Heating In Agitated & Non-Agitated Vessels

IBD/BFBi Midland Section Engineering Symposium on Heat Transfer and Refrigeration

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Contents

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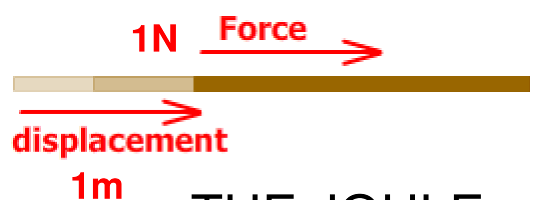
Heat Energy

- Quantifying Energy
  - SI Unit of Heat Energy - ***the joule***
  - 1 joule (J) = 1 newton force through 1 metre (Nm)

Heat Transfer – Rate of Change

  - SI Unit of Power - ***the watt***
  - 1 watt (W) = 1 joule transferred in 1 second (J/s)
  - **1 kW = 1,000 W**
  - 1 MW = 1,000,000 W



THE JOULE

- Imperial units
  - 1 kW = 3,412 Btu/hr

Heat Energy

- Two Basic Forms
- Sensible Heat
  - Heat associated with temperature (T)
  - Also dependent on material property

    Specific Heat Capacity (c_p)

$$\text{Heat energy} = \text{mass} \times c_p \times T$$

- Energy referenced to a datum (0^oC)

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Heat Energy

- Typical c_p values for common materials

Material	Specific Heat Capacity kJ/kg.^{o}C
Water	4.18
Wort	4.00
Beer	4.05
Stainless Steel	0.50
Copper	0.39
Air	1.01
Carbon Dioxide	0.83

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Heat Energy

- Two Basic Forms
- Latent Heat
  - Heat associated with change in state
  - Solid to liquid (fusion)
  - Liquid to vapour (vaporisation)
  - Material property - latent heat (h_{fg})

$$\text{Heat energy} = \text{mass} \times h_{fg}$$

- Not dependent on temperature

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Heat Energy

- Typical latent heat values for water

Material	Type	Latent Heat kJ/kg
Ice – Water	Fusion	334
Water – Steam (0 barg)	Vaporisation	2,257
Water – Steam (5 barg)	Vaporisation	2,086
Water – Steam (10 barg)	Vaporisation	1,999

- Vaporisation energy dependent on pressure – steam tables

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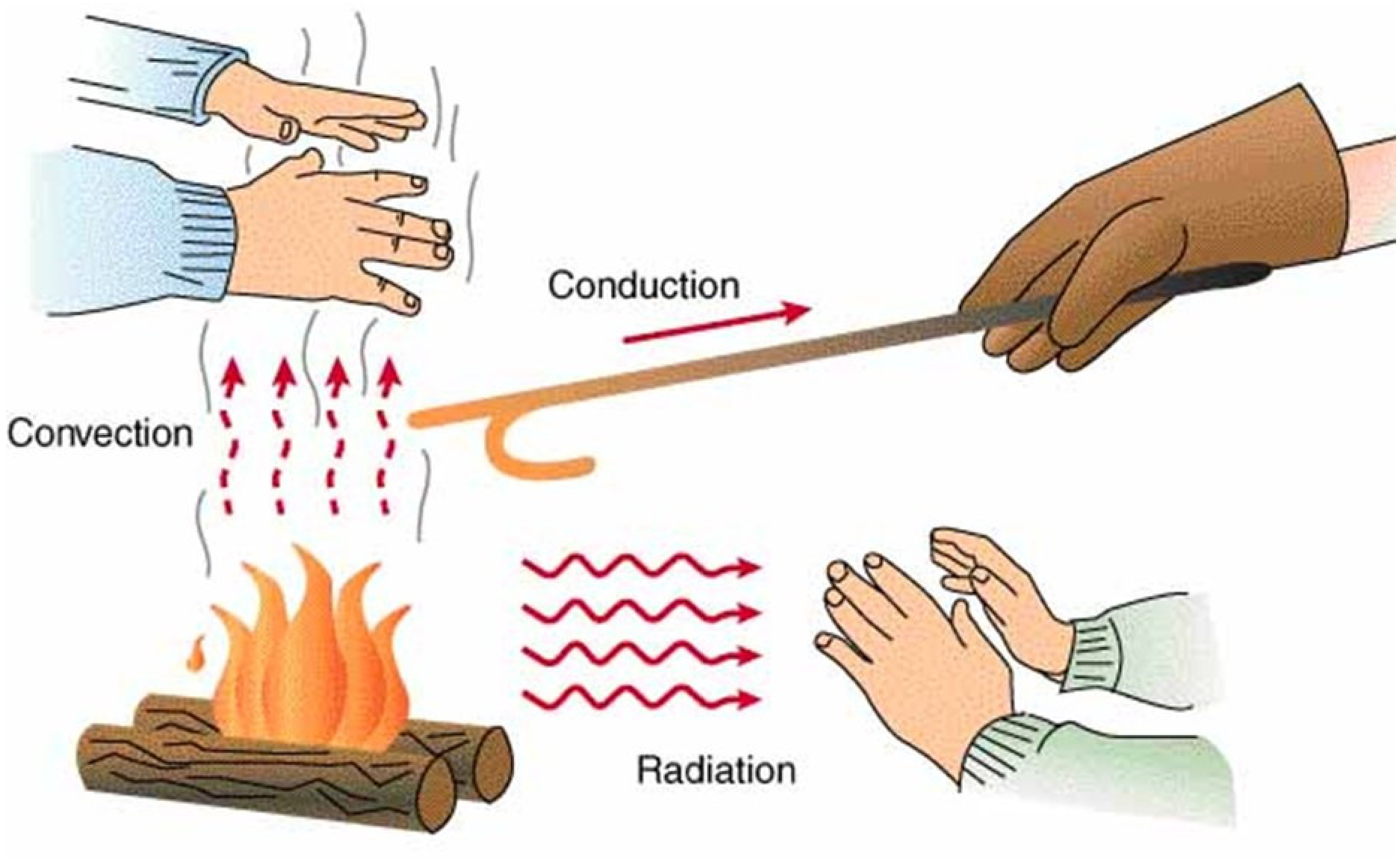
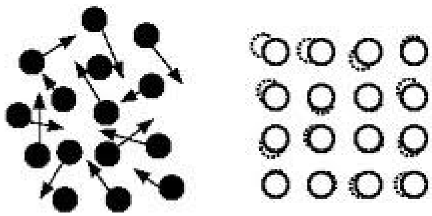
Heat Transfer Mechanisms

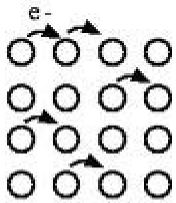


Heat Transfer - Conduction

- Two Primary Mechanisms
- Molecular Interaction



  – Higher temperature molecule imparts energy via impact or vibration
- ‘Free’ Electron Drift



  – Applicable for solids
    - Pure Metals – High electron concentration
    - Non Metallic – Low electron concentration

Heat Transfer - Conduction

- Fourier's Law of Heat Conduction
- (Heat Flux) is proportional to (Temperature Gradient)

$$q = -k.\nabla T$$

- Proportionality constant – Thermal Conductivity
- k = Thermal Conductivity (W/ m.^{o}C)
- 'k' is unique material property

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Heat Transfer - Conduction

- Typical k values for common materials

Material	Thermal Conductivity W/m.°C
Water	0.58
Wort	0.52
Beer	0.55
Stainless Steel	16.0
Copper	401
Wood (oak)	0.17
Air	0.024
Carbon Dioxide	0.015

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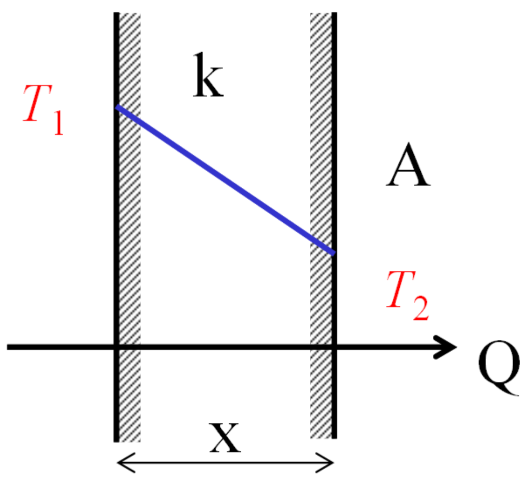
Heat Transfer - Conduction

- Application of Thermal Conductivity

$$\text{Heat Flow} = \frac{\text{Thermal Potential Difference}}{\text{Thermal Resistance}}$$



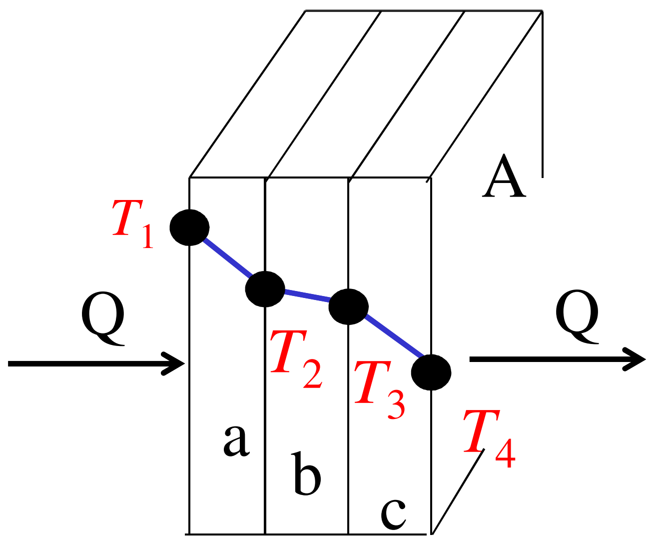
- Thermal Potential = $(T_2 - T_1)$
- Thermal Resistance = x / k

$$Q = \frac{-kA(T_2 - T_1)}{x}$$

Heat Transfer - Conduction

- Thermal Conductivity – Plane Walls

$$\text{Heat Flow} = \frac{\text{Thermal Potential Difference}}{\text{Thermal Resistance}}$$



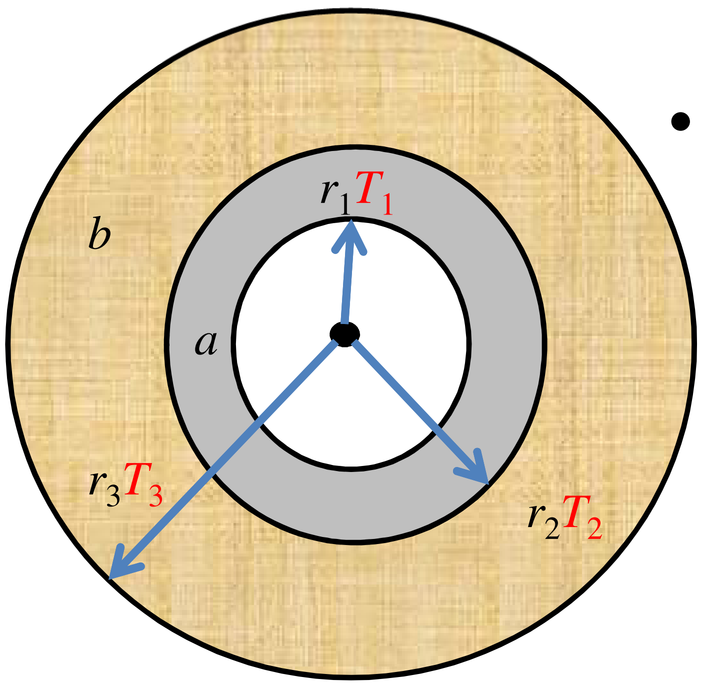
- Resistance added in series

$$Q = \frac{-A(T_4 - T_1)}{\left[\frac{x_a}{k_a} + \frac{x_b}{k_b} + \frac{x_c}{k_c}\right]}$$

Heat Transfer - Conduction

- Thermal Conductivity – Pipe Walls

$$\text{Heat Flow} = \frac{\text{Thermal Potential Difference}}{\text{Thermal Resistance}}$$

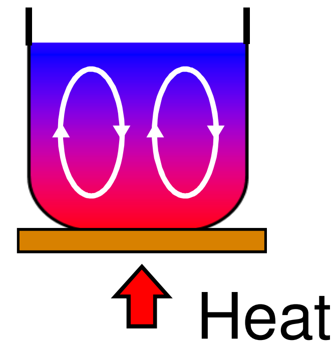


- Variable surface area

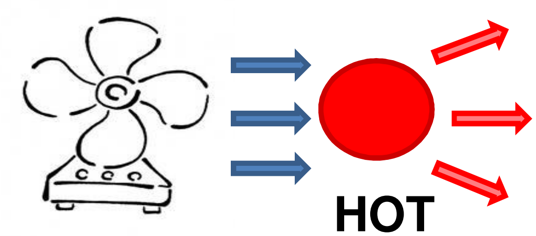
$$Q = \frac{-(T_3 - T_1)}{\frac{ln(r_2/r_1)}{2\pi L k_a} + \frac{ln(r_3/r_2)}{2\pi L k_b}}$$

Heat Transfer - Convection

- Energy exchange between a surface and a fluid
- Natural Convection
  - – Fluid next to solid boundary causes circulation currents due to density difference



- Forced Convection
  - – Fluid next to solid boundary forced past its surface



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Heat Transfer - Convection

- Newton's Law of Cooling
- (Heat Flux) is proportional to (Temperature Difference)

- Proportionality constant – Convective Heat Transfer Coefficient (Film Coefficient)
- h = Film Coefficient (W/ $m^2.^oC$)

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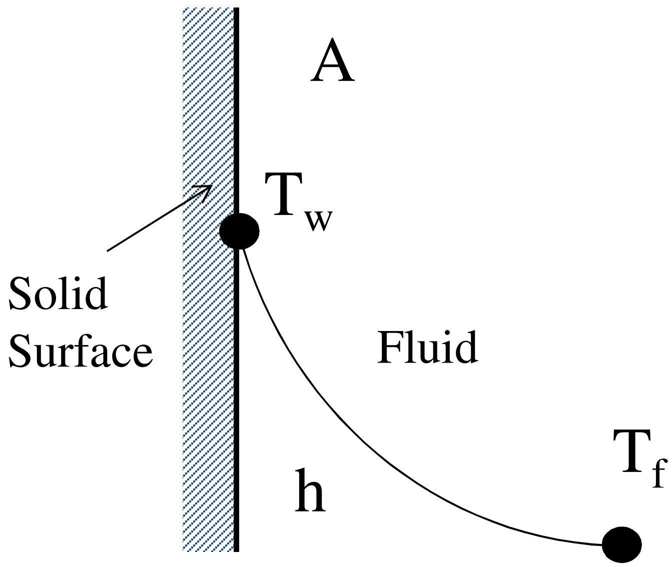
Heat Transfer - Convection

- Application of Convection

$$\text{Heat Flow} = \frac{\text{Thermal Potential Difference}}{\text{Thermal Resistance}}$$



- Thermal Potential = $(T_w – T_f)$
- Thermal Resistance = 1 / hA

$$Q = hA(T_w - T_f)$$

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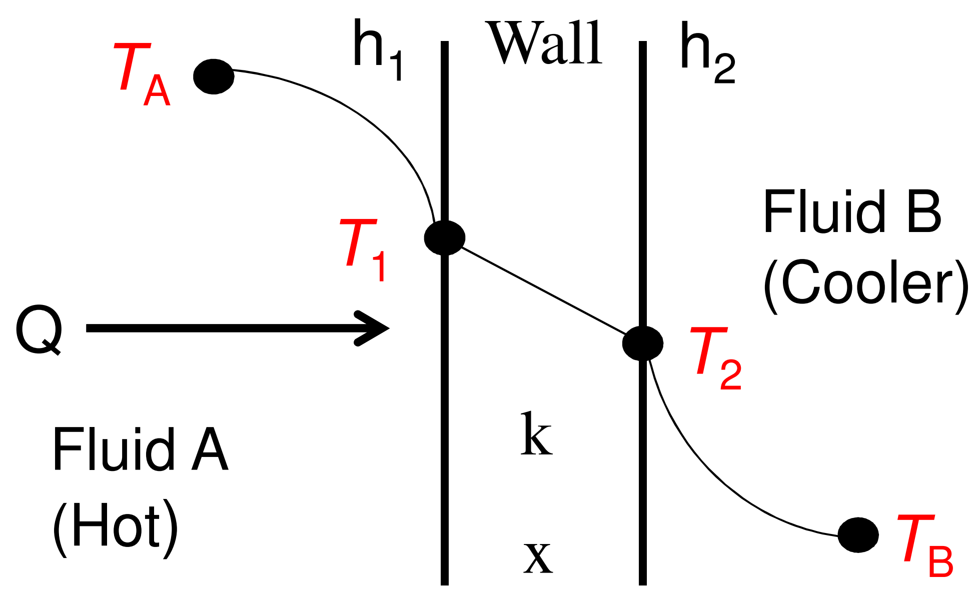
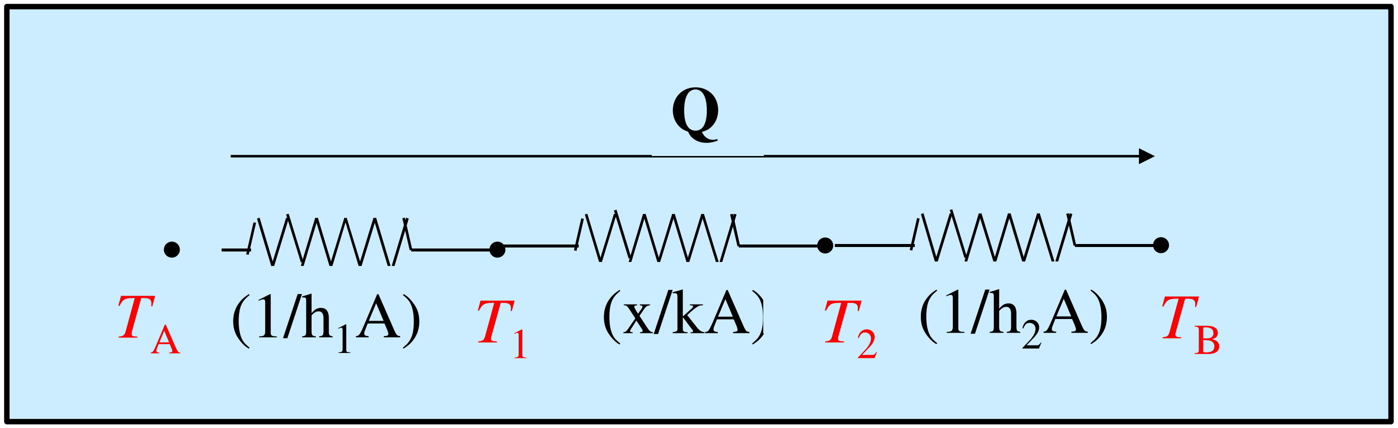
Overall Heat Transfer Coefficient

- Combining Conduction and Convection

$$\text{Heat Flow} = \frac{\text{Thermal Potential Difference}}{\text{Thermal Resistance}}$$



Overall Heat Transfer Coefficient



$$Q = \frac{T_A - T_B}{\frac{1}{h_1 A} + \frac{x}{kA} + \frac{1}{h_2 A}} = U.A.\Delta T$$

$$U = \frac{1}{\frac{1}{h_1} + \frac{x}{k} + \frac{1}{h_2}} = \frac{1}{\text{System Resistance}}$$

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Overall Heat Transfer Coefficient

- Fouling Factors – ‘Clean’ surface altered that affects heat transfer capability
  - Scale build up / Corrosion

$$U = \frac{1}{\frac{1}{h_1} + \mathbf{R_{f1}} + \frac{x}{k} + \mathbf{R_{f2}} + \frac{1}{h_2}}$$

  - U experimentally determined in different conditions

$$R_f = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}}$$

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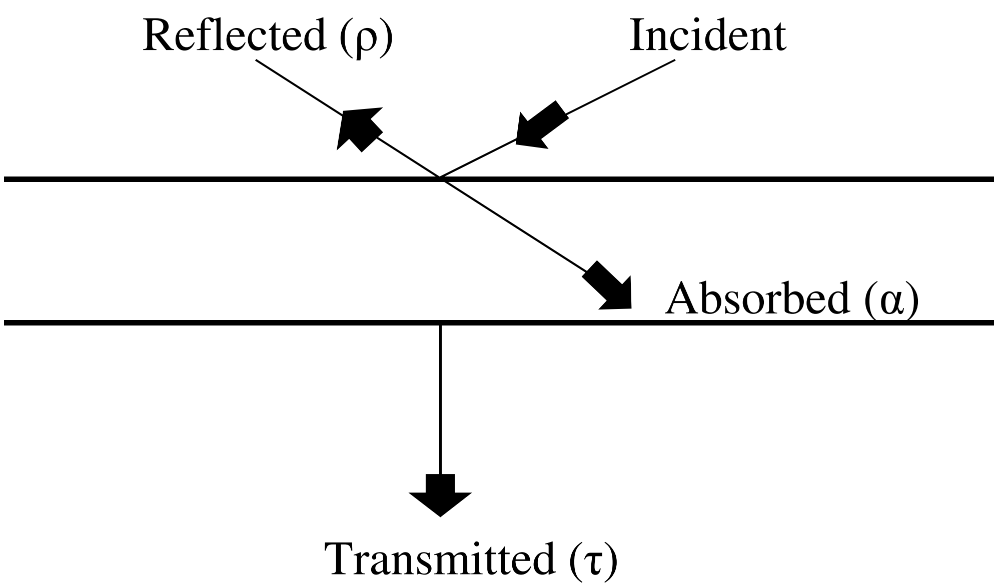
Heat Transfer – Radiation

- Heat Transfer attributed to electromagnetic waves - No transfer medium required
- Heated bodies emit thermal radiation onto subsequent bodies



$$\alpha + \tau + \rho = 1$$

Typically for solid objects

$$\alpha + \rho = 1$$

Heat Transfer – Radiation

- Pure black bodies are perfect absorbers

$$\alpha = 1$$

- Perfect absorbers are also perfect radiators (emitters) – Defines 'emissivity', ε

$$\alpha = \varepsilon = 1$$

- For non-perfect bodies, Kirchhoff's law applies: -

$$\alpha = \varepsilon = \frac{E}{E_{black}}$$

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Heat Transfer - Radiation

- Typical ε values for common materials

Surface	Emissivity (new)	Emissivity (typical)
True Black Body	1	1
Real object	< 1	< 1
Copper	0.04	0.78
Stainless steel	0.08	0.85
Carbon steel	0.02	0.90
Aluminium	0.04	0.31

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Heat Transfer – Radiation

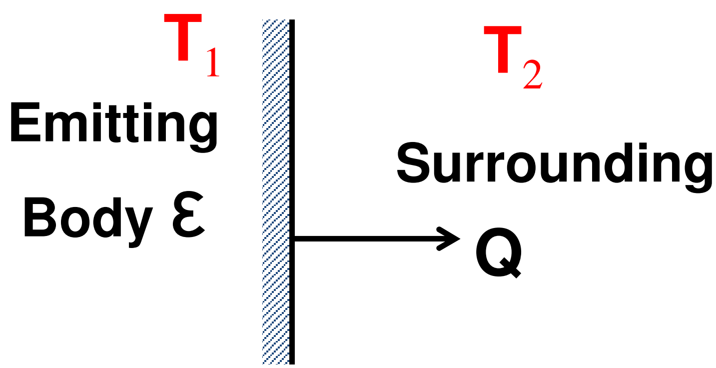
- Heat transferred by radiation – Energy emission

$$Q_{\text{black}}(W) = A\sigma T^4$$

Where σ = Stefan-Boltzmann constant, $Wm^{-2}K^{-4}$ (5.67×10^{-8})

T = Absolute temperature, K (K = ^{o}C + 273.15)

- For a non-black body in non-black surroundings



$$Q = \sigma\varepsilon A(T_1^4 - T_2^4)$$

- Heat loss significant in large vessels

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Heat Transfer Coefficients

- Summary For Steady State Heat Transfer

$$\mathbf{Q = U.A.\Delta T}$$

Q = Heat Transfer (W)
U = **Overall** Heat Transfer Coefficient ($W/m^2.^oC$)
A = Heat Transfer Surface Area (m^2)
ΔT = Temperature Difference of System (^oC)

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Heat Transfer Coefficients

- Typical U values for common systems

Example	Material	Typical Overall HTC (W/m². ℃)
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

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Heat Transfer Coefficients

What determines the heat transfer coefficient?

1. Heat transfer mechanism
   – conduction, convection, radiation
2. Fluid dynamics
   – e.g. velocity, turbulence, pressure
3. Media and surface properties
   – e.g. composition, heat capacity, density, absorptivity, fouling
4. Heat transfer geometry
   – e.g. fluid paths, surface orientations

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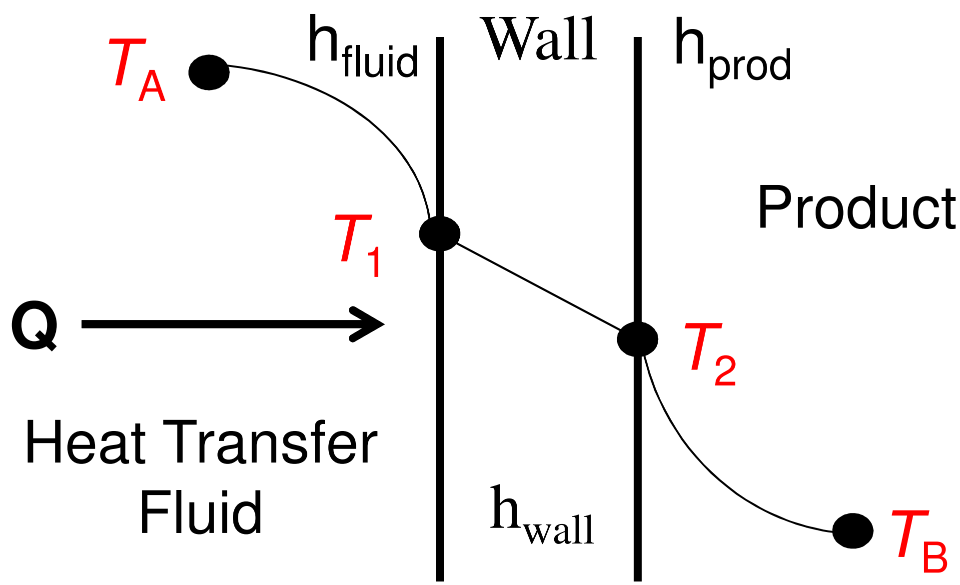
Heat Transfer Coefficients

- Usually one individual coefficient controls the entire system



$$\frac{1}{U} = \frac{1}{h_{fluid}} + \frac{1}{h_{wall}} + \frac{1}{h_{prod}}$$

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Heat Transfer Coefficients

$$\frac{1}{U} = \frac{1}{h_{fluid}} + \frac{1}{h_{wall}} + \frac{1}{h_{prod}}$$

- Real Case Study Values ($W/m^2.^oC$)
- $h_{fluid} = 4488$, $h_{wall} = 3260$, $h_{prod} = 290$, $U = 251$
- 50% increase in h_{fluid}, 2% increase in U
- 50% increase in h_{wall}, 3% increase in U
- 50% increase in h_{prod}, **40% increase in U**
- Product coefficient is controlling

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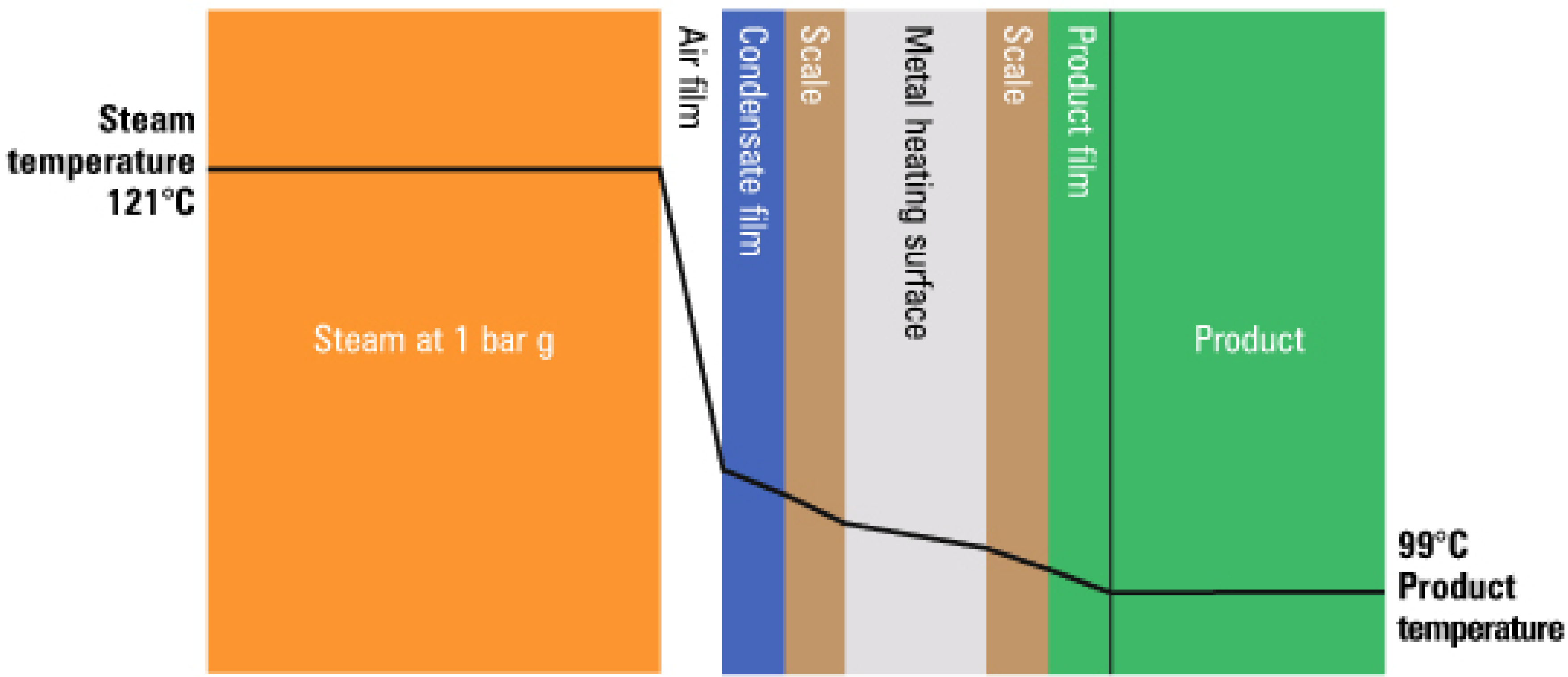
Heat Transfer Coefficients



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Heat Transfer Coefficients

- Product convection currents are generally controlling
- Described by dimensionless groups that link physical and system properties
- Forced convection using vessel agitation promotes movement and turbulence

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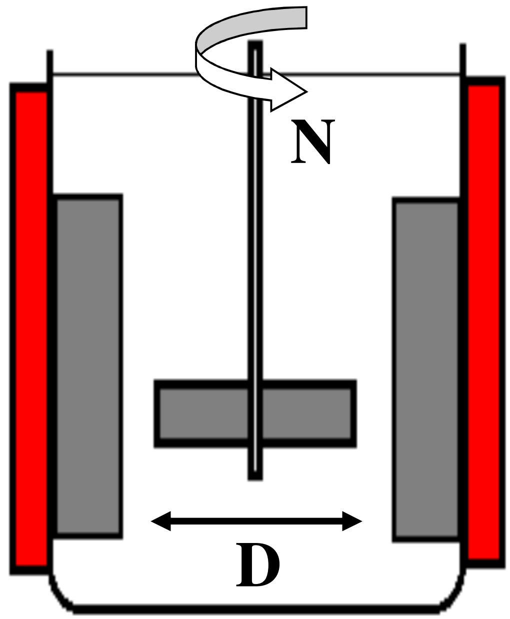
Heat Transfer Coefficients

- Forced Convection is a function of *Reynolds Number* (Re) and *Prandtl* (Pr) Number

$$Re = \frac{\rho N D^2}{\mu}$$

$$Pr = \frac{c_p \mu}{k}$$

$$h = \left(\frac{k}{D}\right) 0.023 Re^{0.8} Pr^{0.4}$$



- HTC dependent on physical properties density (ρ), viscosity (μ), specific heat capacity (c_p) and conductivity (k)
- HTC dependent on system properties agitator diameter (D) and agitator speed (N), and agitator type

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Heat Transfer Coefficients

- Natural convection even more complicated!
- For turbulent and laminar flow

$$h = \left(\frac{D}{k}\right) 0.14. Gr^{0.36} \left(Pr^{0.175} - 0.55\right) \qquad Gr \geq 10^9$$

$$h = \left(\frac{D}{k}\right) 0.68. Gr^{0.25} Pr^{0.175} \left(\frac{Pr}{0.861 + Pr}\right)^{0.25} \quad Gr < 10^9$$

- Grashof Number (Gr) a function of buoyancy force as this creates the fluid velocity

Vessel Heat Transfer

- Vessel heating commonly performed using jackets, coils and external recirculation loops

- Relative merits of heating jackets

Advantages	**Disadvantages**
Fluids in contact with vessel wall	Low heat transfer performance
Low contamination potential	Relatively high flows needed
Easy to clean	Limited surface area

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Vessel Heat Transfer

Full Jackets

- Viscous fluids
- Hygienic applications
- Clean-in-place
- Zoned heating
- External surface area maximised
- High cost

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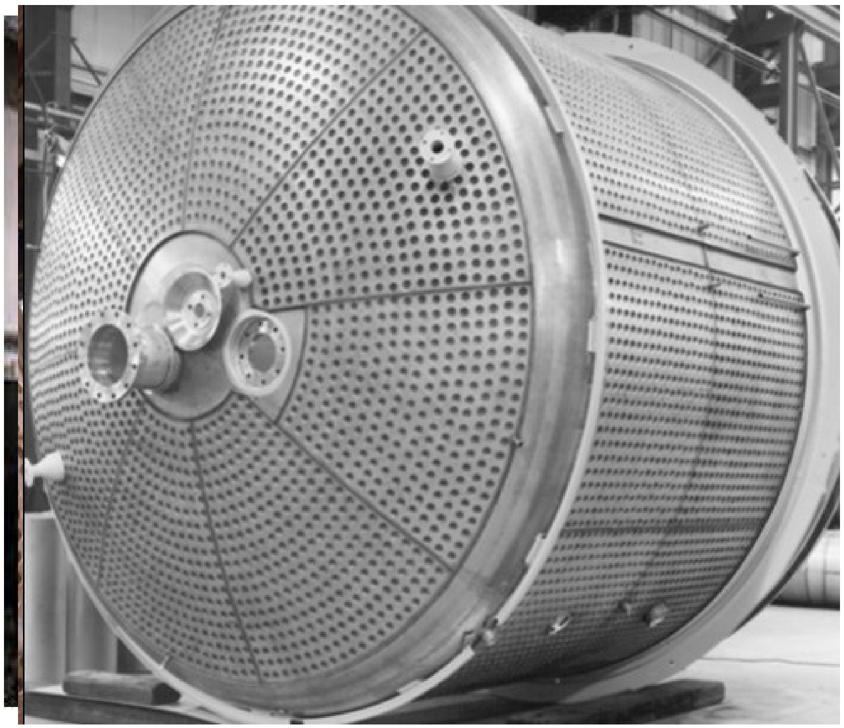
Vessel Heat Transfer



Dimple Jackets

- Welds located in a regular 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

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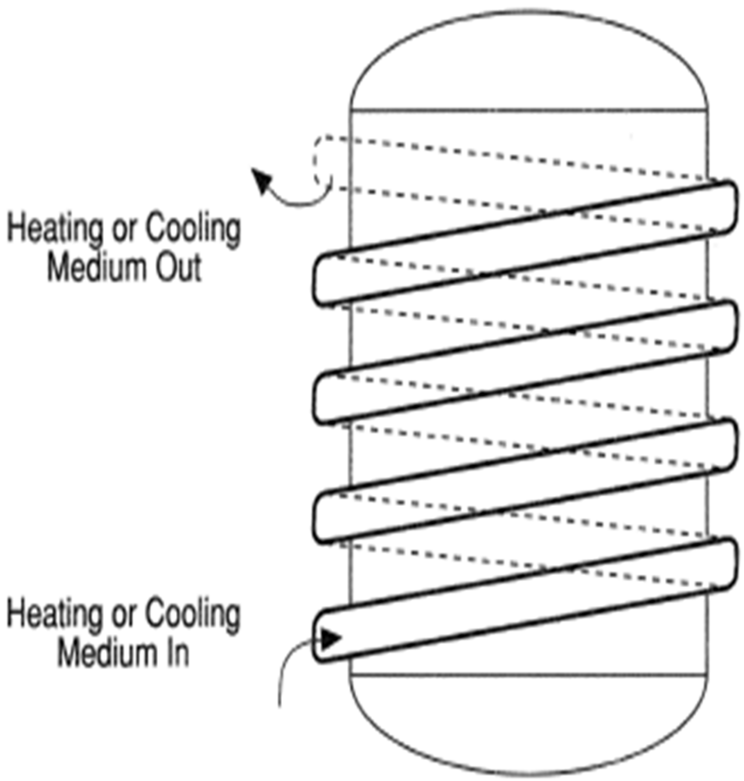
Vessel Heat Transfer



Limpet Jackets

- Half pipe configuration around vessel shell
- Uniform fluid velocity
- Good distribution and contact time with vessel wall
- High pressure capability (pipe)
- High cost

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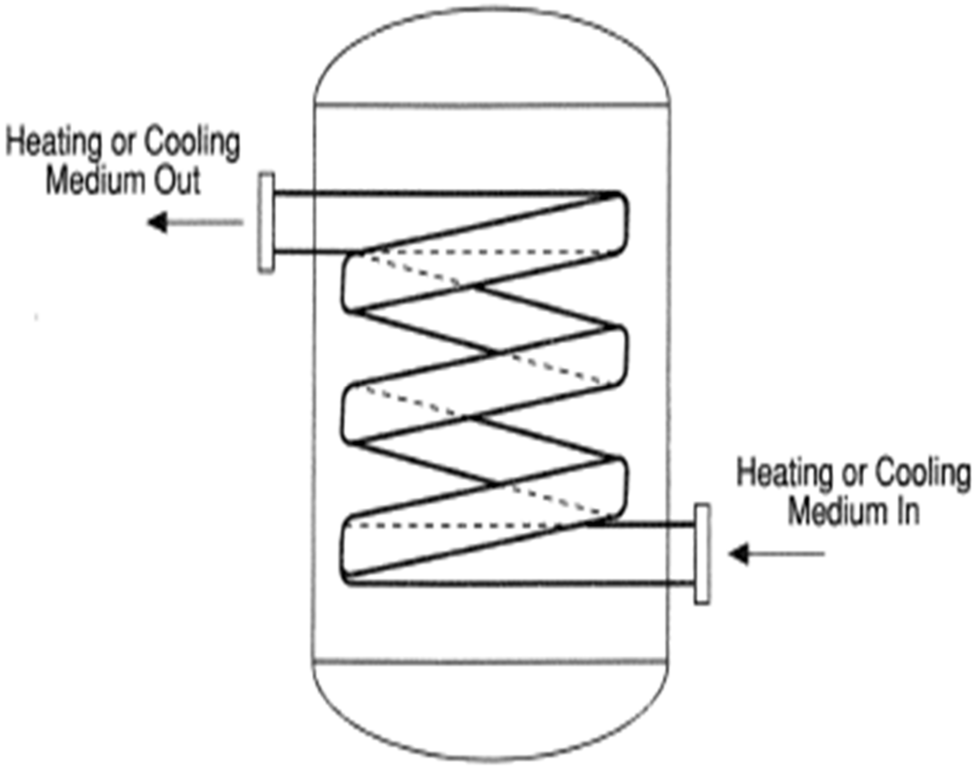
Vessel Heat Transfer



Vessel Coils

- Most commonly used for batch processes
- Full helical or small ringlet coils used
- Larger surface areas can be created
- Poor hygiene and CIP capability

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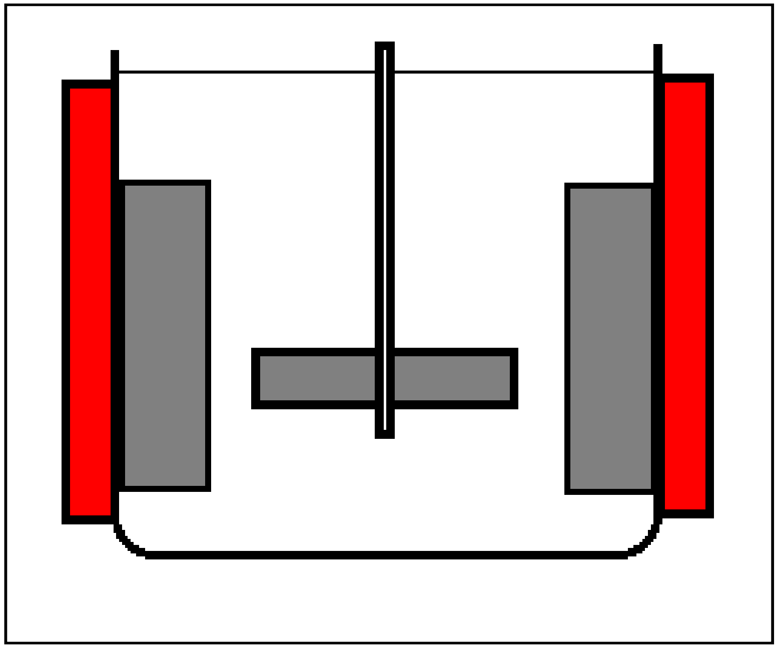
Vessel Agitation

- Agitators promote mixing and facilitate heat transfer
- Five common types of agitator:-
  - Propeller
  - Turbine
  - Paddle
  - Anchor
  - Helical Ribbon
- Many proprietary design agitators exist



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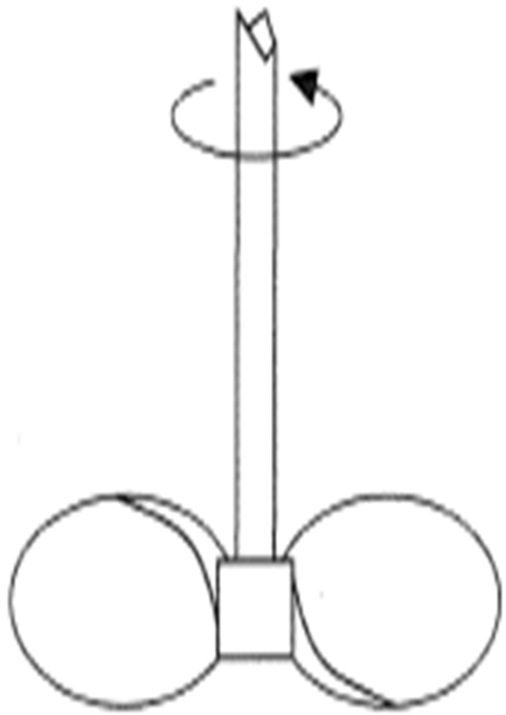
Vessel Agitation

Propeller Agitator

- Simple three blade device
- Creates axial flow patterns within the vessel fluid
- Smaller diameter – operated at high speed to compensate
- Relatively low cost



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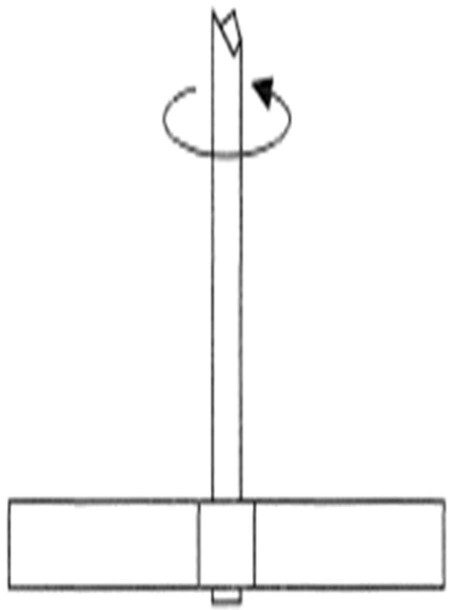
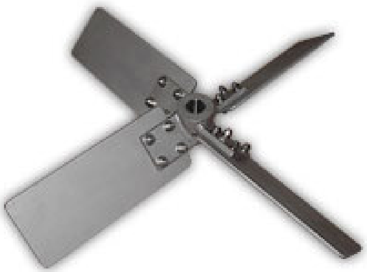
Vessel Agitation

Turbine Agitator

- Simple design to facilitate low capital and cleaning
- Operated at high speed in low viscosity liquids
- Larger diameter than propeller type
- Blades can be flat, curved or pitched
- Commonly used within solid-liquid applications





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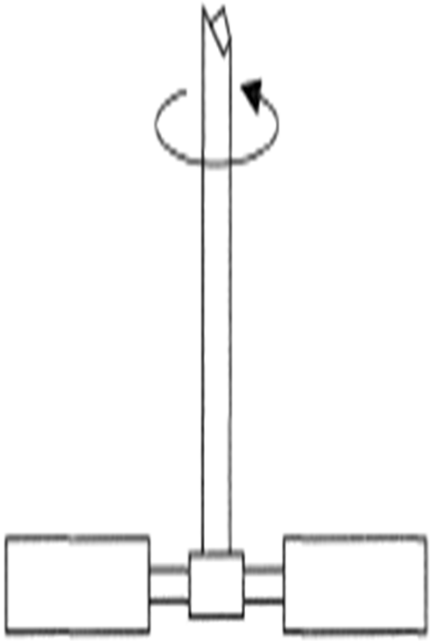
Vessel Agitation

Paddle Blade Agitator

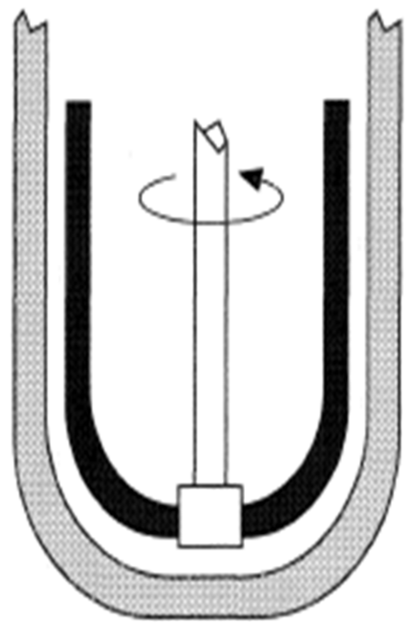
- Can be used at high and low speeds of rotation
- Low speed creates axial flow patterns
- High speed and pitched blades generate radial patterns
- Generally larger diameter and cost



Vessel Agitation

Anchor Agitator

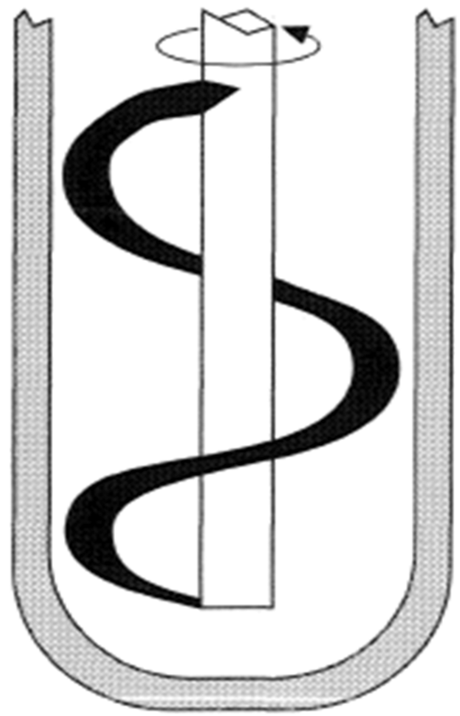
- Used for viscous applications - Laminar
- Low speed and large diameter
- Disturbance close to vessel wall
- Suitable for jacket heating
- Higher complexity and cost



Vessel Agitation

Helical Ribbon Agitator

- Similar applications and concept as anchor type
- Imparts intimate mixing at vessel wall and core of the product
- Highest complexity and cost



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Vessel Agitation

- Mixer type summary

	Propeller	Turbine	Paddle	Ribbon	Anchor
Viscosity	Low	Low	High & Low	High	High
Speed	High	High	High & Low	Low	Low
Diameter	Small	Small	Large & Small	Large	Large
Typical Diameter (%)	25-35	35-45	50-70	75-95	80-95

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Vessel Agitation

Effective Mixing for Low Viscosity Applications

- Vortex formation for centrally driven mixers
- Poor mixing and heat transfer

- **Vortex breaking mechanisms includes**
  - Vessel baffles
  - Offset angle agitators
  - Offset vertical agitators

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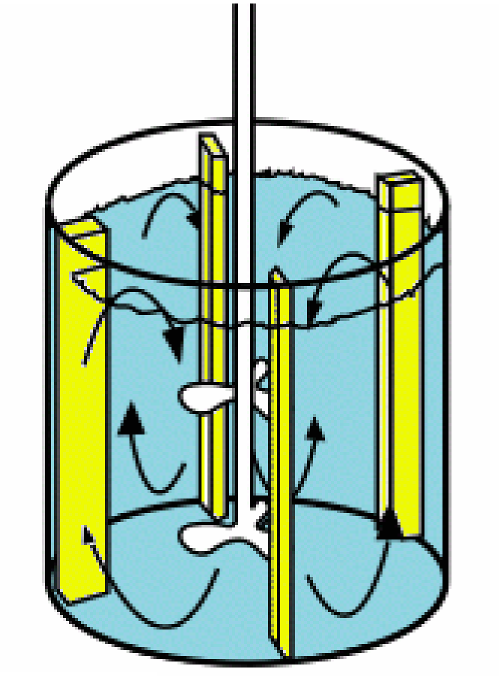
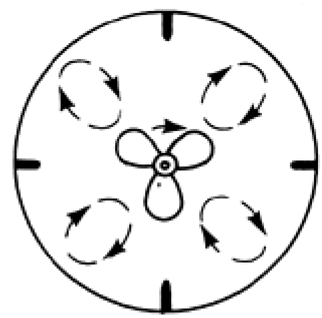
Vessel Agitation

Vessel Baffles

- Typically 3-4 baffles create localised mixing zones
- Increased turbulence aids heat transfer and uniformity
- Baffle width 8-10% of diameter
- Mounted off the vessel wall
- Increased power consumption
- Low hygiene / CIP capability





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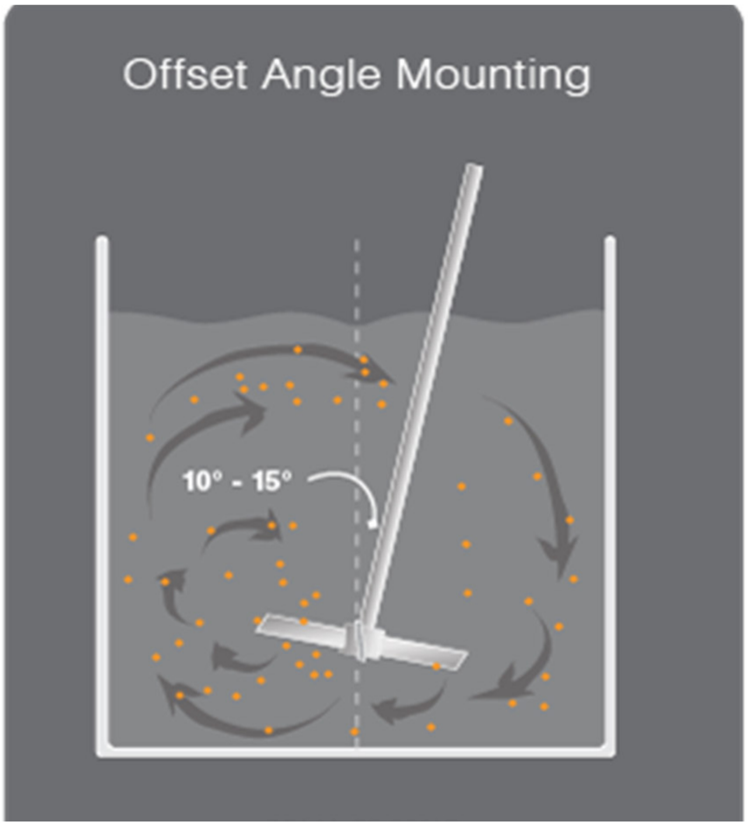
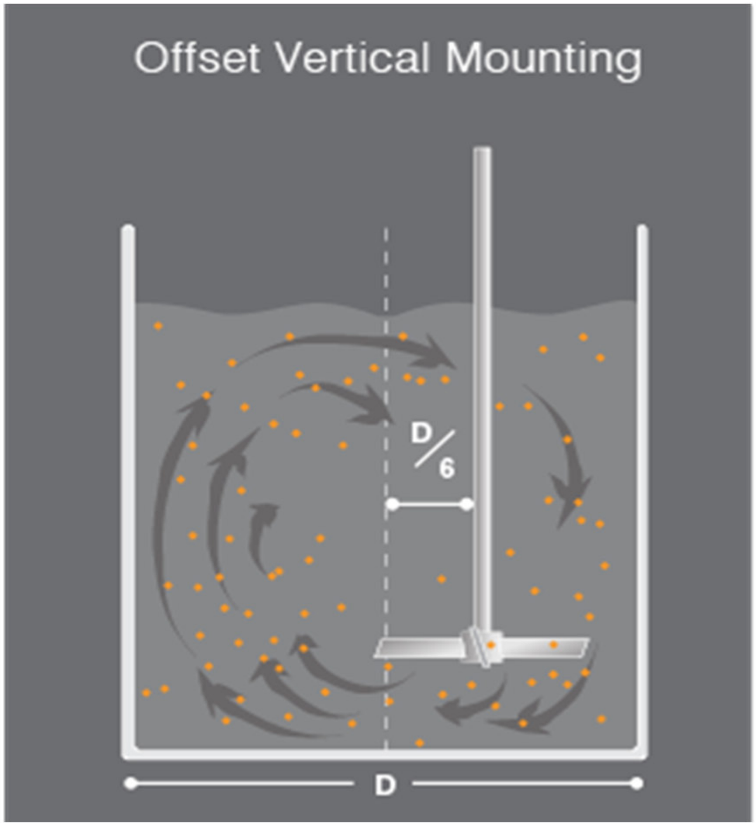
Vessel Agitation



Offset Angle Agitators

- Typically 10-15% from vertical
- Unbalanced forces can become severe
- Limited power delivery
- Complicated installation in larger vessels

Vessel Agitation



Offset Vertical Agitators

- Mounted 15-20% off vessel centre
- Typically used with hygienic beverage industries
  - Effective mixing
  - Good CIP capability
  - Low capital cost

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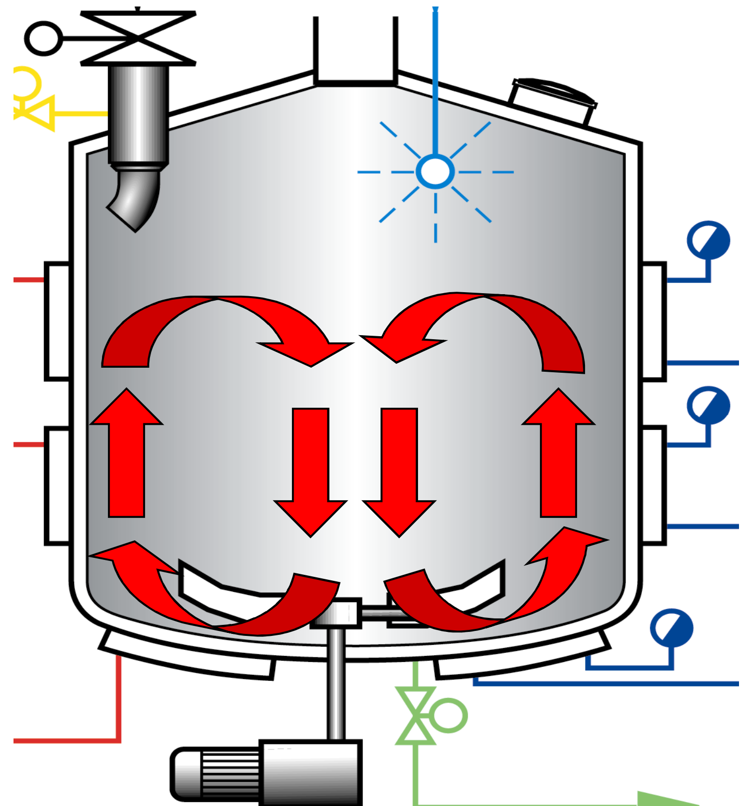
Vessel Agitation

Proprietary Agitation



Mash Conversion Vessel

- Offset configuration
- Large diameter / HTC
- Low speed / shear
- Solids mixing / suspension

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MCV Heating

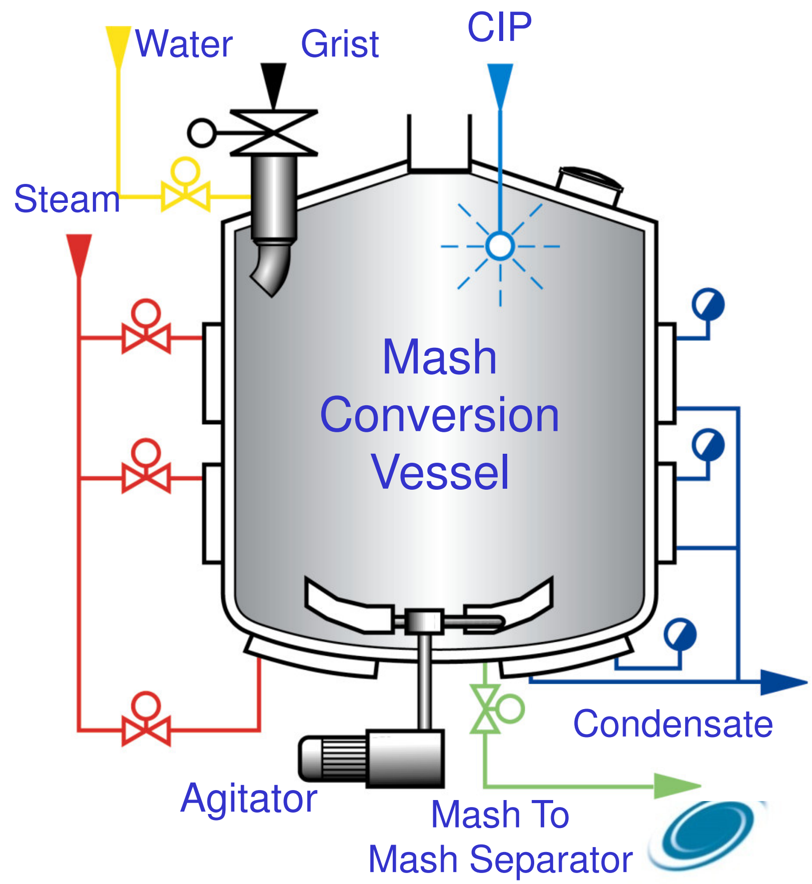
Example

A stainless steel MCV contains 48 tonne of mash with a specific heat capacity of 3.9 kJ/kg.^{o}C. The vessel is heated using 3.0 barg saturated steam. The mash requires to be heated from 65^{o}C to 76^{o}C.

a) Calculate the mass of steam required to heat the vessel contents assuming a fully insulated system and an isothermal process.

b) If the fully insulated system has a heating jacket surface area of 42m^2 and an overall heat transfer coefficient of 1100 W/m^2.^{o}C, calculate the heating time required to achieve 76^{o}C.

c) Calculate the radiated heat loss from the vessel to its 20^{o}C surroundings if a surface area of 50m^2 with emissivity 0.5 is fully exposed when at 76^{o}C.



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MCV Heating

a) Calculate the mass of steam required to heat the vessel contents assuming a fully insulated system and an isothermal process.

From steam tables, T_{steam} (3.0 barg) = 144°C,
latent heat (h_{fg}) = 2,133 kJ/kg.°C

For an isothermal process

$$T_{steam}\ (In) = T_{steam}\ (Out)$$

Therefore steam condensation is the heat source to the mash

System Energy Balance (0°C datum)

Energy required to heat mash;

$$E_{mash} = m_{mash} c_p \Delta T$$
$$E_{mash} = (48 \times 1000) \times 3.9 \times (76 - 65)$$
$$E_{mash} = 2{,}059{,}200\ \mathrm{kJ}$$

MCV Heating

a) Calculate the mass of steam required to heat the vessel contents assuming a fully insulated system and an isothermal process.

Energy provided by steam

$$\mathrm{E_{steam}} = \mathrm{E_{mash}}$$

$$\mathrm{E_{steam}} = \mathrm{m_{steam}} h_{fg}$$ (isothermal process)

$$\mathrm{m_{steam}} = \frac{2{,}059{,}200}{2{,}133}$$

$$\mathbf{m_{steam} = 965\ kg}$$

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MCV Heating

b) If the fully insulated system has a heating jacket surface area of $42m^2$ and an overall heat transfer coefficient of 1100 $W/m^2.{}^oC$, calculate the heating time required to achieve 76^oC.

For steady state heat transfer

$$Q = mc_pT = UA\Delta T$$

Batch heating is an unsteady steady process due to a continuously changing product temperature. Differential equations are required to describe this rate of change;

$$Q = m_{mash}c_p\frac{dT}{dt} = UA(T_{steam} - T_{mash})$$

Integration of the this equation generates;

$$\int_{T_i}^{T_f}\frac{dT}{T_{steam}} = \frac{UA}{m_{mash}c_p}\int_o^t dt$$

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MCV Heating

b) If the fully insulated system has a heating jacket surface area of 42m^2 and an overall heat transfer coefficient of 1100 W/m^2.^{o}C, calculate the heating time required to achieve 76^{o}C.

$$\int_{T_i}^{T_f} \frac{dT}{T_{steam}} = \frac{UA}{m_{mash} c_p} \int_o^t dt$$

$$\ln\left(\frac{T_{steam} - T_{mashi}}{T_{steam} - T_{mashf}}\right) = \frac{UA}{m_{mash} c_p} t$$

$$t = \frac{m_{mash} c_p}{UA} . \ln \frac{(T_{steam} - T_{mashi})}{(T_{steam} - T_{mashf})}$$

$$t = \frac{(48 \times 1000) \times (3.9 \times 1000)}{1100 \times 42} \times \ln \frac{(144 - 65)}{(144 - 76)}$$

$$\mathbf{t = 609\ sec = 10.1\ min}$$

MCV Heating

b) If the fully insulated system has a heating jacket surface area of $42m^2$ and an overall heat transfer coefficient of $1100\ W/m^2.^oC$, calculate the heating time required to achieve 76^oC.

Note; for non-isothermal processes (such as using hot water instead of steam as the heating medium), the log mean temperature difference (LMTD) is used to describe temperature differential and the mass flowrate of the heating medium is required: -

$$\ln\left(\frac{T_{heat}-T_{mashi}}{T_{heat}-T_{mashf}}\right) = \frac{MC_{pheat}}{m_{mash}c_p}.\left(\frac{e^{\frac{UA}{MC_{pheat}}}-1}{e^{\frac{UA}{MC_{pheat}}}}\right).t$$

where M is the mass flowrate of the heating medium with a specific heat capacity C_{pheat} and inlet temperature of $T_{heat.}$

MCV Heating

b) Calculate the radiated heat loss from the vessel to its 20^oC surroundings if a surface area of $50m^2$ with emissivity 0.5 is fully exposed when at 76^oC.

Heat transfer equation for radiation (non-black bodies)

$$Q = \sigma \varepsilon A(T_1^4 - T_2^4)$$

$$Q = 5.67 \times 10^{-8} \times 0.5 \times 50 \times [\,(76 + 273)^4 - (20 + 273)^4]$$

$$Q = 10{,}582\ W$$

$$\mathbf{Q = 10.6\ kW}$$

Note: if ^oC is instead of K used then

$$Q = 5.67 \times 10^{-8} \times 0.5 \times 50 \times (\,76^4 - 20^4)$$

$$\mathbf{Q = 0.05\ kW}$$

<u>Very different answers!</u>

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Heating In Agitated & Non-Agitated Vessels