Fluid Flow and Heat Transfer in Brewing

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IBD Midlands / BFBi – Derby - February 2019

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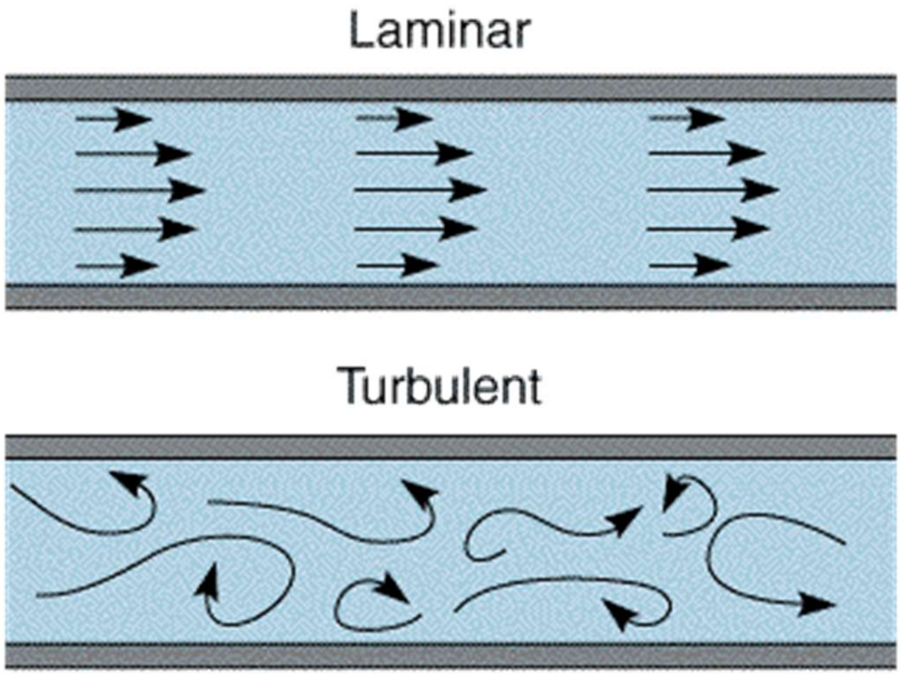
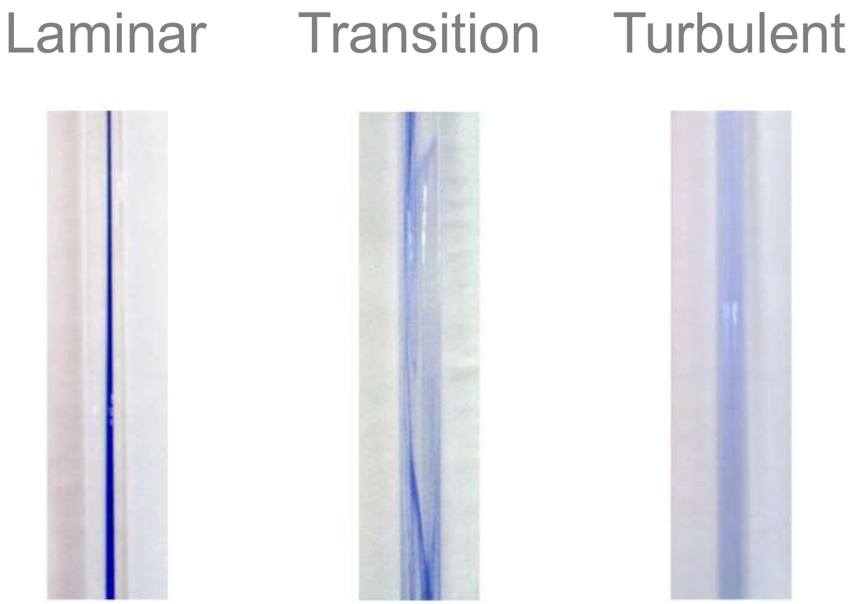
Fluid Flow and Heat Transfer in Brewing

- Fluid Flow
    - Laminar & Turbulent Flow
    - Pump Sizing
    - Energy Savings
- Heat Transfer
    - Heat Transfer Theory
    - Heat Exchanger Designs
    - Brewing Examples

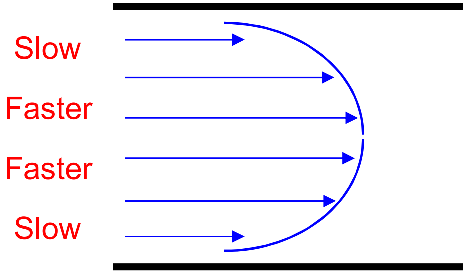
Fluid Flow – Turbulent & Laminar Flow



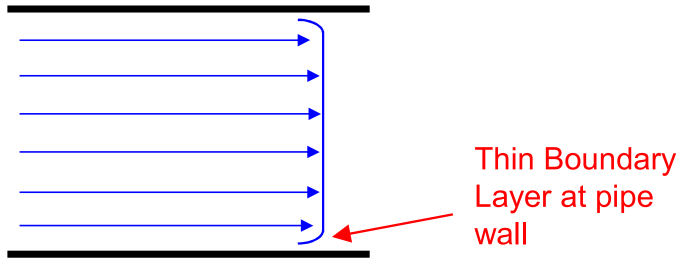


Fluid Flow – Velocity Profile

- Laminar Flow
  - Streamline flow
  - Velocity profile, faster at pipe centre
  - Ineffective CIP



- Turbulent Flow
  - Flat velocity profile
  - Thin boundary layer
  - Effective CIP



Fluid Flow – Reynolds Number

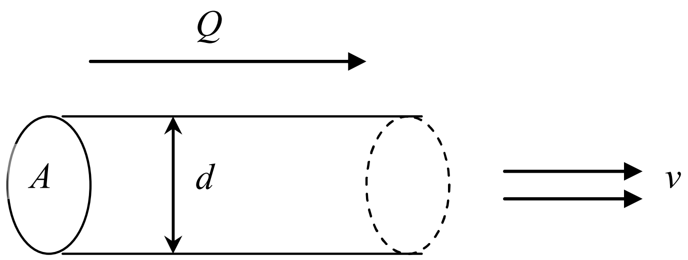
$$Re = \frac{\rho u d_i}{\mu}$$

- Re = Reynolds Number (Dimensionless)
- ρ = Density of Fluid (kg/m³)
- u = Velocity (m/s)
- d_i = Inside Diameter of pipe (mm) [m]
- μ = Viscosity (cP) [kg/m/s]

Flow	Laminar	Transition	Turbulent
Reynolds No.	< 2,000	2,000-4,000	> 4,000

Fluid Flow – Pipework Sizing

Diagram



Equations

$$v = \frac{Q}{3600 \times A}$$ Equation 1

where

$$A = \frac{\pi d^2}{4}$$ Equation 2

Nomenclature

$\boldsymbol{v}$ = Fluid Pipe Velocity (speed), m/s
Q = Fluid Volumetric Flowrate, m^3/hr
A = Cross-sectional Area of Pipe, m^2
d = Inside Pipe Diameter, m

Fluid Flow – Reynolds Number Example Water in 2” O.D. Tube

Fluid	-	Water
Density	kg/m3	1000
Pipe ID	mm	47.6
Pipe cross sectional area	m2	0.0018
Viscosity	cP	1

$$Re = \frac{\rho u d_i}{\mu}$$

Flow rate	m3/h	0.3	0.4	0.5	9.6	12.8	14.1
	hl/h	2.7	4.0	5.4	96.1	128.1	140.9
	brl/h	1.6	2.4	3.3	58.7	78.3	86.1
	l/min	4.5	6.7	9.0	160.2	213.5	234.9
velocity	m/s	0.04	0.06	0.08	1.50	2.00	2.20
Reynolds number	-	2,000	3,000	4,000	71,400	95,200	104,720
Flow Character	-	LAMINAR	TRANSITION	TURBULENT	TURBULENT	TURBULENT	TURBULENT

Recommended Maximum Velocity for water in 2” tube

Fluid Flow – Reynolds Number Example Yeast in 2” O.D. Tube

Fluid	-	Yeast
Density	kg/m3	1100
Pipe ID	mm	47.6
Pipe cross sectional area	m2	0.0018
Viscosity	cP	200

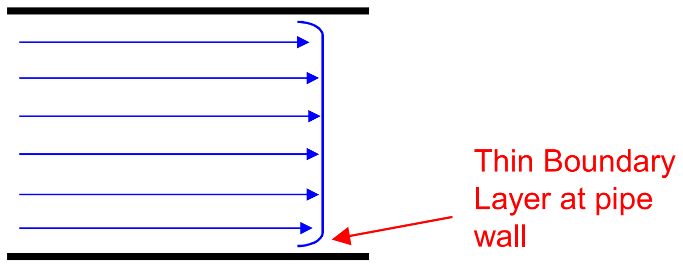
$$Re = \frac{\rho u d_i}{\mu}$$

Flow rate	m3/h	6.4	48.9	73.4	97.9
	hl/h	64.1	489.4	734.1	978.8
	brl/h	39.1	299.1	448.6	598.1
	l/min	106.8	815.7	1223.5	1631.3
velocity	m/s	1.00	7.64	11.46	15.28
Reynolds number	-	262	2,000	3,000	4,000
Flow Character	-	LAMINAR	LAMINAR	TRANSITION	TURBULENT

Recommended Maximum Velocity for yeast in 2” tube

Fluid Flow – Mains CIP

- Always Turbulent Flow
  - Reynolds Number >4000
- Minimise boundary layer
  - Laminar layer on internal pipe wall
- Target CIP velocity in process pipe
  - > 1.5 m/s
- Avoid Excessive velocity
  - High pressure drop/Energy Input



- Other CIP factors
  - Temperature
  - Time
  - Chemical

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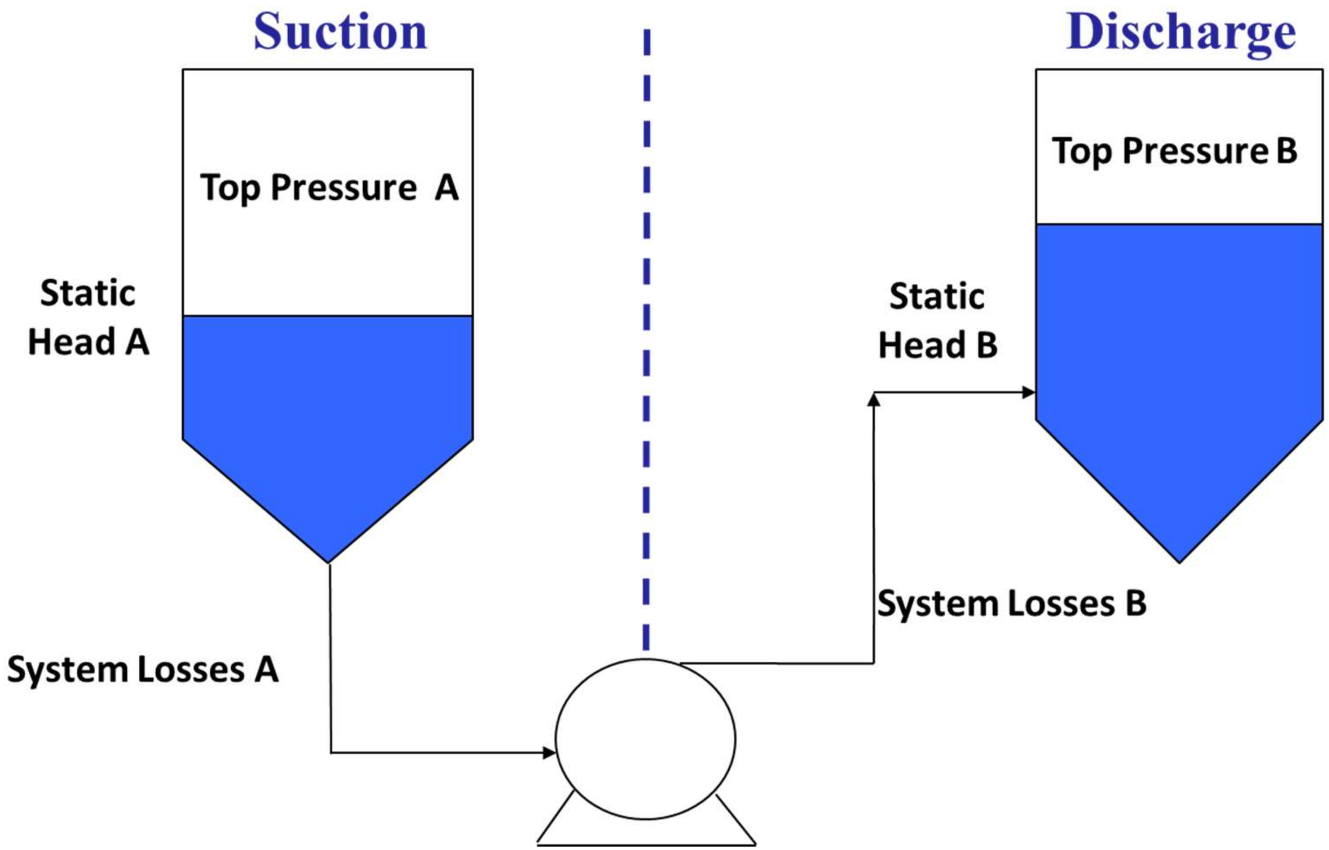
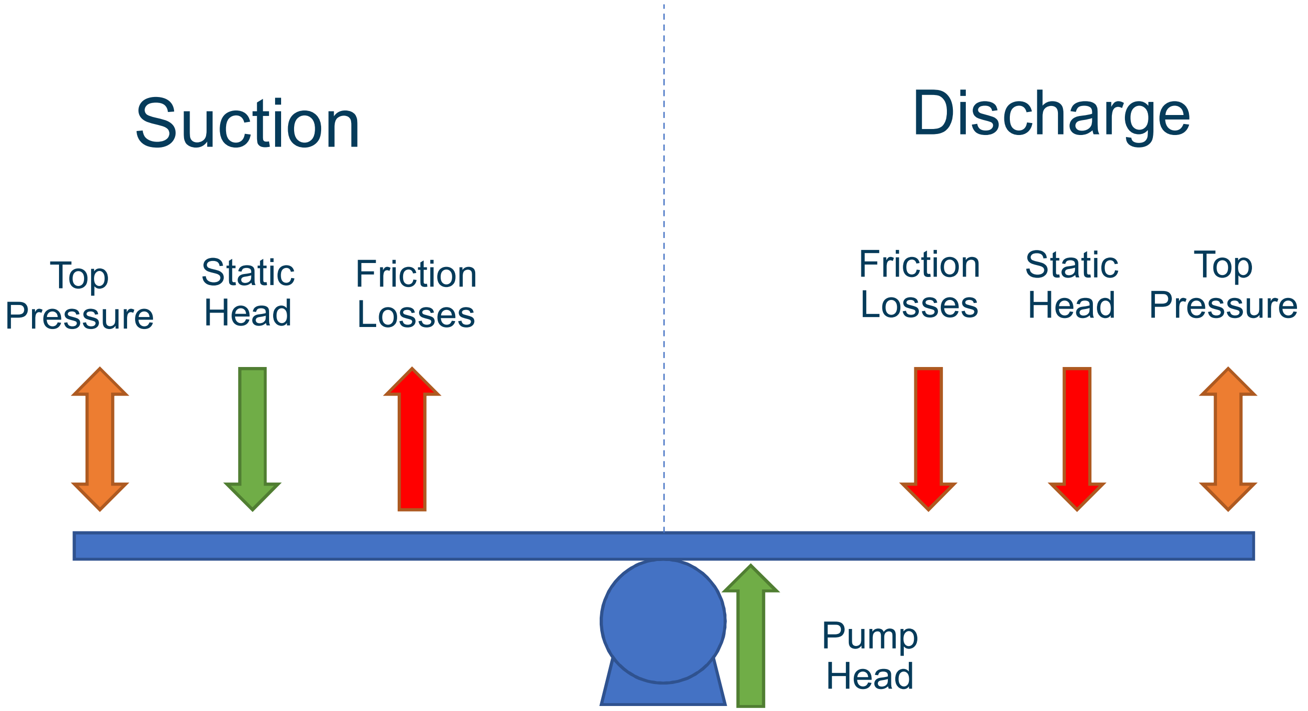
Fluid Flow – Pump Sizing

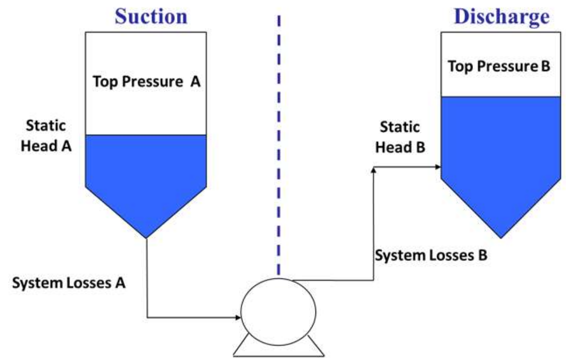
- Consistent Calculation Needed
  - Pressure (P) or Head (h)
  - $P = \rho g h$



- ρ = Density of Fluid (kg/m³)
- g = gravity (m/s²)
- h = head (m)

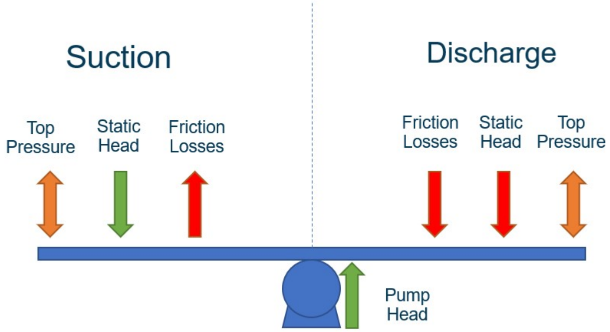
Fluid Flow – Pump Sizing

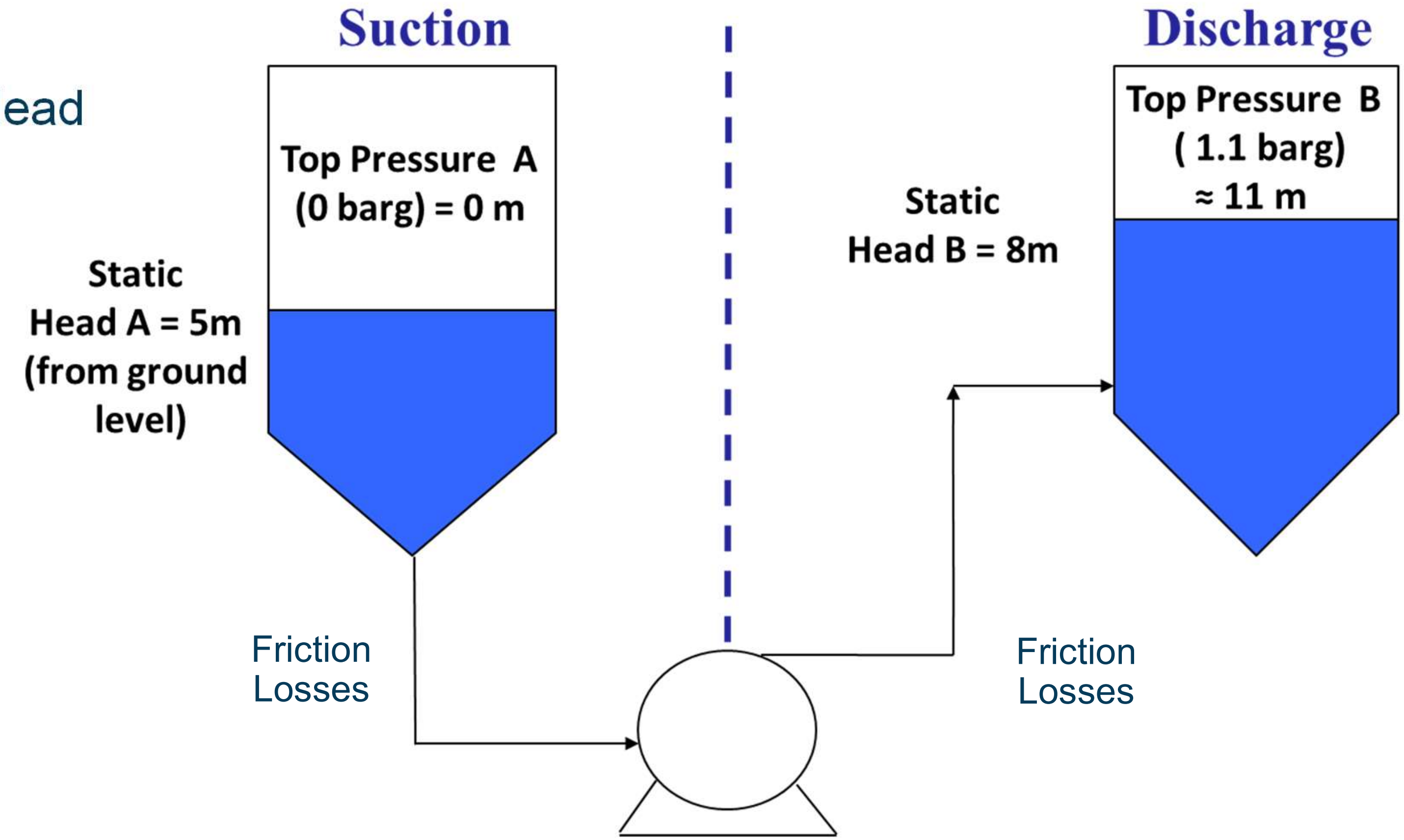




Fluid Flow – Pump Sizing

- Top Pressure and Static Head
  - ρ = 1,000 kg/m^3
  - g = 9.81 m/s^2
- 1.0 barg = 10^5 Pa





Fluid Flow – Pump Sizing

- System losses can be broadly categorised into:
  - Frictional Losses in (straight) Pipework
  - Frictional Losses in Fittings, bends and In-line Equipment

- Pipework Losses
  - The Darcy Equation
  - Need to obtain a friction factor
  - Darcy *not* Fanning   ($f_{darcy} = 4 \, . f_{fanning}$)

$$h_f = f \frac{L}{d_i} \frac{u^2}{2g}$$

- h_f = Fictional Head Loss (m)
- f = Friction Factor (Dimensionless)
- L = Pipe Length (m)
- d_i = Inside Diameter of pipe (m)
- u = Viscosity (m/s)
- g = gravity (m/s^2)

Fluid Flow – Pump Sizing

Pressure drops of fittings in metre equivalent pipe length

Applies to: Pipe roughness k = 0.05 mm
Flow speed v = 1-3 m/s
(error >10% deviation in speed)
(Accuracy ± 5%)

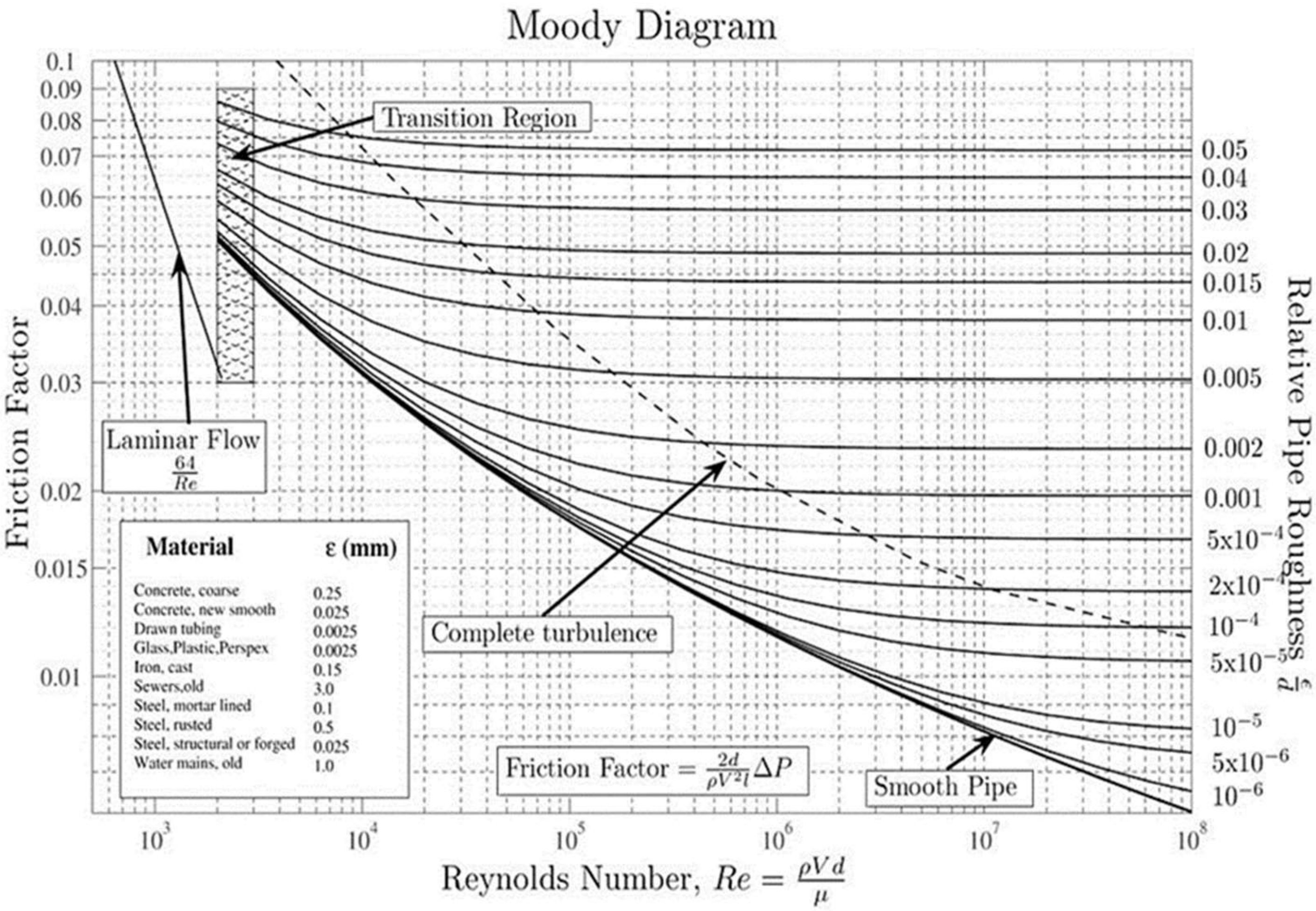
Also make allowances for inline equipment such as control valves, Heat Exchangers, filters etc

Fitting	Nominal Diameter in mm								
	25	32	40	50	65	80	100	125	150
ζ = 0.05 Reducer Tee	0.05	0.07	0.09	0.12	0.17	0.20	0.28	0.40	0.48
ζ = 0.15 Bend 45°	0.14	0.20	0.27	0.35	0.50	0.60	0.85	1.20	1.40
ζ = 0.25 Bend 90° Expansion Butterfly valve Inlet (Tank outlet)	0.25	0.35	0.45	0.60	0.80	1.00	1.35	1.90	2.4
ζ = 0.90 Tee	0.90	1.20	1.60	2.00	3.00	3.70	5.20	7.00	8.80
ζ = 1.30 Tee	1.20	1.80	2.30	3.00	4.30	5.40	7.40	10.00	12.50
ζ = 1.5 Reflux valve	1.40	2.10	2.70	3.50	5.00	6.30	8.50	11.50	14.50

Source - GEA Manual for the Design of Pipe Systems and Pumps

Fluid Flow – Pump Sizing

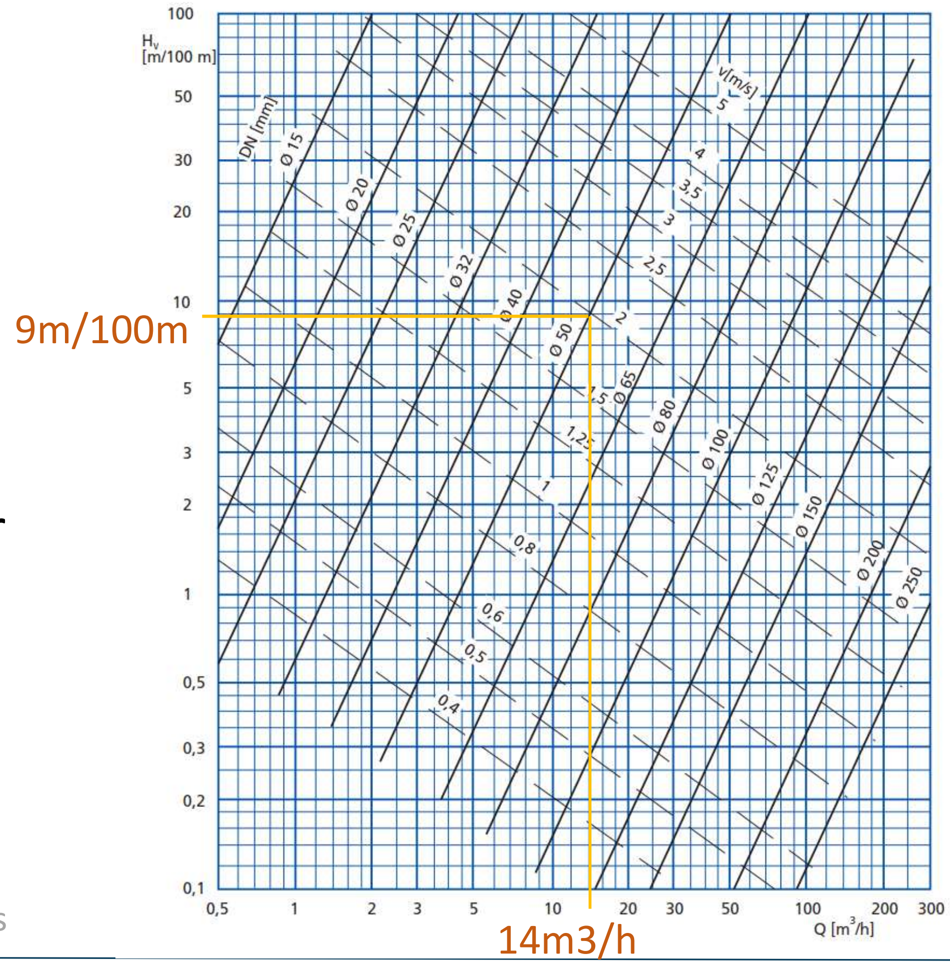
- The Moody Chart used to calculate friction factor *f*
- Function of: -
  - Reynolds No.
  - Pipe internal diameter & roughness
- e/d = pipe roughness / pipe diameter
- Stainless Steel Roughness ~0.05mm ($0.05x10^{-3}$m)



Fluid Flow – Pump Sizing

ALTERNATIVE - Diagram for the quick calculation of pressure drops

Pressure drops Hv per 100 m pipe length for stainless steel pipes with a surface roughness of k = 0.05 and media with 1 cP viscosity (= water) (accuracy ± 5%)



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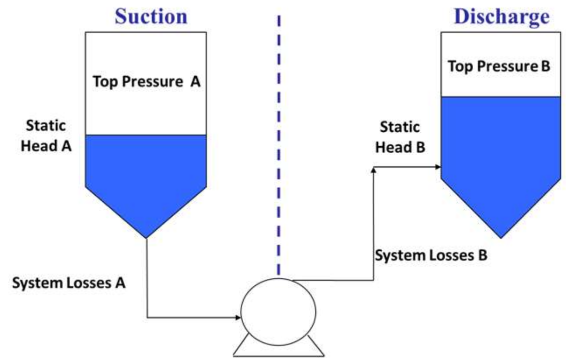
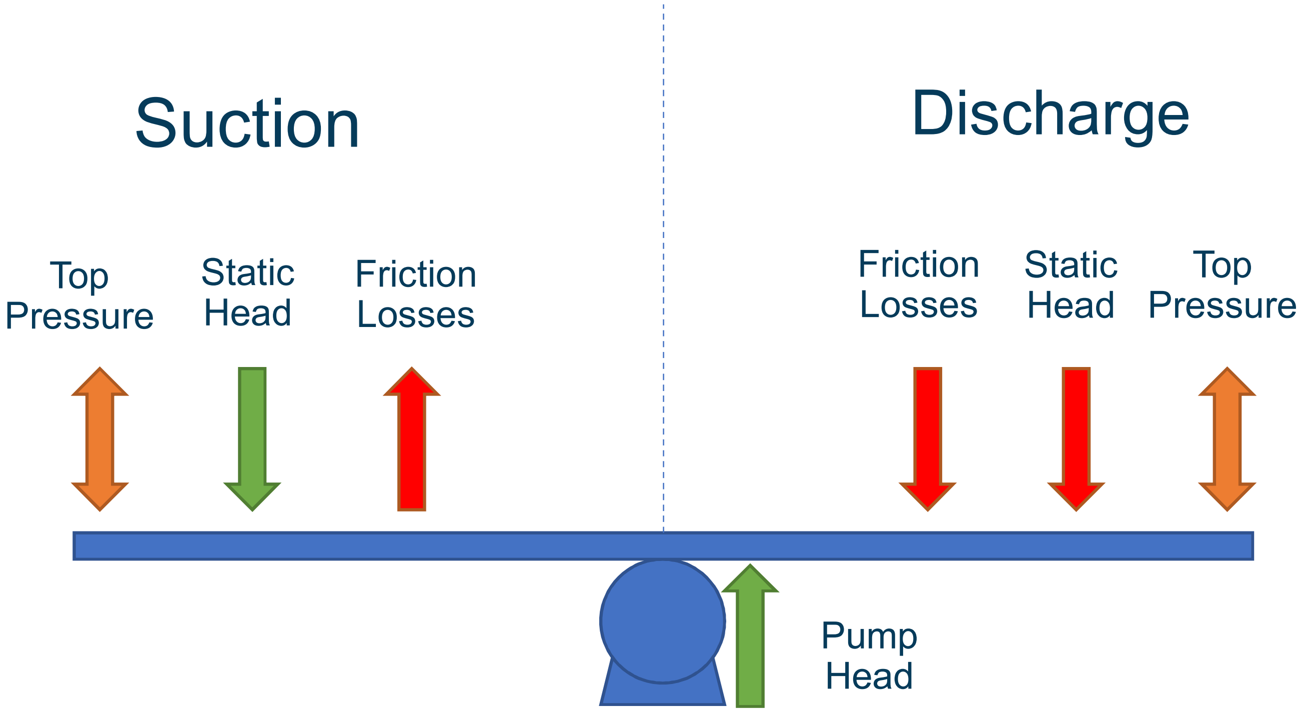
Fluid Flow – Pump Sizing





Fluid Flow – Pump Sizing

- Pump curve require to meet this duty point (flow and head)
- Alternatively the pump Dynamic Pressure at required flowrate is 5.6 bar

	Suction (A)	Discharge (B)	Total
Top Pressure	↓ 0m	↓ 11m	↓ 11m
Static Head	↓ 5m	↓ 8m	↓ 3m
Losses	↑ 3m	↓ 40m	↓ 43m
Dynamic Head	↓ 2m	↓ 59m	↓ **57m**

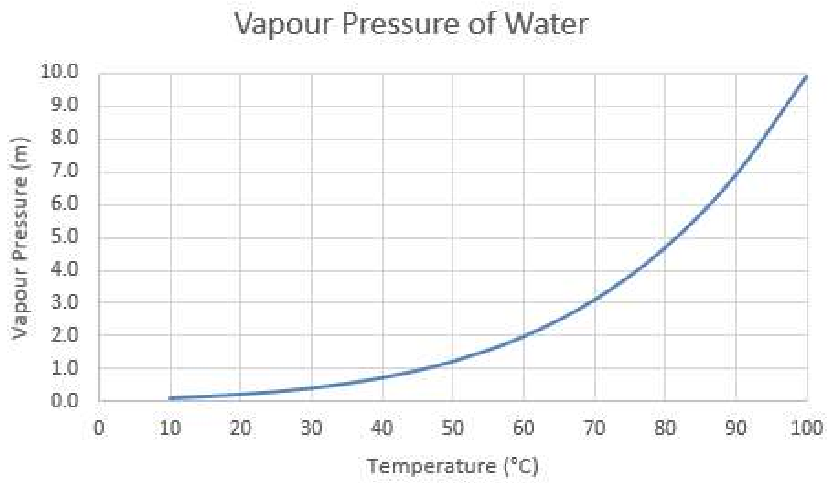
Also make allowances for inline equipment such as control valves, Heat Exchangers, filters etc

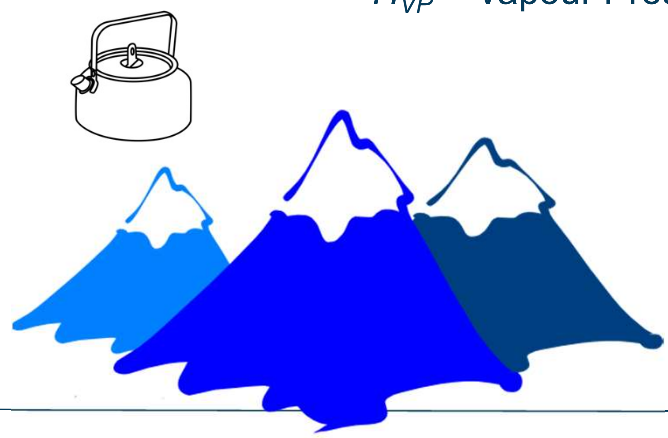
Fluid Flow – Pump Sizing

- Net Positive Suction Head (NPSH) additionally critical (esp. at high temp.)

$$NPSH_A = H_{SP(abs)} + H_{SS} - H_{FS} - H_{VP}$$

- $NPSH_A$ = Net +ve Suction Head available (m)
- H_{SP} = Suction top pressure absolute (m)
- H_{SS} = Static Suction Head (m)
- H_{FS} = Suction Friction Losses (m)
- H_{VP} = Vapour Pressure at pumping temp. (m)





Everest 8848m tall
Air Pressure 337 mBar
Boiling Point 71°C

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Fluid Flow – Pump Sizing

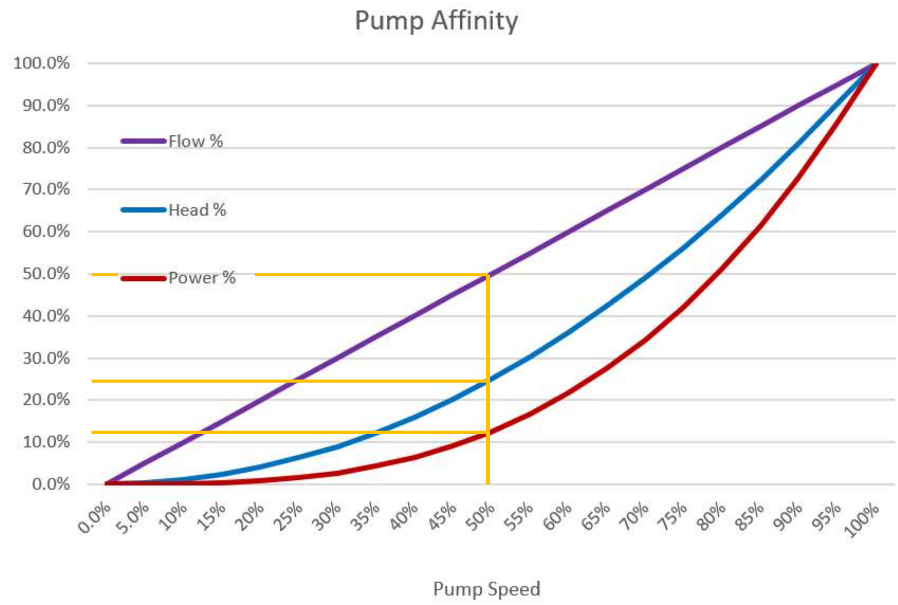
- Pump duty at a specified flowrate is a function of
  - Static Head
  - System Losses (Friction)
  - Top (or Injection) Pressure
- Undersized pipework will mean long term high pump power use and may increase the design pressure of the system

$$P_p = \frac{Q\rho g h}{(n*3600*1000)}$$

- P_p = Pump Power (kW)
- Q = Flow Rate (m^3/h)
- ρ = Density (kg/m^3)
- g = gravity (m/s^2)
- h = differential head (m)
- n = Pump efficiency (%)

Fluid Flow – VSD Control

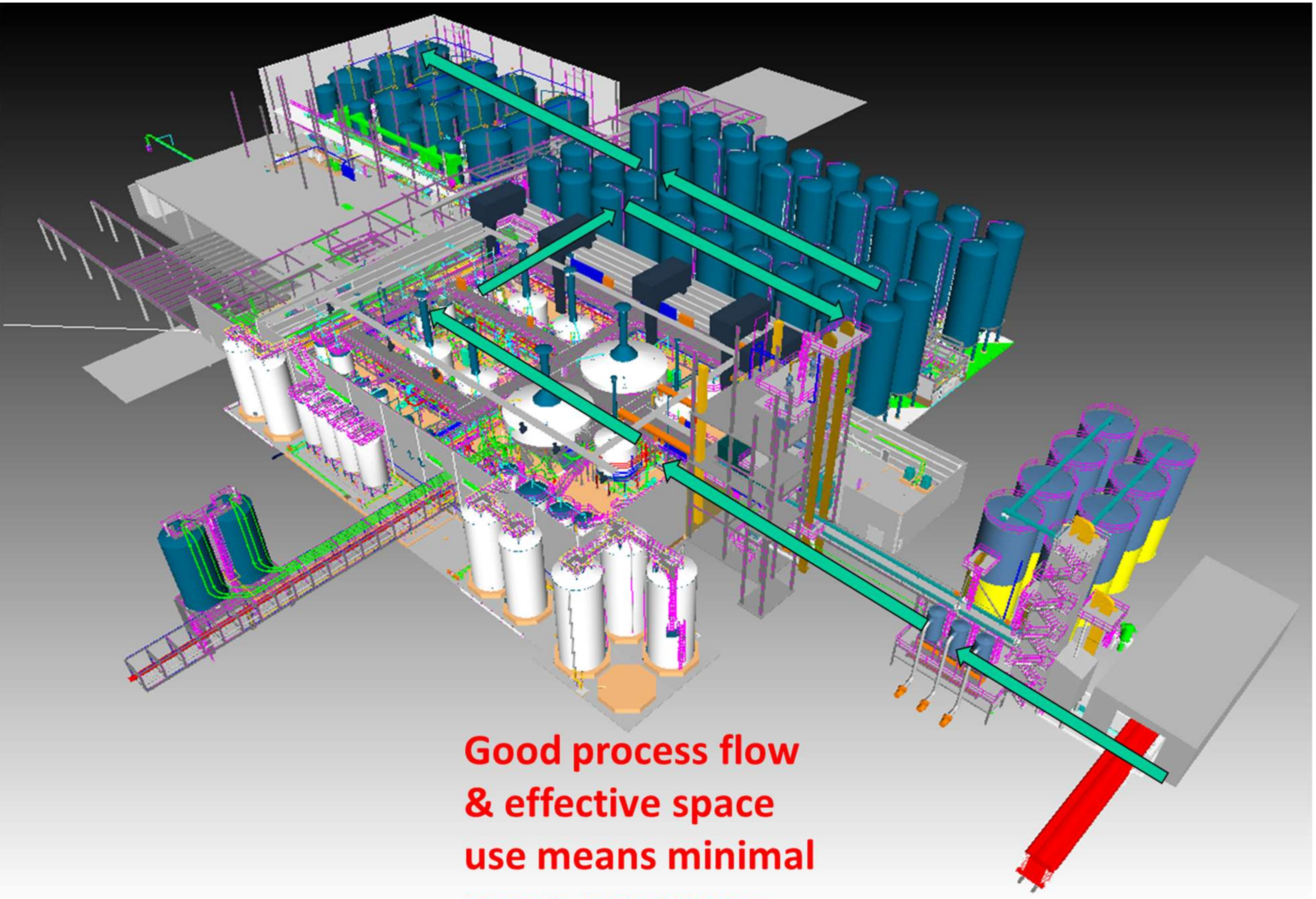
- In reality pumps often have a range of duties.
- Example – filling a tank at constant flow and variable level
- Pump Affinity Laws
    - Flow proportional to RPM (speed)
    - Head (pressure) proportional to $(\text{speed})^2$
    - Power is proportional to $(\text{speed})^3$
- Pump Speed 50%
  Head 25%
  Power Consumption 12.5%



Fluid Flow – VSD Operational Savings

- **Scenario 1 – Flow Control valve**
- Water Flow 50m3/h
- Dynamic Head 40m
- 1bar pressure drop across control valve
- Absorbed Power 11.4kW
- Annual Running Cost £10k

- **Scenario 2 – Variable Speed Drive**
- Water Flow 50m3/h
- Dynamic Head 30m
- Pump speed reduced, no Control Valve
- Absorbed Power 9.1kW
- Annual Running Cost £8k
- **SAVING £2k**



Good process flow & effective space use means minimal pump power use.

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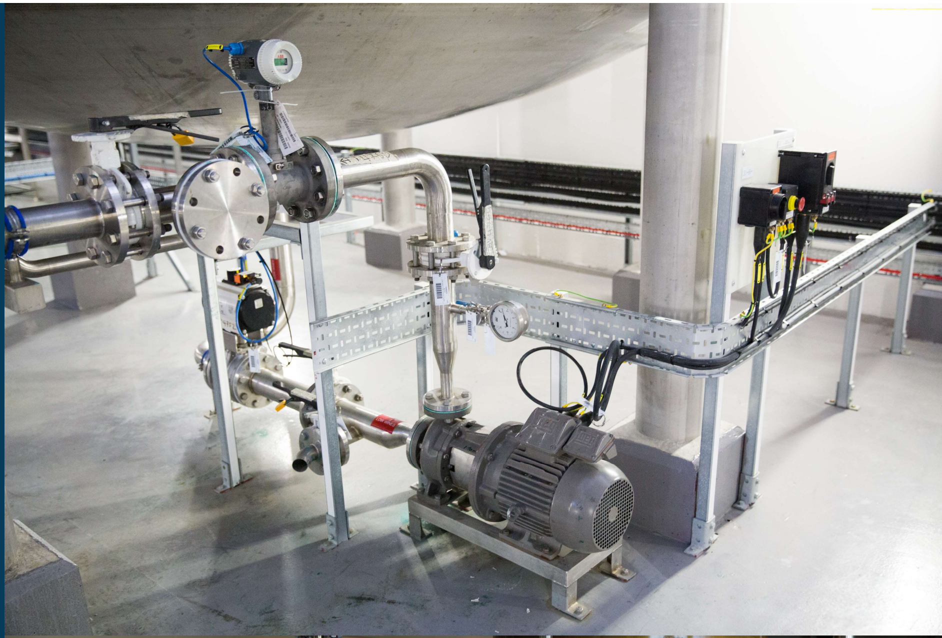
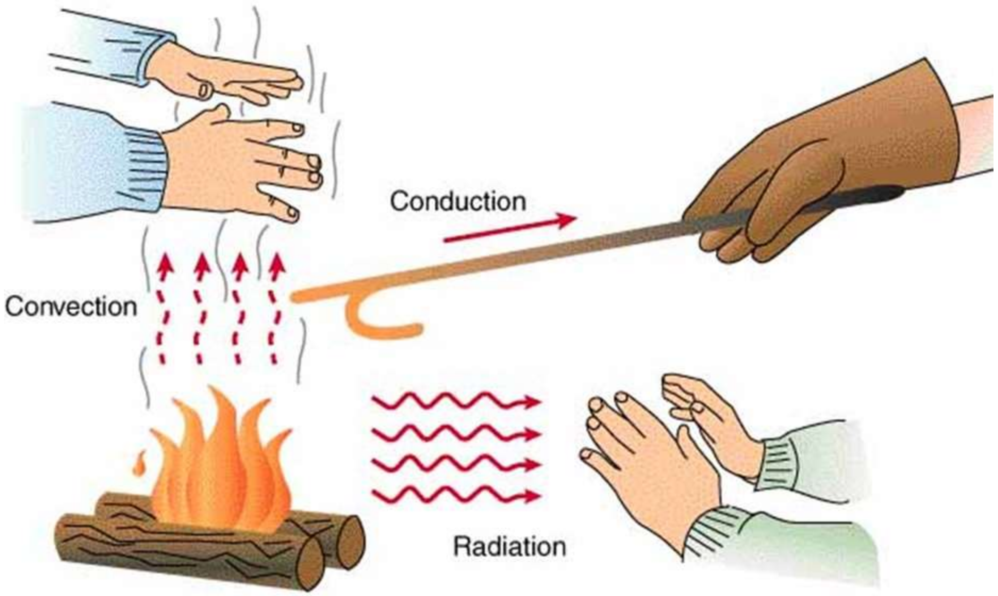


Heat Transfer - Overview

- Conduction – Transfer of heat (internal energy) by microscopic collisions of particles, predominantly in solids.
    - e.g. heat transfer through a stainless steel vessel wall or the metal surfaces of a heat exchanger.
- Convection – Particles with more heat energy in a liquid or gas move and take the place of particles with less heat energy.
    - e.g. natural convection during fermentation, heating a liquid in a vessel.
- Radiation – Transmission of heat energy in the form of waves or particles through a solid, liquid or gas.
    - e.g. radiators, hot pipework
- In reality, often all three happen simultaneously, one normally more predominant depending on the situation.



Heat Transfer - Overview

- Types of Heat Energy Transfer
  - Sensible – Temperature Change
    - Gas
    - Liquid
    - Solid
  - Latent – Phase Change
    - Solid-Liquid (Melting)
    - Liquid-Solid (Freezing)
    - Liquid-Gas (Evaporating)
    - Gas-Liquid (Condensing)
  - Exothermic/Endothermic – Chemical Reaction
    - e.g. Fermentation
  - SI unit of energy is the Joule (J)
  - 1000 J = 1 kJ

Heat Transfer – Brewery Applications

- Brewhouse
  - Mashing
  - Wort Pre-Heating
  - Wort Boiling
  - Wort Cooling
  - Wort Sterilisation (Yeast Prop)
  - CIP
  - Hot Water
  - Chilled Water
  - Energy Store

Heat Transfer – Brewery Applications

- Beer Cellar
  - Yeast Cooling
  - Fermentation (Exothermic)
  - FV/MV Crash Cool
  - Beer Filtration
  - Bright Beer
  - CIP/SIP
- Packing
  - Keg/Cask Sanitisation
  - Flash Pasteurisation
  - Tunnel Pasteurisation
- Utilities
  - Steam Generation
  - Refrigeration
  - Building Services (Air-Conditioning)

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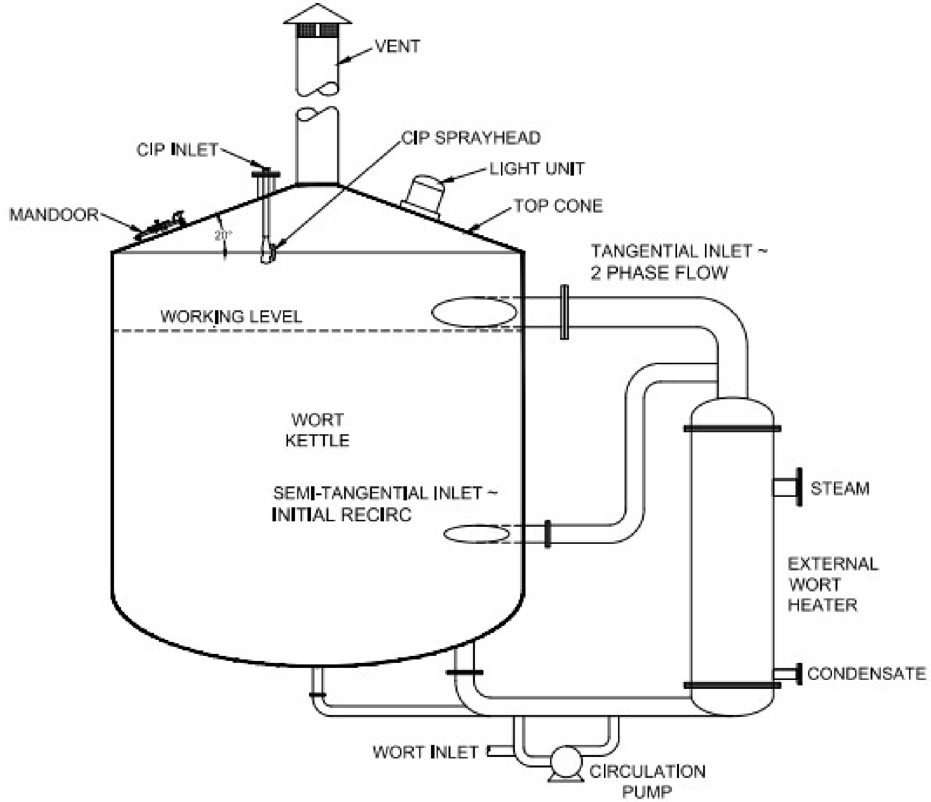
Heat Transfer – Calculation

- What is the total quantity of steam (kg) required to heat 1000 hl batch of wort from 75°C to 100°C and then evaporate 5% of the wort volume?

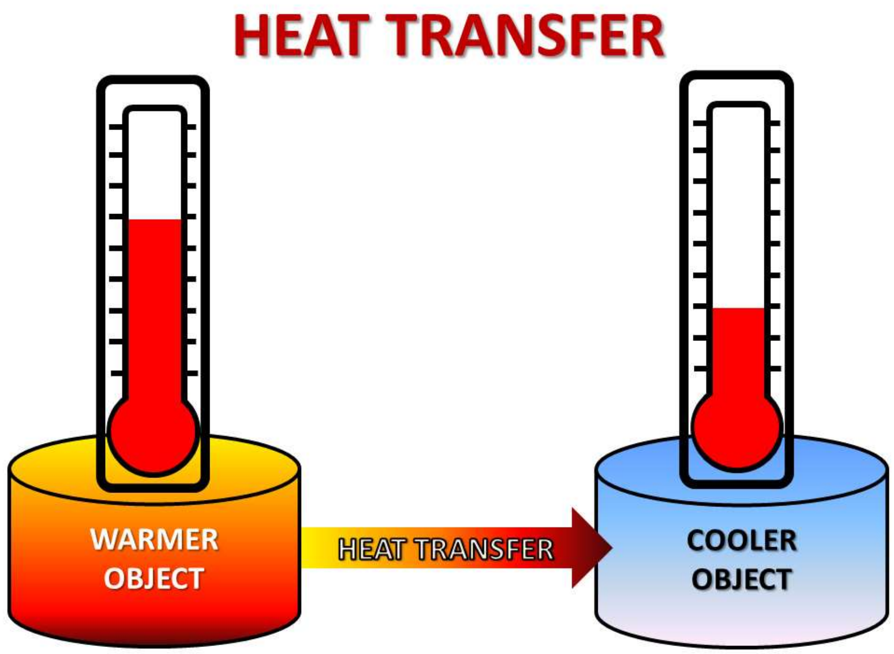
- We need to:
  - Calculate sensible heat energy (kJ).
  - Calculate latent heat energy (kJ).
  - Calculate quantity of steam required (kg).

- For simplicity we will discount losses to the local environment from hot surfaces.



Heat Transfer – Sensible Heat

- Exchange of sensible heat leads to a change in temperature of a body e.g. a mass of liquid.
- No change in physical state
- Equation for calculating heat transfer energy (kJ)
- $Q = m.c_p.\Delta T$
- Q = Total Energy Transferred (kJ)
  - m = Mass (kg)
  - c_p = Specific heat capacity ($kJ.kg^{-1}.K^{-1}$)
  - ΔT = Temperature change (K or °C)
- One media gets warmer, the other media gets cooler.



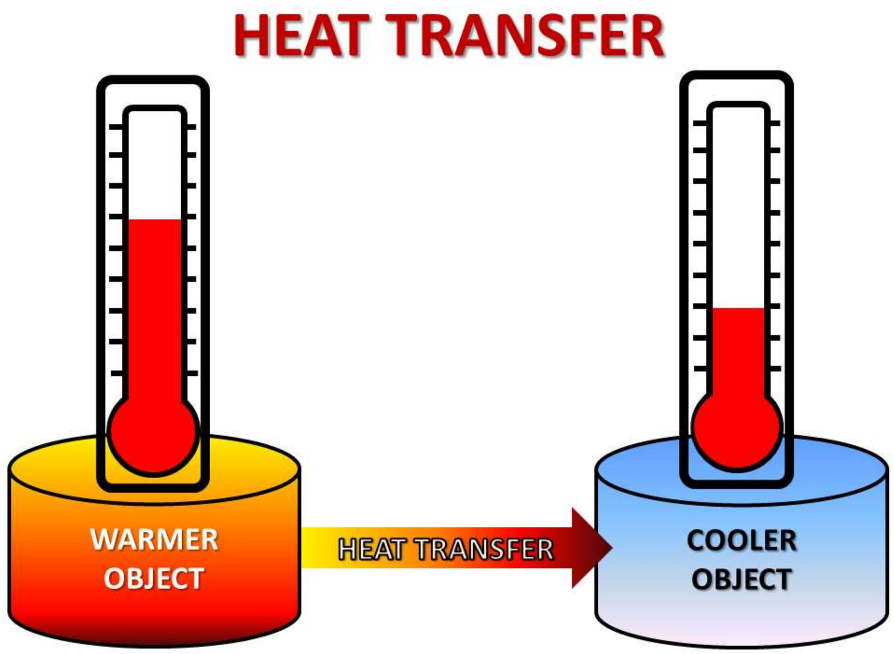
Heat Transfer – Specific Heat Capacity

- When dealing with changes in sensible heat, we need to know the specific heat of the substance being heated or cooled.
- c_p = specific heat at constant pressure
- The energy (kJ) required to raise the temperature of 1 kg mass of a substance by 1K.
- SI units $kJ.kg^{-1}.K^{-1}$
- For liquids and gases c_p varies with temperature, not normally by much!
- We generally consider c_p as a fixed value, for water $c_p = 4.186\ kJ.kg^{-1}.K^{-1}$

Material	Form	Specific Heat
		($kJ\ kg^{-1}\ K^{-1}$)
Air	Gas	1.01
Carbon dioxide	Gas	0.83
Hydrogen	Gas	14.20
Ammonia	Liquid	4.60
Water	Liquid	4.186
Beer	Liquid	4.013 to 4.104
Gas oil	Liquid	1.99
Prop.Glycol solution	Liquid	3.717
Ind. Alcohol solution	Liquid	4.144
$CaCl_2$ solution	Liquid	2.982
Ice	Solid	0.206
Iron	Solid	0.444
Stainless steel	Solid	0.500
Copper	Solid	0.39
Concrete	Solid	0.84

Heat Transfer – Sensible Heat

- Heat 1000 hl wort from 75°C to 100°C
- $Q = m.c_p.\Delta T$
- Mass (m) = volume x density = 1000hl x 103.2 kg/hl = 103,200kg
- Specific heat of wort (c_p) = 4.0 $kJ.kg^{-1}.K^{-1}$
- Temperature change = (100°C - 75°C) = 25°C
- Total Energy Input = $Q = m.c_p.\Delta T$
- Q = 103,200 x 4.0 x 25 = **10,320,000 kJ**

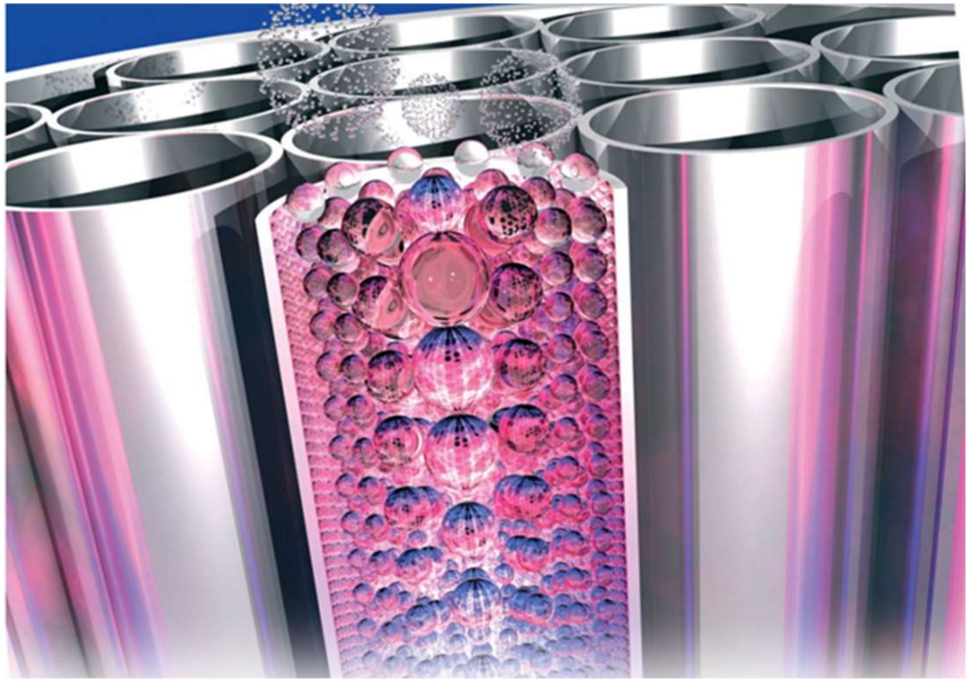


Heat Transfer – Latent Heat

- Latent heat is applied to cause a change in state e.g. causing liquid to boil into a vapour.
- Often energy intensive.
- No change in temperature.
- Latent heat for boiling = heat of evaporation Δh_{vap}
- For boiling water $\Delta h_{vap} = 2257\ kJ.kg^{-1}$
- Equation for calculating heat transfer energy (kJ)
- $Q = M_E . \Delta h_{vap}$
- Q = Total Energy Transferred (kJ)
    - M_E = Mass to be evaporated (kg)
    - Δh_{vap} = Heat of evaporation ($kJ.kg^{-1}$)

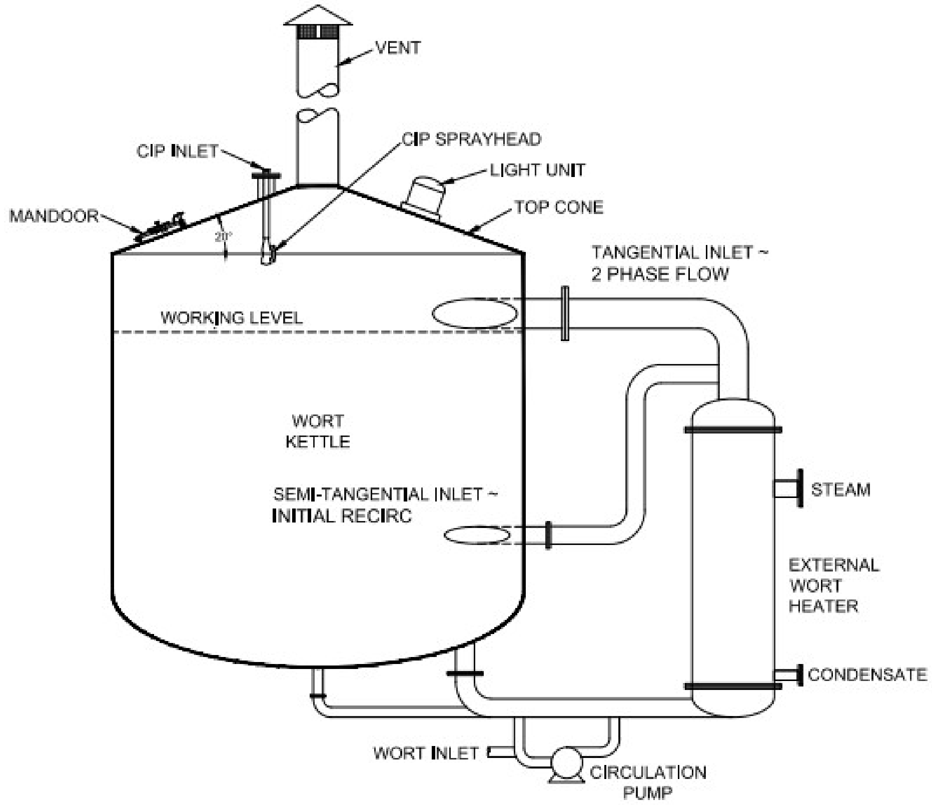
Heat Transfer – Latent Heat

- Boil 5% volume water off 1000 hl wort
- SG of water = 1.0
- M_E = mass water evaporated = 0.05 x (1000 x 100) x 1.0 = 5000 kg
- Total Energy Input = Q = $M_E . \Delta h_{vap}$
- Q = 5000 kg x 2257 kJ.kg^{-1} = **11,285,000 kJ**



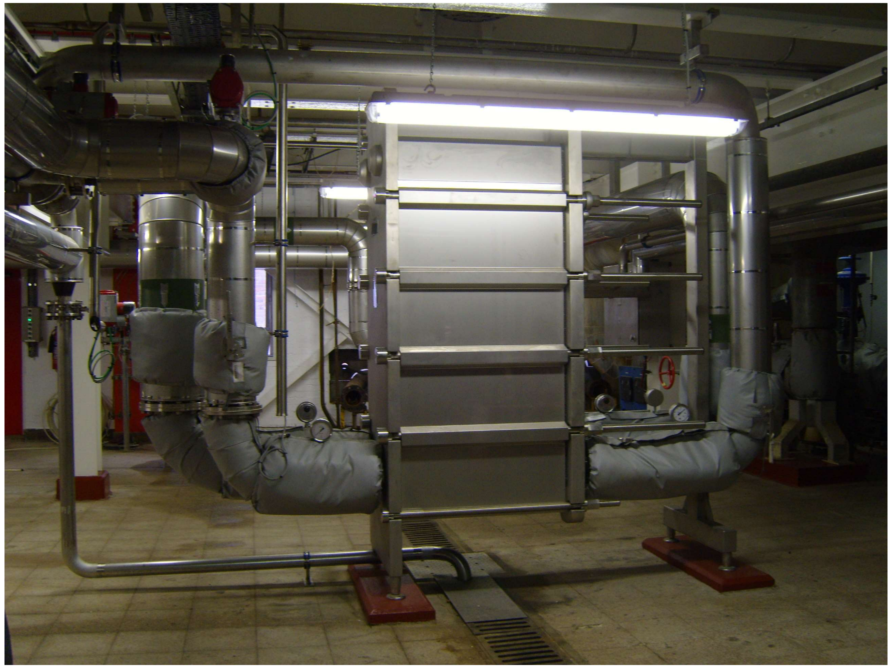
Heat Transfer – Combined Energy

- We now know the total energy required to heat up the batch of wort and evaporate 5% of the volume.
- 10,320,000 kJ + 11,285,000 kJ = **21,605,000 kJ**
- Heating medium is dry saturated steam at 3.0 barg.
- Steam will condense into water by transferring it's own latent heat to the wort.
- Latent heat of steam at 3.0 barg = 2133 $kJ.kg^{-1}$
- Total Energy Input = Q = M_E. Δh_{vap}
- Total Mass steam = M_E = Q / Δh_{vap}
- M_E = 21,605,000 / 2133 = **10,129 kg of steam**.



Heat Transfer – Rate of Energy Transfer

- For sizing heat transfer equipment engineers are also interested in the rate of energy transfer over a period of time this is termed ‘power’ and sometimes called ‘heat load’ q.
- q (kJ.s^{-1}) = Q (kJ) / t (s)
  - 1 kJs^{-1} = 1 kW.
- Based on the previous calculation, what is the steam flow required to:
  1. Heat the wort from 75-100°C in 45 minutes.
  2. Boil off 5% of the volume in 60 minutes
  3. Which operation has the highest steam demand on the boiler?



Heat Transfer – Rate of Energy Transfer

- For both operations
    - Calculate rate of heat transfer ($kJ.s^{-1}$)
    - Calculate steam flow rate (kg/h)

1. For the wort heating stage (sensible heat) we already know the total energy required Q = 10,320,000kJ.
    - Therefore the rate of energy transfer q = 10,320,000 / (45 x 60) = 3822 $kJ.s^{-1}$ = 3822 kW
    - Steam flow m = q / Δh_{vap} = 3822 / 2133 = 1.79 kg/s = **6,450 kg/h**
2. For the wort boiling stage (latent heat) we already know the total energy required Q = 11,285,000kJ.
    - Therefore the rate of energy transfer q = 11,285,000 / (60 x 60) = 3134 $kJ.s^{-1}$ = 3134 kW
    - Steam flow m = q / Δh_{vap} = 3134 / 2133 = 1.46 kg/s = **5,289 kg/h**
3. From the above we can see the wort heating operation has a higher steam demand than the boiling operation. Heat load is a function of energy & time.

BRIGGS BREWING

Fluid Flow and Heat Transfer in Brewing

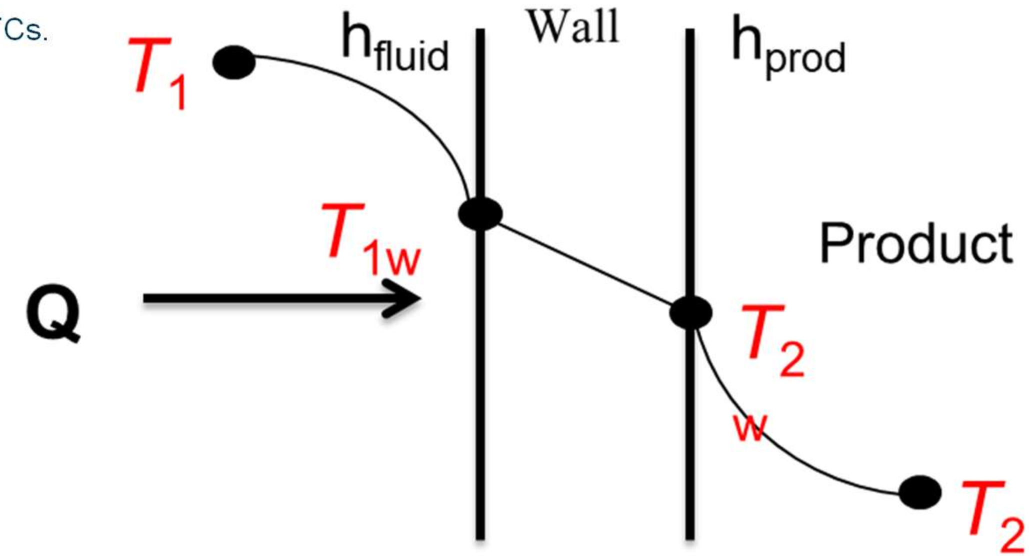
- Fluid Flow
  - Laminar & Turbulent Flow
  - Pump Sizing
  - Energy Savings
- Heat Transfer
  - Heat Transfer Theory
  - Heat Exchanger Designs
  - Brewing Examples

Heat Transfer – Heat Exchanger Design

- To size a heat exchanger an engineer needs to calculate the heat transfer area required.
- Need to fix some of the variables. For an in-line heat exchanger we typically define:
  - Mass transfer rate m (kg/s).
  - Temperature T_1 (°C) at inlet to HX.
  - Temperature T_2 (°C) at outlet of HX.
- Need to calculate the heat load q (kW) required
  - **q = Q/t = (m.cp.ΔT)/t**
- The calculated q value can be used to calculate the heat exchanger surface area A (m^2) using the equation.
  - **$q = U.A.\ \Delta T_{LM}$**
- U = Overall heat transfer coefficient (W/m^2K)
- A = Surface area required (m^2)
- ΔT_{LM} = Log mean temperature difference (°C)

Heat Transfer – Overall Heat Transfer Coefficient

- **$q = U.A.\ \Delta T_{LM}$**
- Overall Heat Transfer Coefficient 'U' is composed of several film HTCs. Heating fluid, product & wall.
- All HTCs are dependent on several factors.
    - Heat Transfer Mechanism
        - Convection, Conduction, Radiation
    - Fluid Dynamics
        - Velocity, Turbulence
    - Fluid Properties
        - Composition, heat capacity, density
    - Surface Properties
        - Material, wettability, conductivity, shape
    - Heat Transfer Geometry
        - Single pass, multi-pass, plate or tube shape.
    - Fouling
        - CIP regularity, velocity, direction, temperature, detergents



Heat Transfer – Overall Heat Transfer Coefficient

- Typical ‘U’ values for common systems

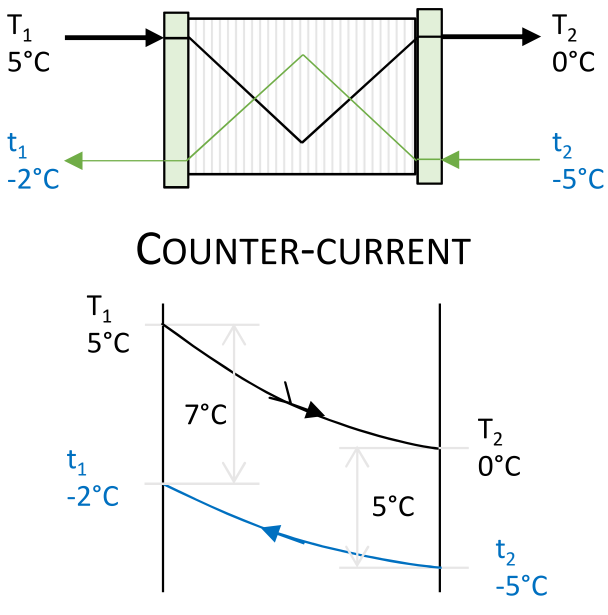
Example	Material	Typical Overall HTC (W/m². °C)
Radiator central heating	Liquid Water	5-15
Steam radiator	Vapour Water	5-20
Steam jackets - vessels with stirrers	Condensing Water Vapour	300-1000
Heat exchanger – water / water	Liquid Water	900-2500
Condensers - steam / water	Condensing Vapour Water	1000-4000
Evaporators - steam / water	Condensing Vapour Water	1500 - 6000

- Important to compare U values when comparing heat exchanger designs from different suppliers, can have big impact on total surface area, size/weight & price!

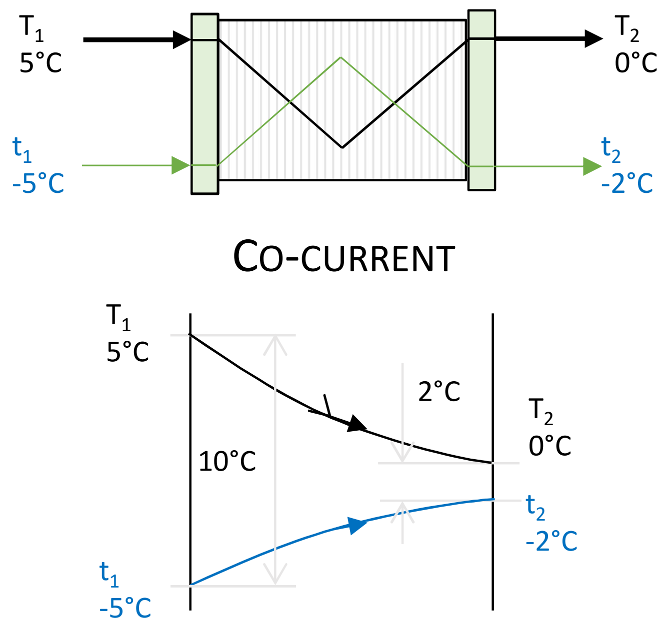
Heat Transfer – Log Mean Temperature Difference

- **q = U.A. ΔT_{LM}**
- Log Mean Temperature Difference (LMTD) Depends on
- Counter-current vs co-current Flow
- Temperature of fluid streams in & out.

$$\Delta T_{LM} = \frac{(T_1 - t_1) - (T_2 - t_2)}{\ln \frac{(T_1 - t_1)}{(T_2 - t_2)}}$$



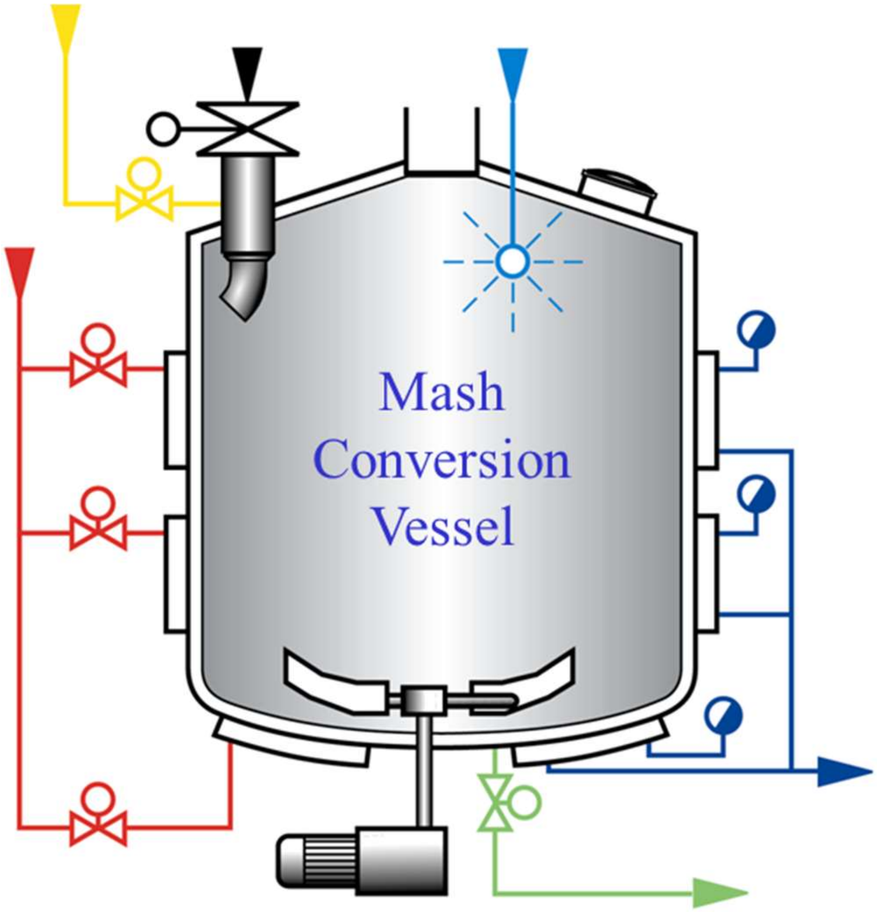
ΔT_{LM} = 5.94°C
Higher ΔT_{LM}
Smaller Heat Exchanger



ΔT_{LM} = 4.97°C
Lower ΔT_{LM}
Larger Heat Exchanger
Reduced freezing risk

Heat Transfer – Batch Heat Transfer

- For steady-state heat transfer across a heat exchanger, such as in-line heating or cooling, all of the variables stay relatively fixed for the duration of the transfer.
- For batch heating using jackets or recirculation via HX, the temperature of the product is changing over time
- The return temperature of the heating or cooling medium may also be changing over time.
- There may also be changes in product physical properties as the product heats or cools.
- The level of mixing/agitation in the vessel also plays a part.
- Differential equations are often required to calculate the heating or cooling time.
- Most engineering companies which manufacture vessels such as Briggs, have in-house calculation programmes to calculate the jacket or coil surface area required to achieve a particular heating or cooling rate.



Heat Transfer – Exothermic Heat

- Exothermic heat Δh_{EX} is released as part of a chemical reaction.
- An example in brewing is fermentation of sugar to create alcohol & CO_2.
- Heat released is approximately 1217 kJ per kg of glucose fermented
- Beer fermentation is largely anaerobic and releases a relatively low quantity of exothermic heat when compared to fully aerobic fermentation e.g. commercial yeast manufacture.
- Temperature rise will occur over time unless heat removed.
- Jackets on Fermenters traditionally used for heat removal.
- Another example of an exothermic process is combustion of natural gas to generate heat to raise steam.

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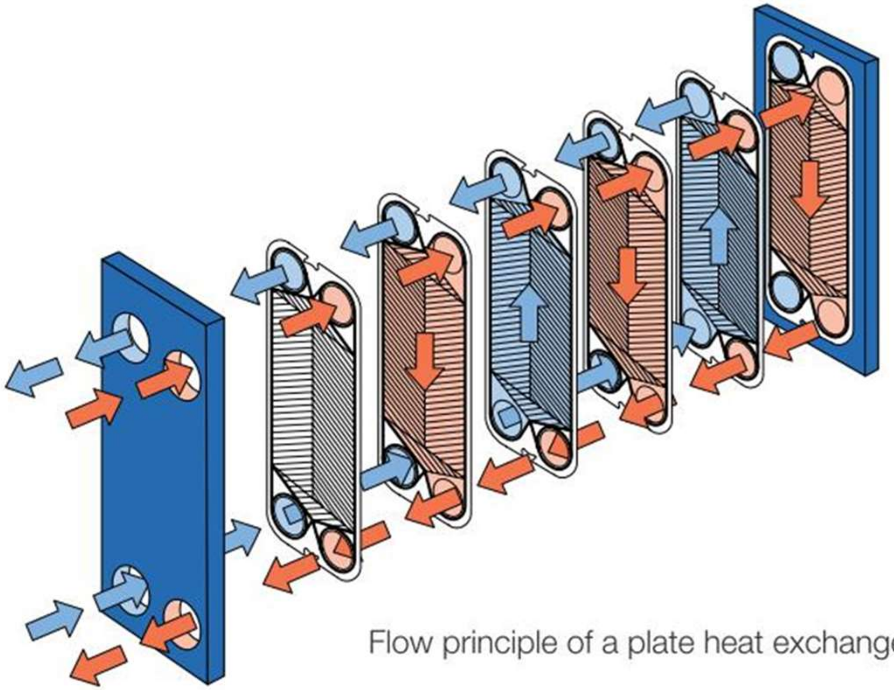
Heat Exchanger Design – Plate & Frame

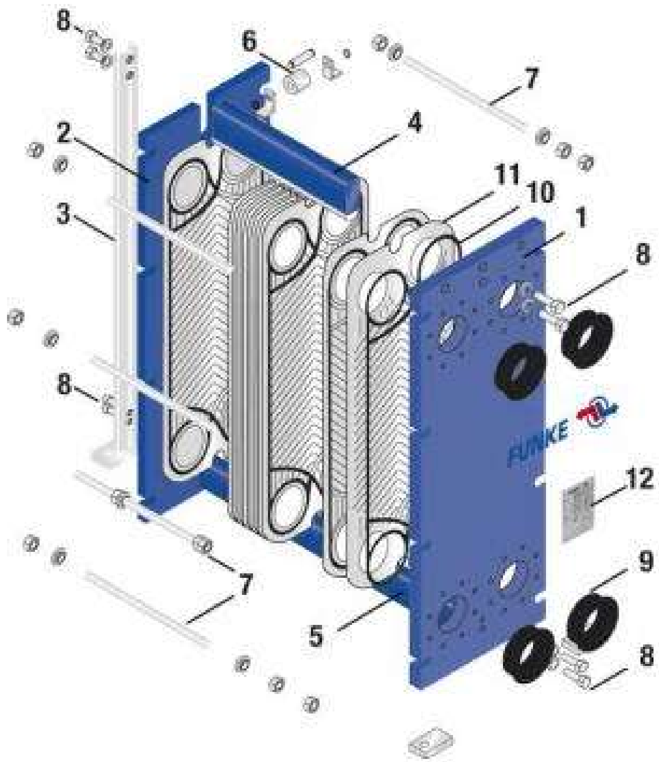
- Single or Multi-Pass
- Co-Flow or Counter-Flow
- Generally higher heat-transfer coefficients than shell & tube
- Hygienic designs – ‘self cleaning’ to a degree,
- Poor solid handling capability
  - Wide gap variant
- Generally higher pressure drop vs Shell & Tube
- Less robust than Shell & Tube
  - High pressure or double walled variant, reduced HTC.
- Easy to modify/expand
- High surface area available with a relatively compact footprint.
- Normally lower cost vs shell & tube
- Typical applications, wort heating & cooling, beer pasterurisation, CIP heating.



Flow principle of a plate heat exchanger

Heat Exchanger Design – Plate & Frame

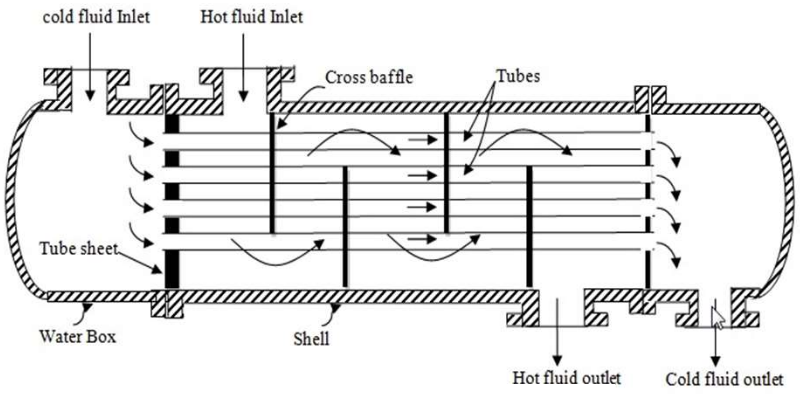
- PHE construction



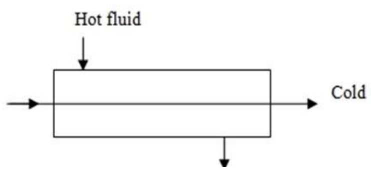
1. Fixed plate
2. Movable plate
3. Support column
4. Carrying bar
5. Lower plate guiding bar
6. Carrier roller
7. Tightening bolt and nuts
8. Fixing bolts
9. Rubber / metal liners
10. Gaskets
11. Heat transfer plates
12. Name plate

Heat Exchanger Design – Shell & Tube

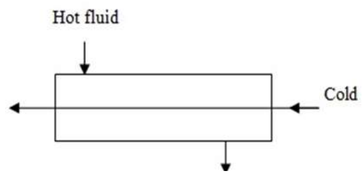
- Single or Multi-Pass
- Co-flow or Counter-flow
- Vertical or Horizontal
- Generally lower heat transfer coefficients vs plate & frame
- More difficult to CIP, especially if shell size has fouled.
- Good solid/slurry handling capability
- Good for boiling/condensing duties.
- More robust than plate & frame.
- Not easy to modify/expand
- Can get very large when high surface area required.
- Relatively small footprint when mounted vertically,
- Normally higher cost vs PHE.
- Typical applications, wort boiling, vapour condensers, ammonia condensers, CO_2 liquefiers.



Co-current shown



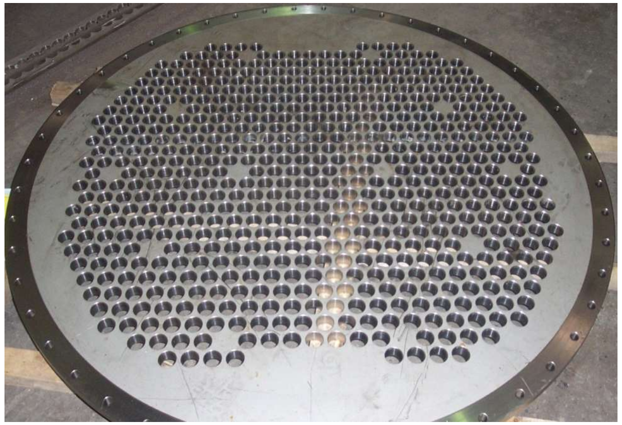
Co-current



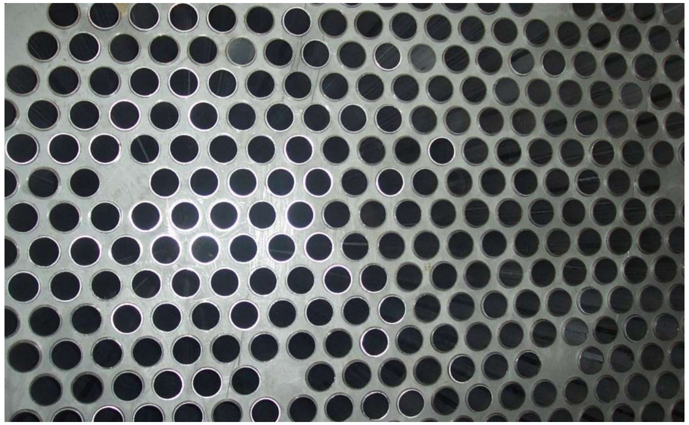
Counter-current

Heat Exchanger Design – Shell & Tube

- Shell & Tube External Wort Heater (EWH) under construction at Briggs



Tubeplate



Tubes assembled into tube plate

Heat exchanger under construction

Heat Exchanger Design – Fouling

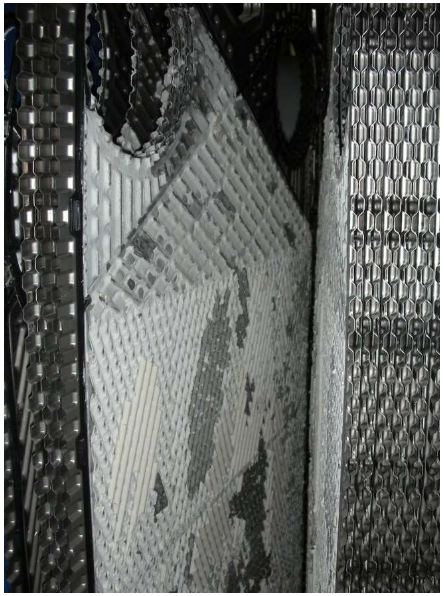
- Shell & Tube Heat Exchanger
- Distillery Grain Worts Cooler – Scaling
- Wort Heater – Extreme Fouling

Scaling

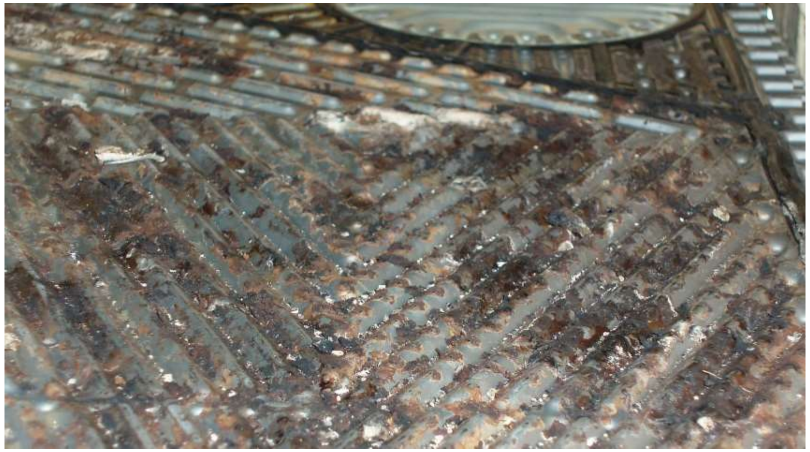
Fouling

Heat Exchanger Design – Fouling

- Plate & Frame Exchanger
- Water Heater– Scaling, hard water
- Wort Cooler - Fouling



Scaling

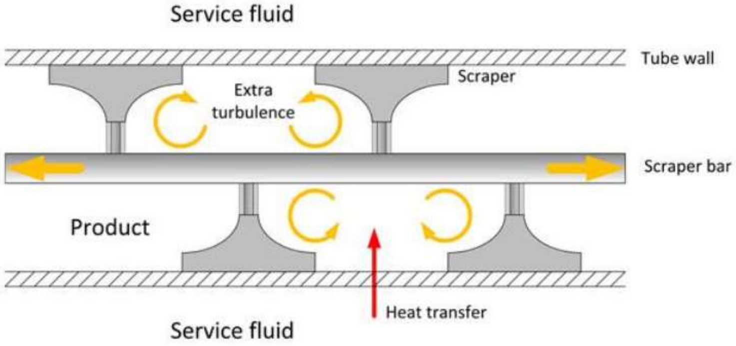


Fouling

Heat Exchanger Design – Other Types

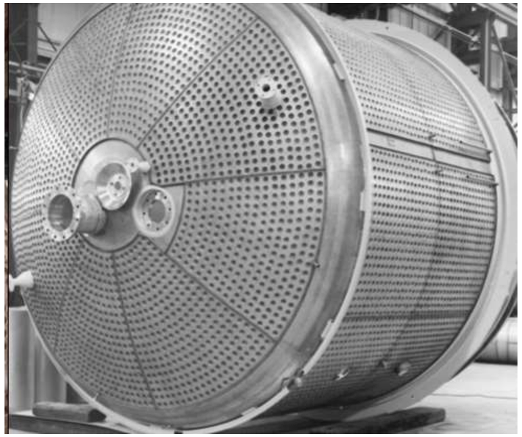
- Used for specialist applications where more conventional solutions not ideal

  - Spiral
    - In concept similar to PHE
    - More robust
    - ‘self cleaning’ to a point
    - Inflexible
    - Expensive
  - Tube in tube
    - Very high viscosity/high solids
  - Corrugated Tubes
    - Enhanced turbulence
  - Scraped surface
    - Very high viscosity/high solids



Vessel Jacket Design – Typical Examples

- Dimple Jacket
  - Welds located in a rectangular pattern
  - Maintains strength using thin shell material
  - Dimples impart turbulence
  - Flow guiding system can be installed for liquid heating to increase contact time.
  - Lower capital cost.
- Limpet Coil Jackets
  - Continuous Spiral – half-pipe configuration
  - Defined Flow Path
  - Uniform fluid velocity
  - Good distribution & contact time with vessel wall.
  - High pressure capability (pipe)
  - Higher cost vs dimple jacket.



Thank you

Any questions?