = \dot{m} C_{pl}(T_H - T_C) - \dot{q}_{SG} - \dot{q}_{loss}$

Where: Cpl = Constant pressure heat capacitynumber of segments

Cvl = Constant Volume Heat Capacity

$\dot{m}$= mass flow rate

L_{th} = Length between heat source and sink

g = gravitational constant

ρ = fluid density

T_H, $T_{C,}$ T_M= hot, cold, and system temperatures, respectively

d_h = hydraulic diameter

$\dot{q}_{SG}$ = heat transfer to steam generator

$\dot{q}_{SG}$ = heat losses in the system

2 Phase Governing Equations (I)

- Loop Momentum Balance
- $\sum_{i=1}^{N}\left(\frac{l_i}{a_i}\right)\frac{d\dot{m}}{dt} = g\rho(T_H - T_C)L_{th} - \frac{\dot{m}^2}{\rho a_c^2}\left\{\sum_{SP}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right] + \frac{\rho_l}{\rho_{TP}}\sum_{TP}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]\right\}$

Where: N = number of segments

l = segment length

a = flow area

$\dot{m}$= mass flow rate

β = thermal expansion coefficient

L_{th} = Length between heat source and sink

g = gravitational constant

ρ = fluid density

T_H, T_C = hot and cold temperatures, respectively

d_h = hydraulic diameter

K = minor loss coefficient

f = coefficient of friction

2 Phase Governing Equations (II)

- Loop Energy Balance
- $M_{sys}\frac{d(e_M - e_l)}{dt} = \dot{m}(h_{TP} - h_l) - \dot{q}_{SG} - \dot{q}_{loss}$

Where: $\dot{m}$= mass flow rate

e_M, e_i = internal energy of the system or liquid, respectively

h_{TP}, h_l = enthalpy of the two phase and liquid regions, respectively

d_h = hydraulic diameter

$\dot{q}_{SG}$ = heat transfer to steam generator

$\dot{q}_{SG}$ = heat losses in the system

- Equilibrium Vapor Quality at Core Exit:
  - $x_e = \frac{h_{TP} - h_f}{h_{fg}}$
- Homogeneous Two-Phase Fluid Mixture Density:
  - $\rho_e = \frac{\rho_f}{1 - x_e\left(\frac{\rho_f - \rho_g}{\rho_g}\right)}$

Advantages/Disadvantages

- Licensing
- Safety
- Cost
- Public Perception

Advantages	Disadvantages
Reduced Cost through Simplicity	Low Driving Head
Pumps Eliminated	Lower Maximum Power per Channel
Possibility of Improved Core Flow Distribution	Potential Instabilities
Better Two-Phase Characteristics as a Function of Power	Low Critical Heat Flux
Large Thermal Inertia	Specific Start up Procedures Required

Instabilities (I)

Class	Type	Mechanism	Characteristic
		Static Instabilities	
Fundamental (or pure) static instabilities	Flow excursion or Ledinegg instabilities	$\left.\frac{\partial \Delta p}{\partial G}\right\|_{\text{int}} \leq \left.\frac{\partial \Delta p}{\partial G}\right\|_{ext}$	Flow undergoes sudden, large amplitude excursion to a new, stable operating condition.
	Boiling crisis	Ineffective removal of heat from heated surface	Wall temperature excursion and flow oscillation
Fundamental relaxation instability	Flow pattern transition instability	Bubbly flow has less void but higher ΔP than that of annular flow	Cyclic flow pattern transitions and flow rate variations
Compound relaxation instability	Bumping, geysering, or chugging	Periodic adjustment of metastable condition, usually due to lack of nucleation sites	Period process of super-heat and violent evaporation with possible expulsion and refilling

Instabilities (II)

Dynamic Instabilities			
Fundamental (or pure) dynamic instabilities	Acoustic oscillations	Resonance of pressure waves	High frequencies (10-100Hz) related to the time required for pressure wave propagation in system
	Density wave oscillations	Delay and feedback effects in relationship between flow rate, density, and pressure drop	Low frequencies (1Hz) related to transit time of a continuity wave
Compound dynamic instabilities	Thermal oscillations	Interaction of variable heat transfer coefficient with flow dynamics	Occurs in film boiling
	BWR instability	Interaction of void reactivity coupling with flow dynamics and heat transfer	Strong only for small fuel time constant and under low pressures
	Parallel channel instability	Interaction among small number of parallel channels	Various modes of flow redistribution
Compound dynamic instability as secondary phenomena	Pressure drop oscillations	Flow excursion initiates dynamic interaction between channel and compressible volume	Very low frequency periodic process (0.1Hz)