ALFA
LAVAL

Heat Transfer Theory

Jennie Borgström

Modes of heat transfer

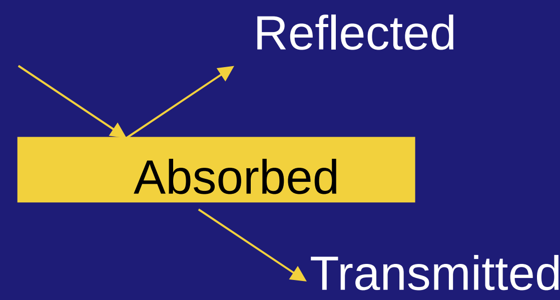
- Law of physics
  - Heat = Energy
  - If you take a hot spot

  … and a cold spot

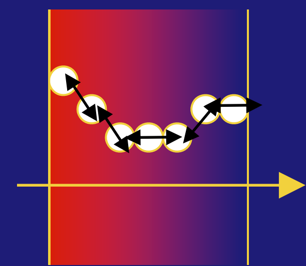
  … the heat will **always** be transferred from the hot to the cold

Three ways to transfer heat

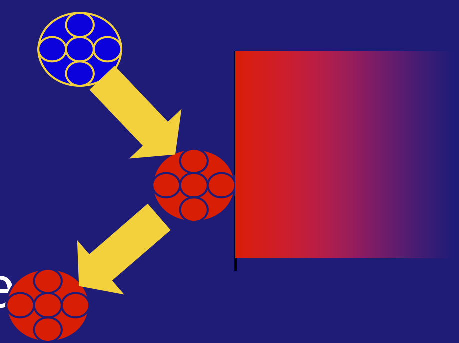
- Radiation
  - Electromagnetic waves
  - When it reaches a body it has 3 options:



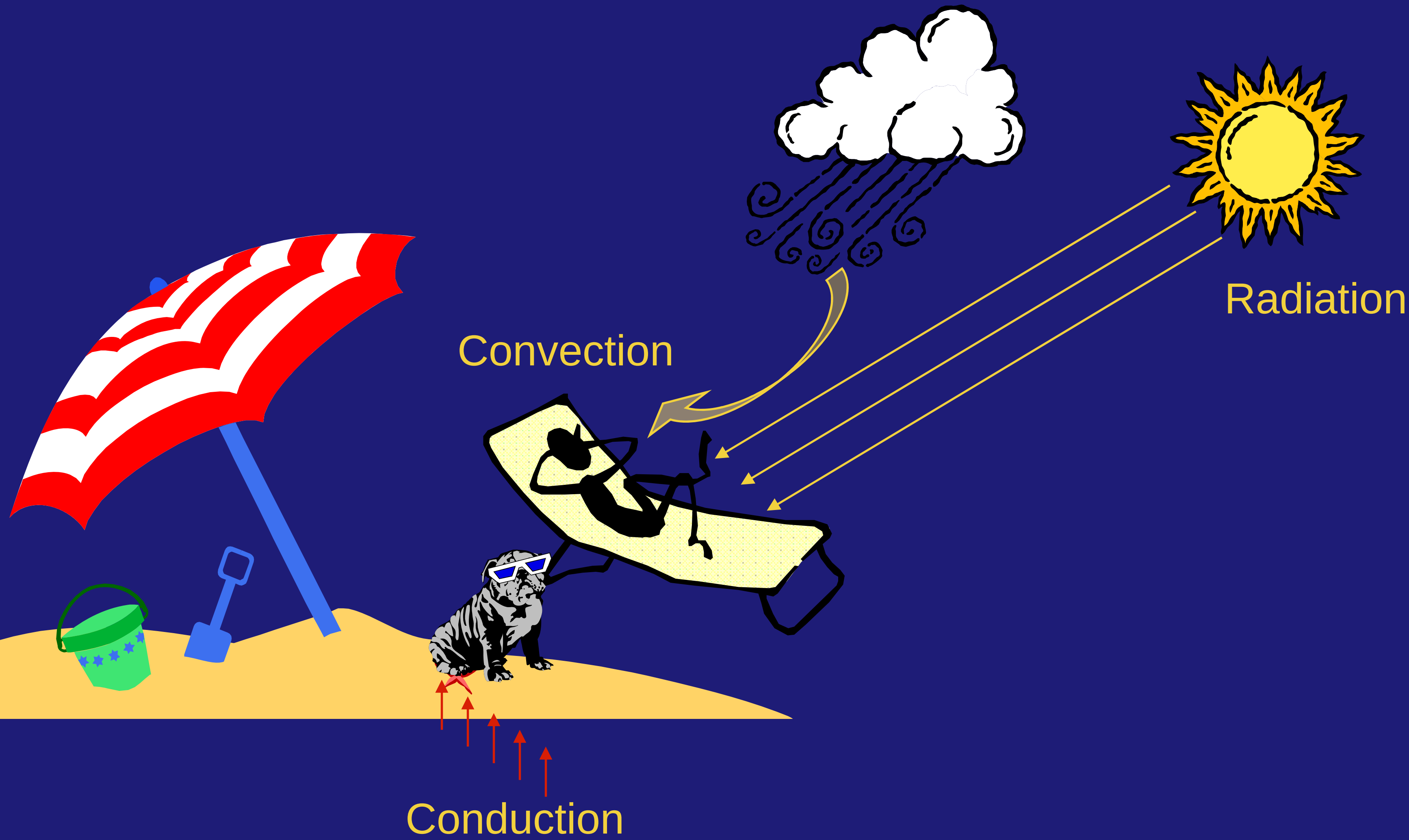
- Conduction
  - Molecular or atomic vibrations
  - No material transport



- Convection
  - Energy is transferred by the motion and intermixing of small mass elements
  - Natural convection caused by density difference
  - Forced convection is man-made (ex., pump)

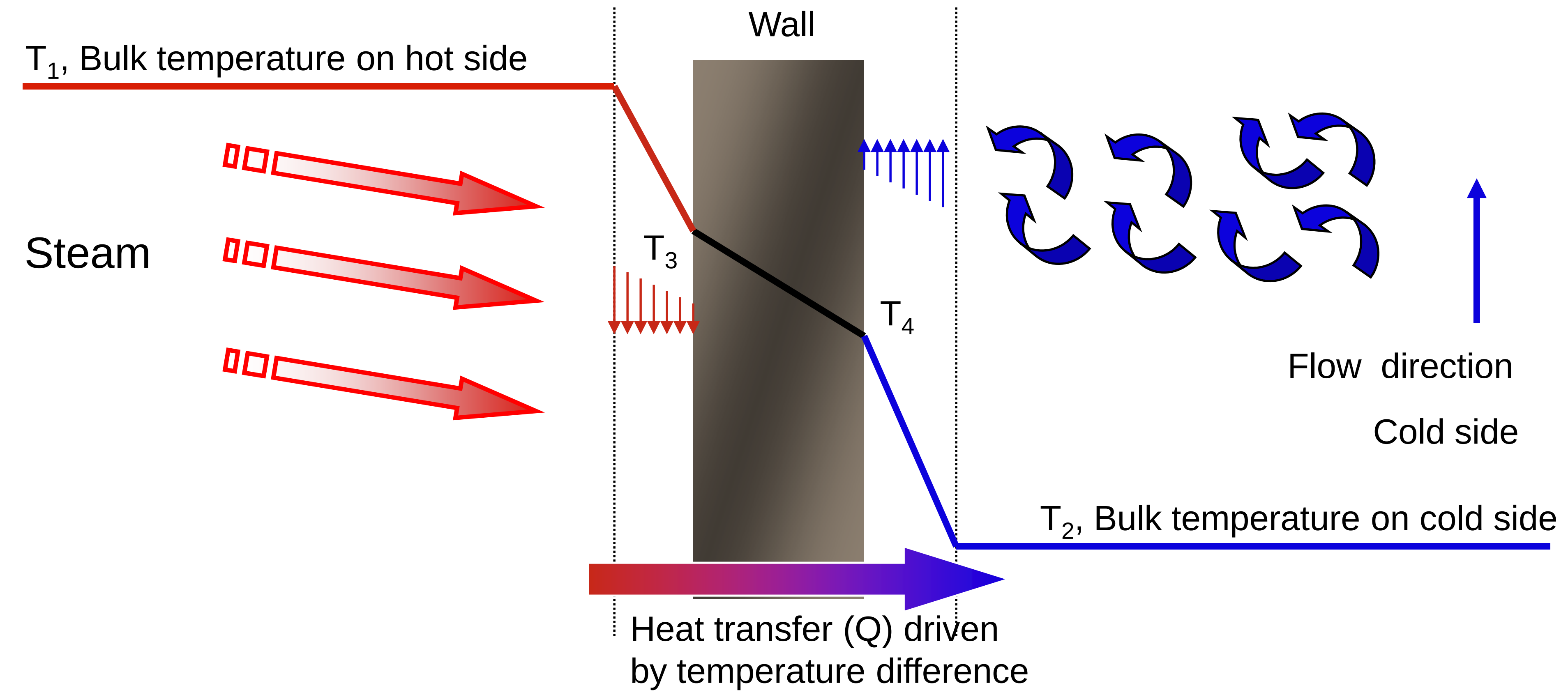


Example, a day at the beach



Heat Transferred in a HE

The temperature profile at one point of the plate wall



The Heat Transfer Equation

$$Q = k \times A \times MTD$$

The Heat Transfer equation

$Q = k * A * LMTD$

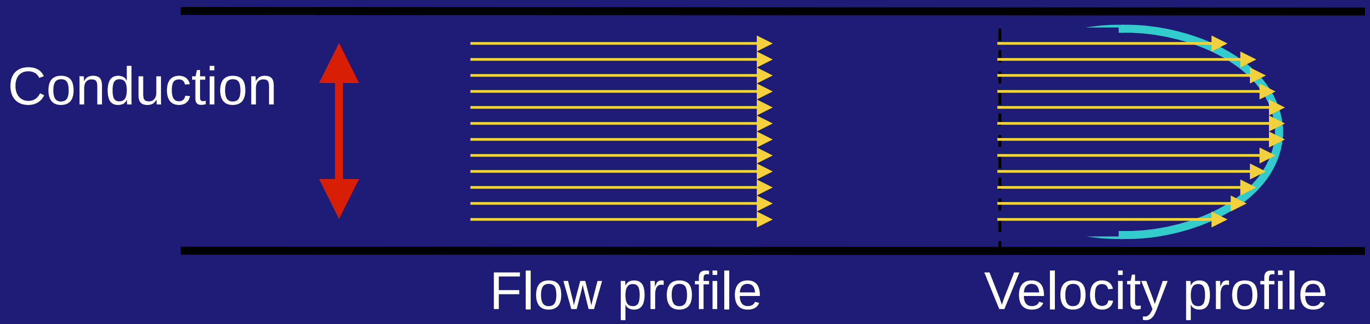
- Q = Heat Load, W (same as $Q_1 = Q_2$ before)
- k = k-value, overall heat transfer coefficient (OHTC), $W/m^2 °C$
  - Higher k-value = More efficient heat transfer
- A = heat transfer area (m^2)
- LMTD= Logarithmic mean temperature difference

The Heat Transfer Equation

$$Q = k \times A \times MTD$$

Flow principles

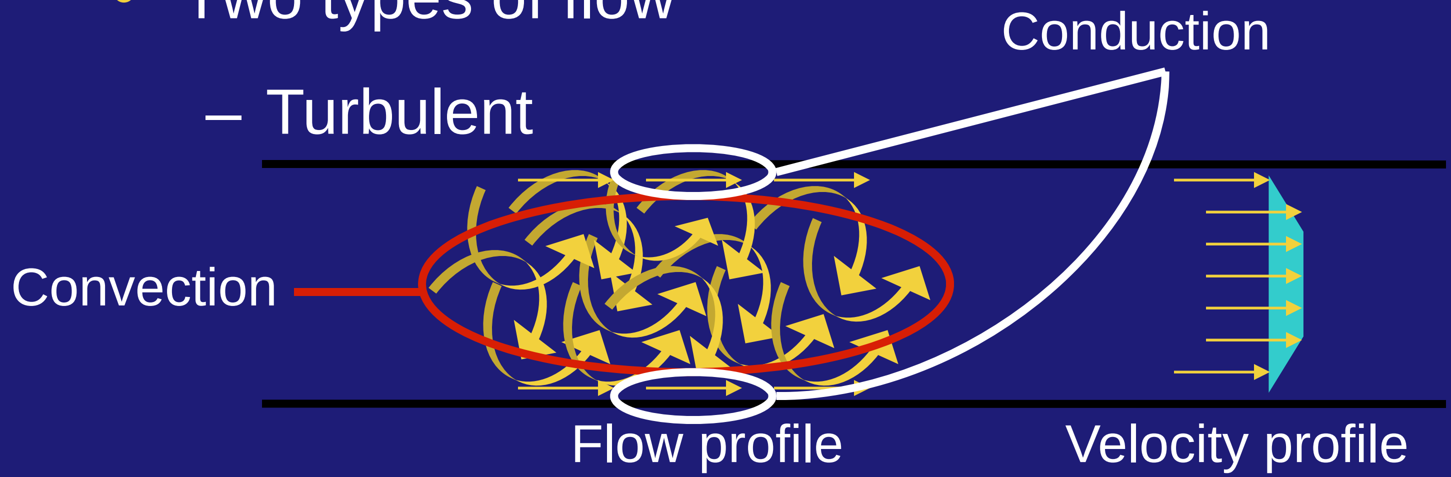
- Two types of flow
  - Laminar



- Orderly flow throughout the fluid
- Parabolic flow profile
  - Fluid at the wall moves slower
  - Due to the friction from the wall surface
- Ex., viscous fluids or water at low velocity

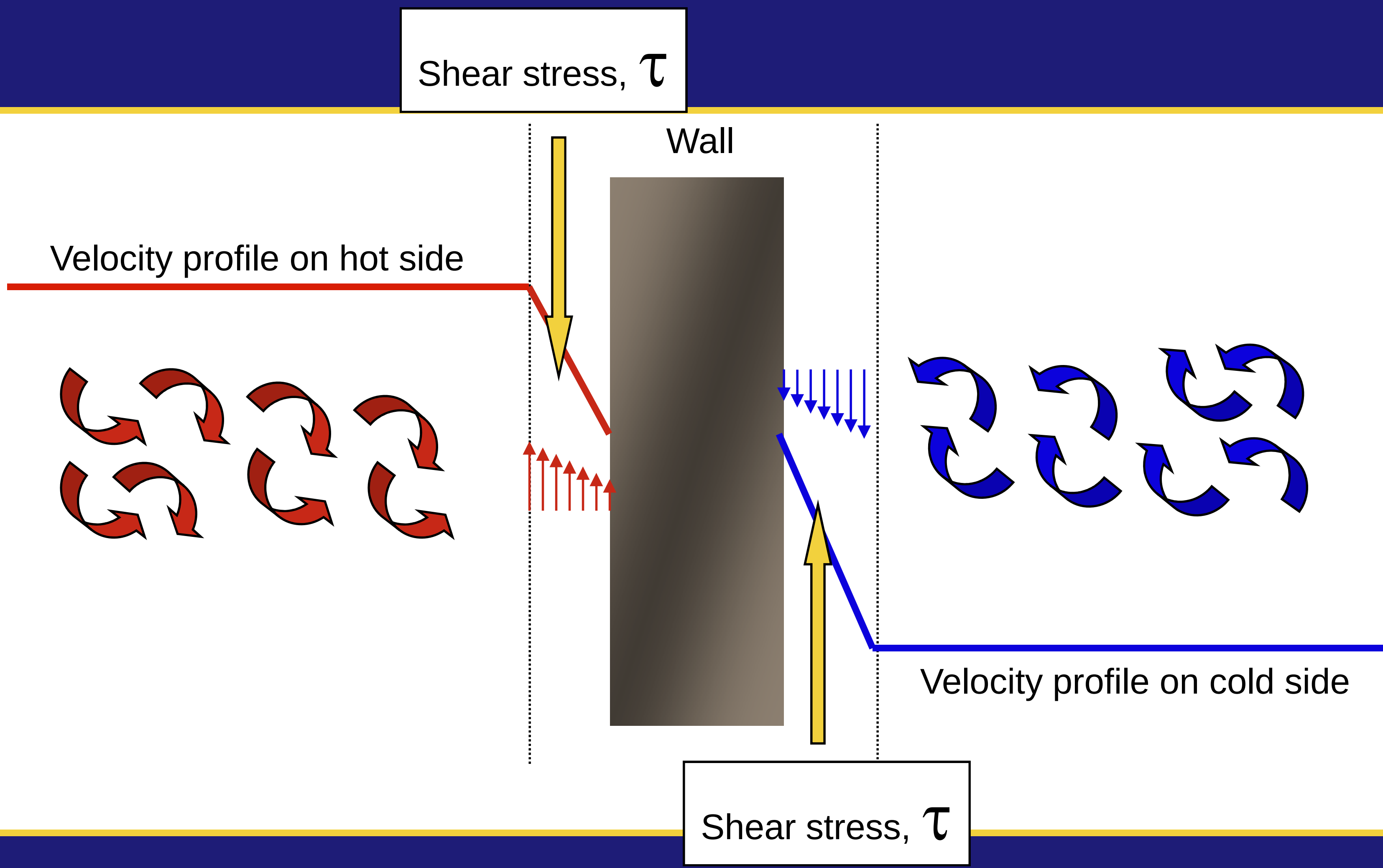
Flow principles

- Two types of flow
  - Turbulent

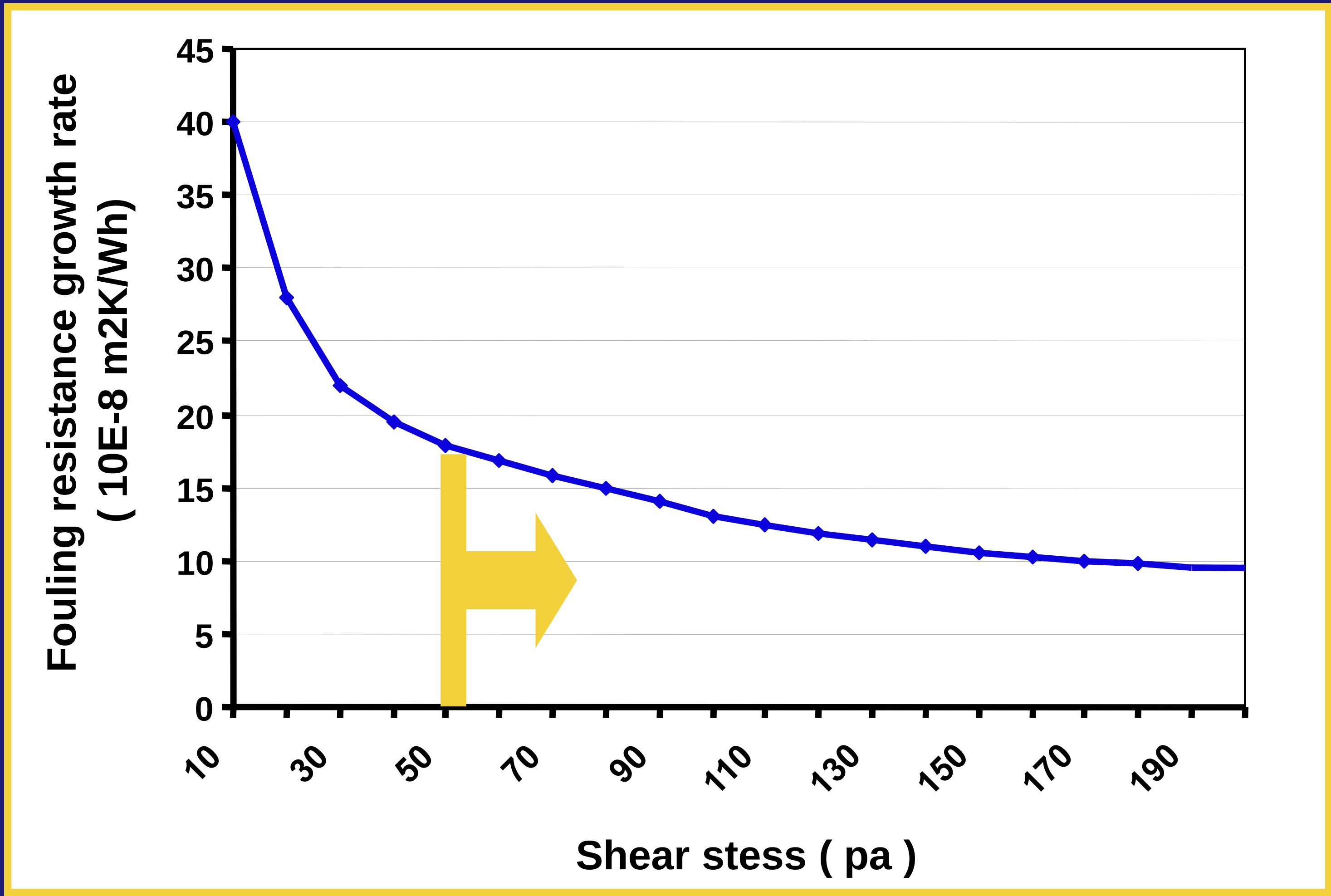


    - No orderly flow
    - Random eddy motion mixes the fluid
    - Always a laminar film closest to the wall
    - Ex., water at higher velocity

Shear Stress

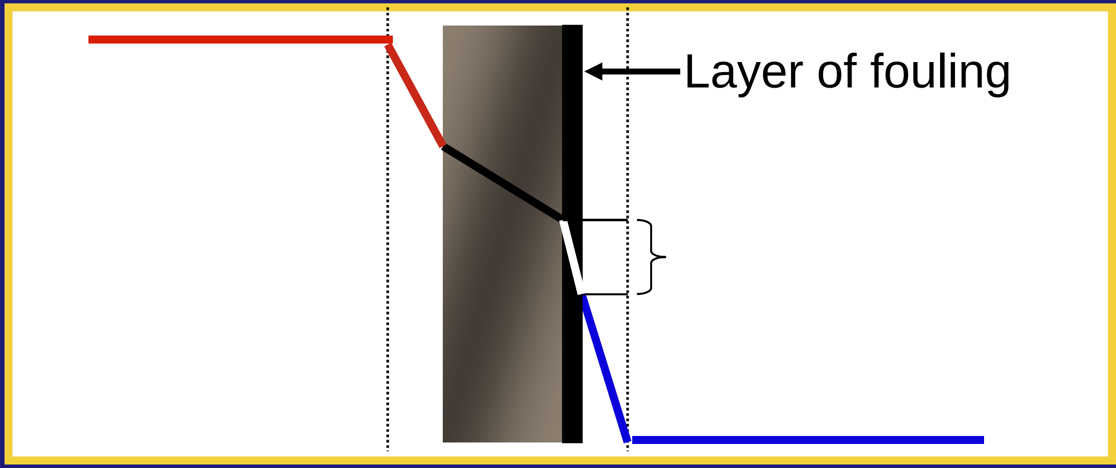


Shear stress versus fouling rate



- Rule of thumb: Try to keep the shear stress >50 Pa

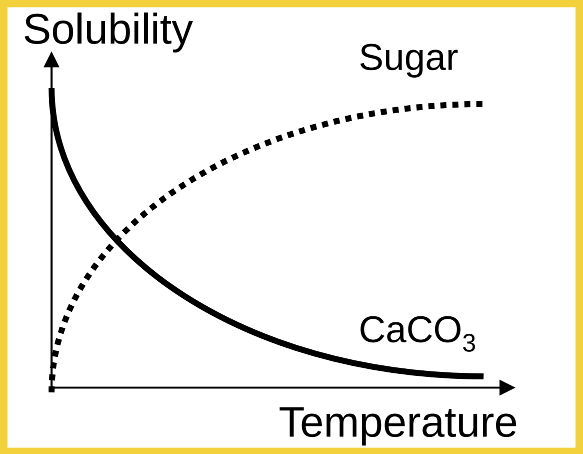
Fouling



- Major debris
- Biological growth
- Scaling
- Sedimentation
- Burn-on

Scaling

- Reversed solubility of dissolved salts
  - Reduced solubility at higher temperature
  - Ex $CaCO_3$ and $Ca(PO_4)_2$
- Common problem
  - Keep wall temperature low
  - Design with high shear stress (τ)



Design Safety Factors

- k-value margin (for PHEs)
  - Defined as a % margin between k_{Clean} and $k_{Service}$

$$\text{Margin} = \frac{k_{clean} - k_{service}}{k_{service}} (\%)$$

$$\text{Margin} = \frac{A_{act} - A_{req}}{A_{req}} (\%)$$

S&T use Rf – the Fouling Factor

– Normal Rf for S&T: $1{,}0 \times 10^{-4}$ $m^{2\,o}C/W$
$5{,}0 \times 10^{-4}$ $ft^{2,o}F,h/Btu$

– Normal k_{Clean} for PHE: 6000 $W/\,m^{2\,o}C$
1000 $Btu/ft^{2,o}F,h$

$$\frac{1}{k_{Service}} = \frac{1}{k_{Clean}} + R_f = \frac{1}{6000} + 10^{-4} \Rightarrow k_{Service} = 3750\ W/\ m^{2\,o}C$$

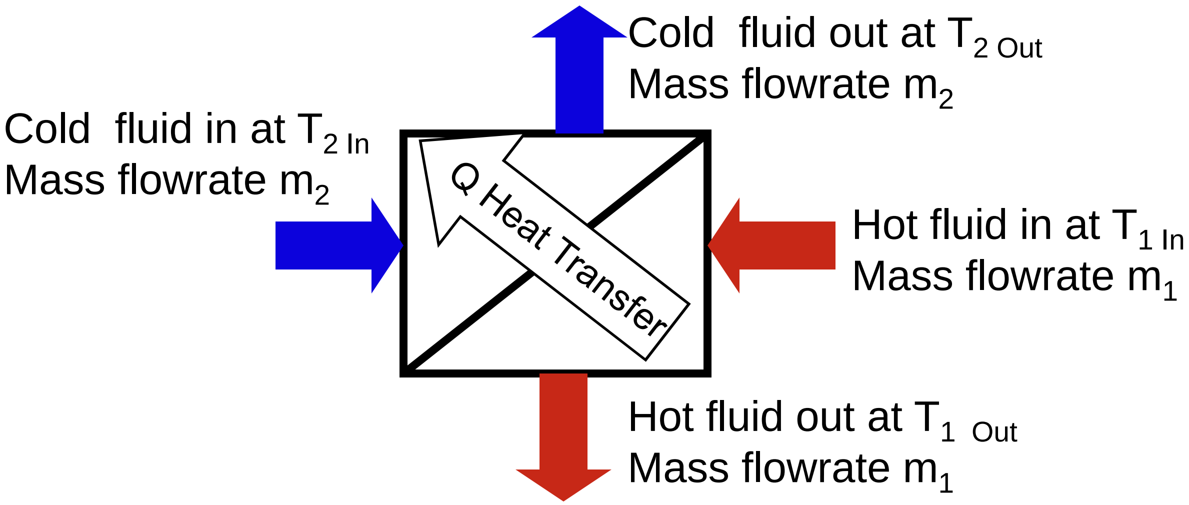
– Corresponding k-value margin

$$Margin = 100 \cdot \frac{k_{clean} - k_{service}}{k_{service}} = 100 \cdot \frac{6000 - 3750}{3750} = 60\%$$

– Much too high margin
  - Too many plates ⇒ Less turbulence ⇒ Fouling !
  - Maybe not competitive?

The Heat Balance

- Liquid-to-liquid



Definitions

Q = Heat load, W (rate of heat transfer)

m = Mass flow rate, kg/s

Cp = Specific heat, J/kg°C (the energy needed to heat 1 kg of the fluid with 1°C)

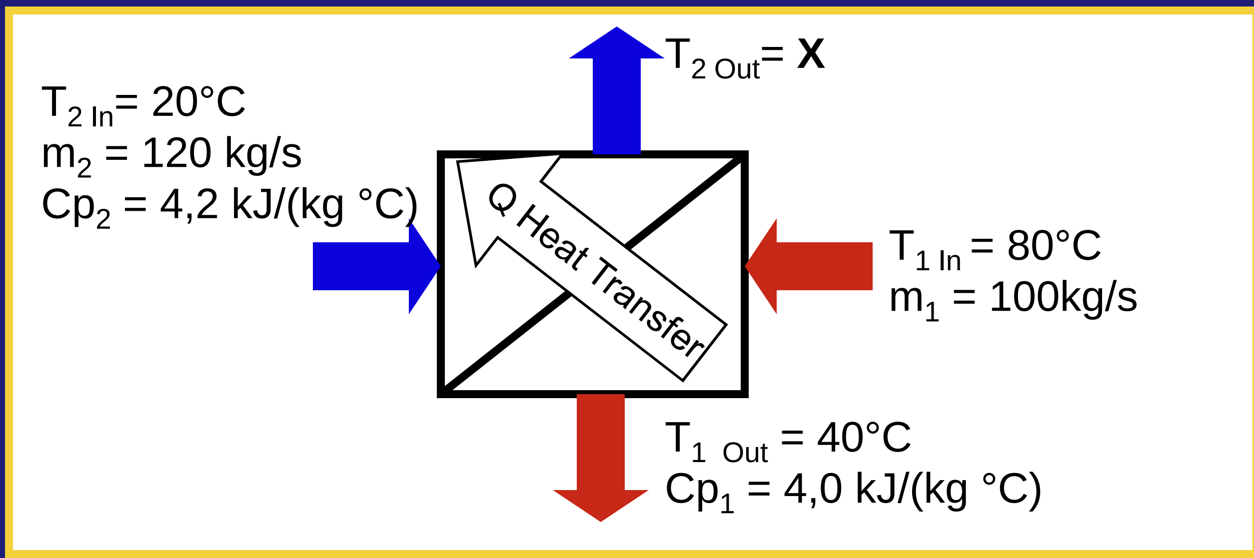
Heat released by the hot fluid: $Q_1=m_1*Cp_1*(T_{1\ In}-T_{1\ Out})$

Heat absorbed by the cold fluid: $Q_2=m_2*Cp_2*(T_{2\ Out}-T_{2\ In})$

Heat losses are negligible $\Rightarrow$ $Q_1= Q_2$

The Heat Balance - calculation

- What is the cold fluid outlet temperature?



Heat Load: $Q_1 = m_1 * Cp_1 * (T_{1\ In} - T_{1\ Out})$ = 100 kg/s * 4.0 kJ/(kg °C) * (80-40)°C

Q_1 = 16 000 kJ/s = 16 000 kW

$Q_1 = Q_2$: 16 000 kW = $Q_2 = m_2 * Cp_2 * (T_{2\ Out} - T_{2\ In})$

16 000 kW = 120 kg/s * 4.2 kJ/(kg °C) * (X-20)°C

X = 16 000 / (120 * 4.2) + 20 = 52°C

The Heat Balance

- Steam-to-liquid

Everyone knows what steam is?

- The three three phases of water:

Solid (s)	Liquid (l)	Gas (g)
Ice, Snow	Liquid water	Steam = water vapour
Crystals, all molecules tight together	Molecules move apart	Molecules leave the liquid and vaporise

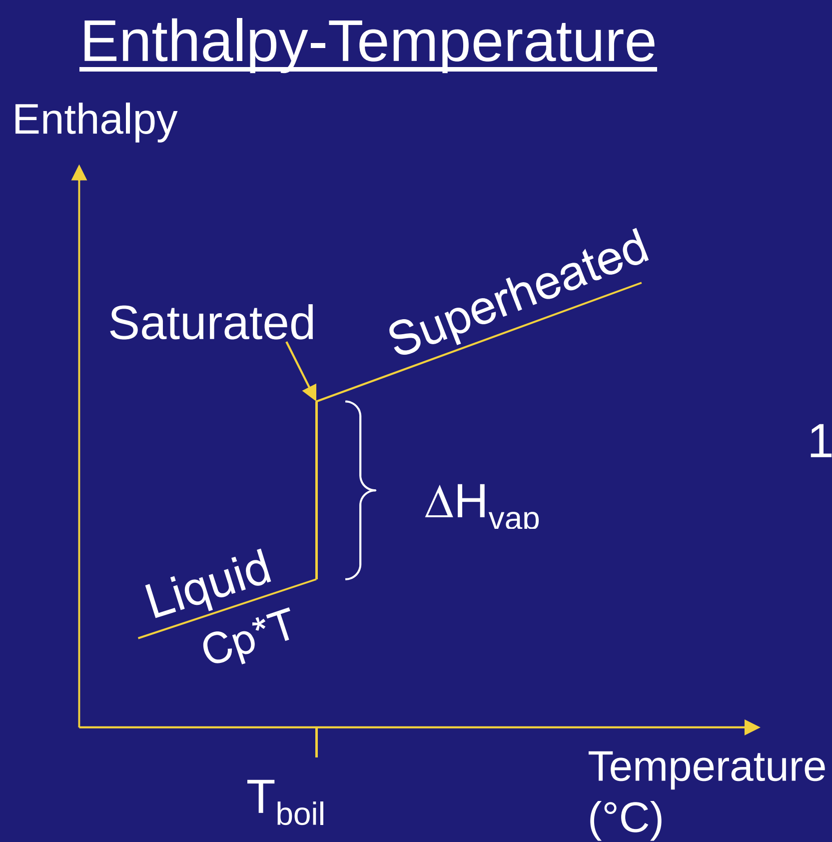
Melting energy

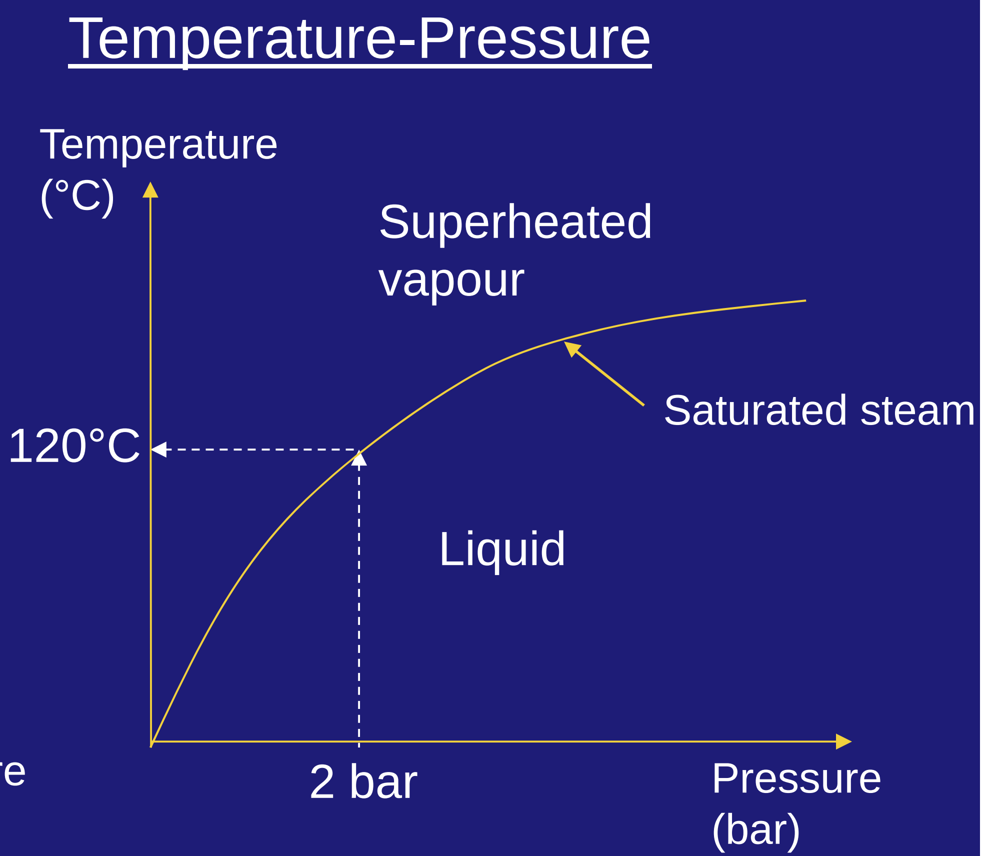
Heat absorbed by the water (Cp)

Heat of vaporisation / Heat of condensation

The Heat Balance

- Steam described in diagrams



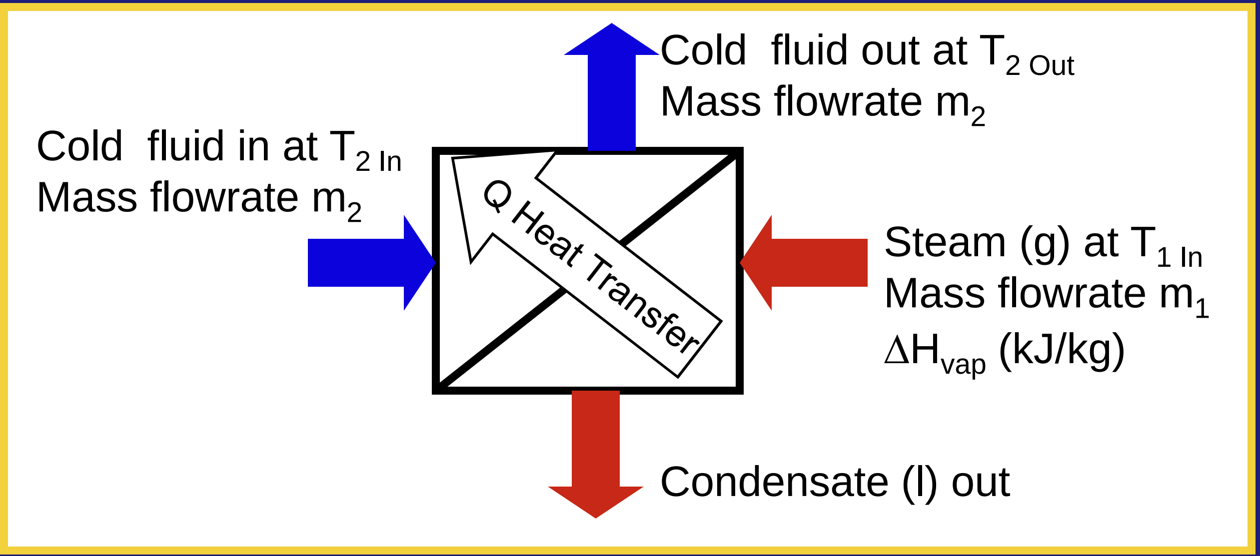


ΔH_{vap} = Heat needed to vaporise 1 kg of a fluid (kJ/kg)

The same amount of energy is released during condensation

The Heat Balance

- Steam-to-liquid



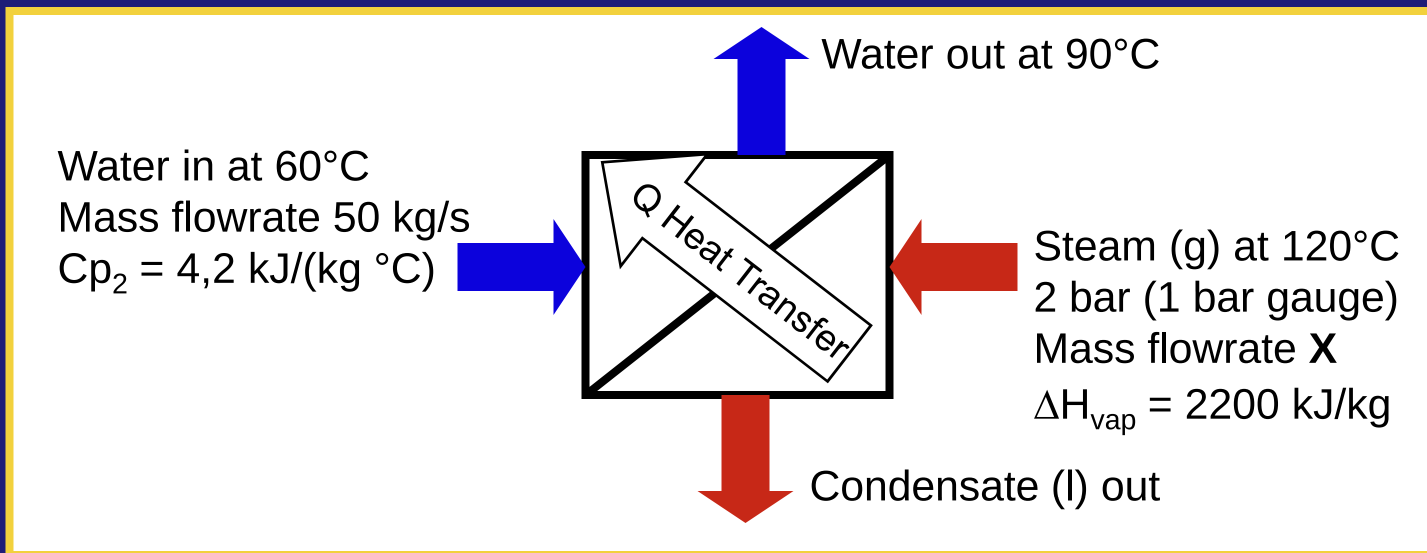
Heat released by the steam: $Q_1 = m_1 * \Delta H_{vap}$

Heat absorbed by the cold fluid: $Q_2 = m_2 * Cp_2 * (T_{2\,Out} - T_{2\,In})$

Heat losses are negligible $\Rightarrow$ $Q_1 = Q_2$

The Heat Balance - calculation

- How much steam is needed to heat the water?



Heat Load: $Q_2 = m_2 * Cp_2 * (T_{2\ Out} - T_{2\ In}) = 50\ kg/s * 4.2\ kJ/(kg\ °C)\ (90-60)°C$

$Q_2 = 6\ 300\ kW$

$Q_2 = Q_1$: $6300\ kW = Q_1 = m_1 * \Delta H_{vap}$

$6300\ kW = X\ kg/s * 2200\ kJ/kg$

The Heat Balance

- So why is steam used?
  - Less than 3 kg steam can heat 50 kg water from 90 to 60°C
  - It is a high-energy carrier !

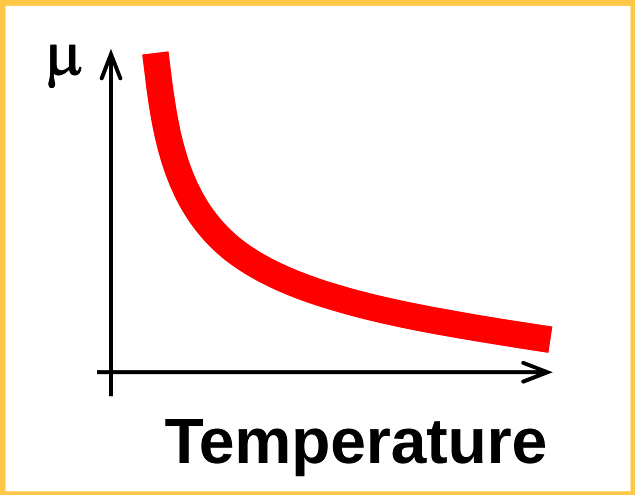
- Steam is the most common way in industry to distribute energy for heating purposes

Physical properties

– Density (ρ)
– Specific heat (Cp)
– Thermal conductivity (λ)

Small variations
One value acceptable

– Viscosity (μ)



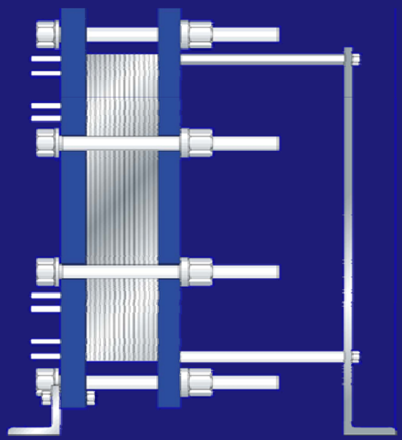
Three values!

Example phys prop

Heating of water 60 to 80°C, 500 kW, steam 2 bar(a)

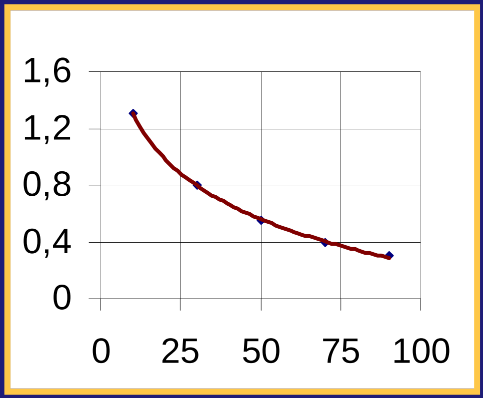
1. Constant viscosity

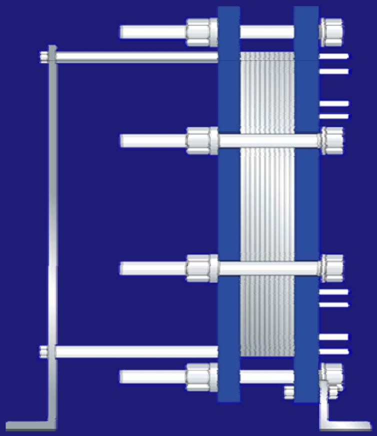
μ = 1 cP



TS6
22 plates

2. True viscosity





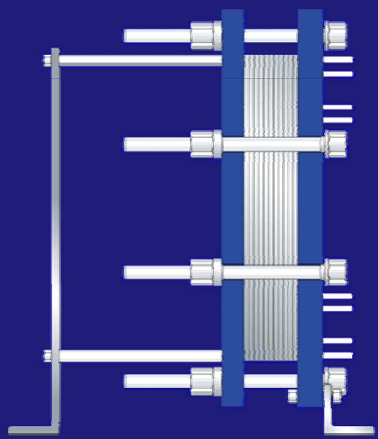
TS6
16 plates

Example phys prop

Heating of HFO 30 to 120°C, 400 kW, steam 6 bar(a)

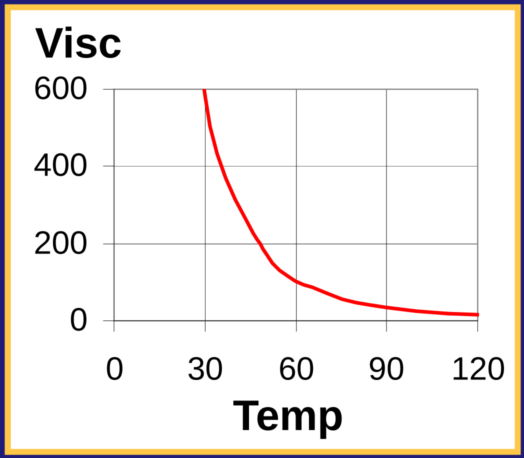
1. Constant viscosity

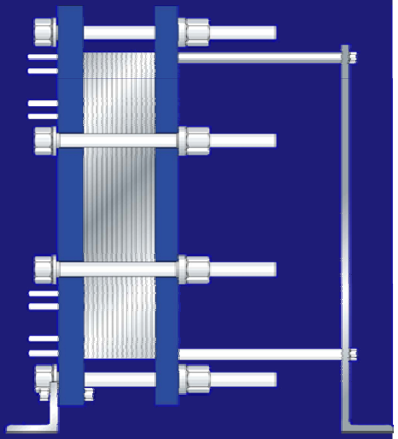
μ = 10 cP



TS6
42 plates

2. True viscosity





TS6
58 plates

Conventional PHE vs Steam PHE

Heating of water 60 to 80°C, 500 kW, steam 2 bar (a)

M10M

TS6M

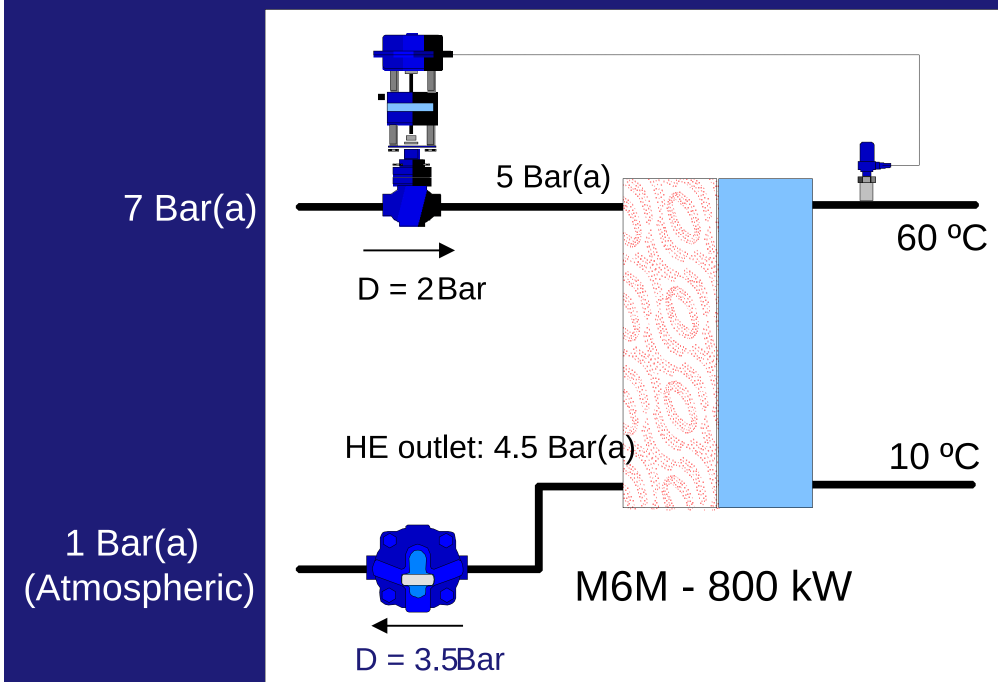
M10M	
Area:	**2,6 m^2**
Margin:	**25%**
P-drop:	**45 kPa**

TS6M	
Area:	**1,9 m^2**
Margin:	**6%**
P-drop:	**35 kPa**

Sizing HE's correctly...

If you ignore the margin……

Margin = 72 %



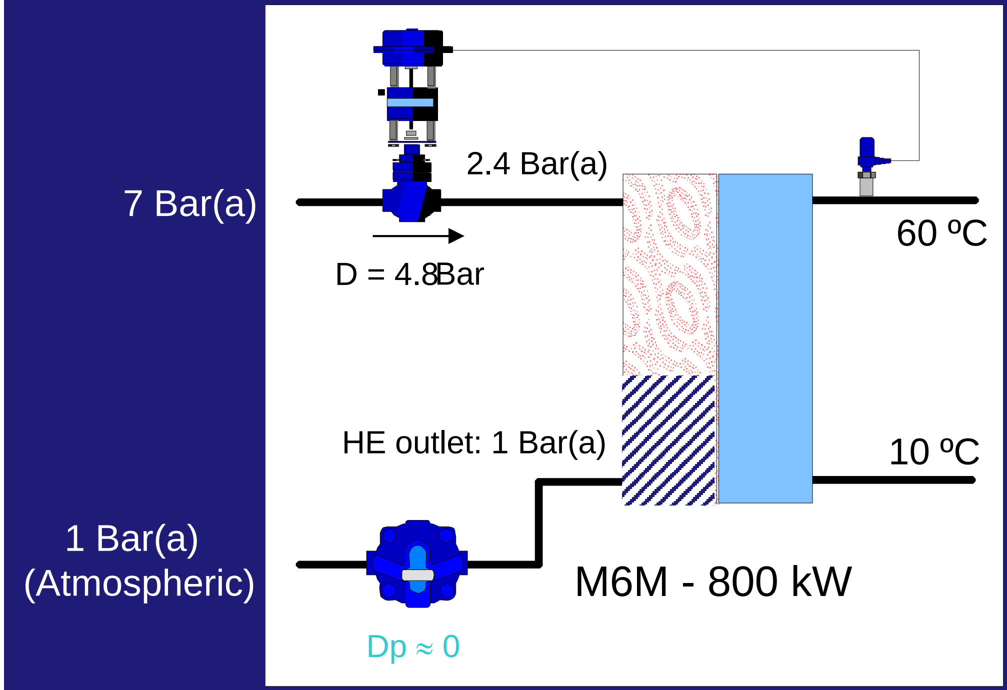
Example of sizing a HE for condensing at 5 Bar(a)

Result: M6M, surface = 1,7 m², margin = 72 %

Sizing HE's correctly...

You could get serious problems !

Actual conditions



Typical margin related problems are:

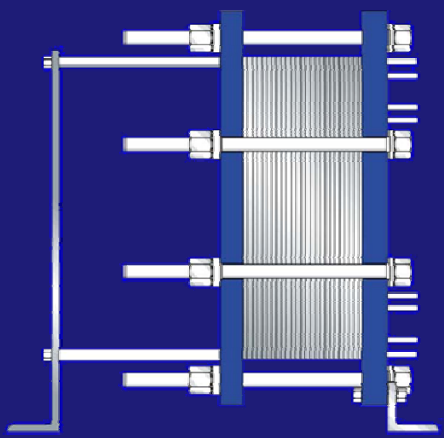
- Over sized control valve
- Under sized steam trap
- Stalled heat exchanger
- High steam velocities

PHE versus S&T in steam applications

- Size and weight
- Fatigue
- Thermal efficiency
- Condensation temperature
- Subcooling of condensate
- Temperature control
- Operation in stall condition

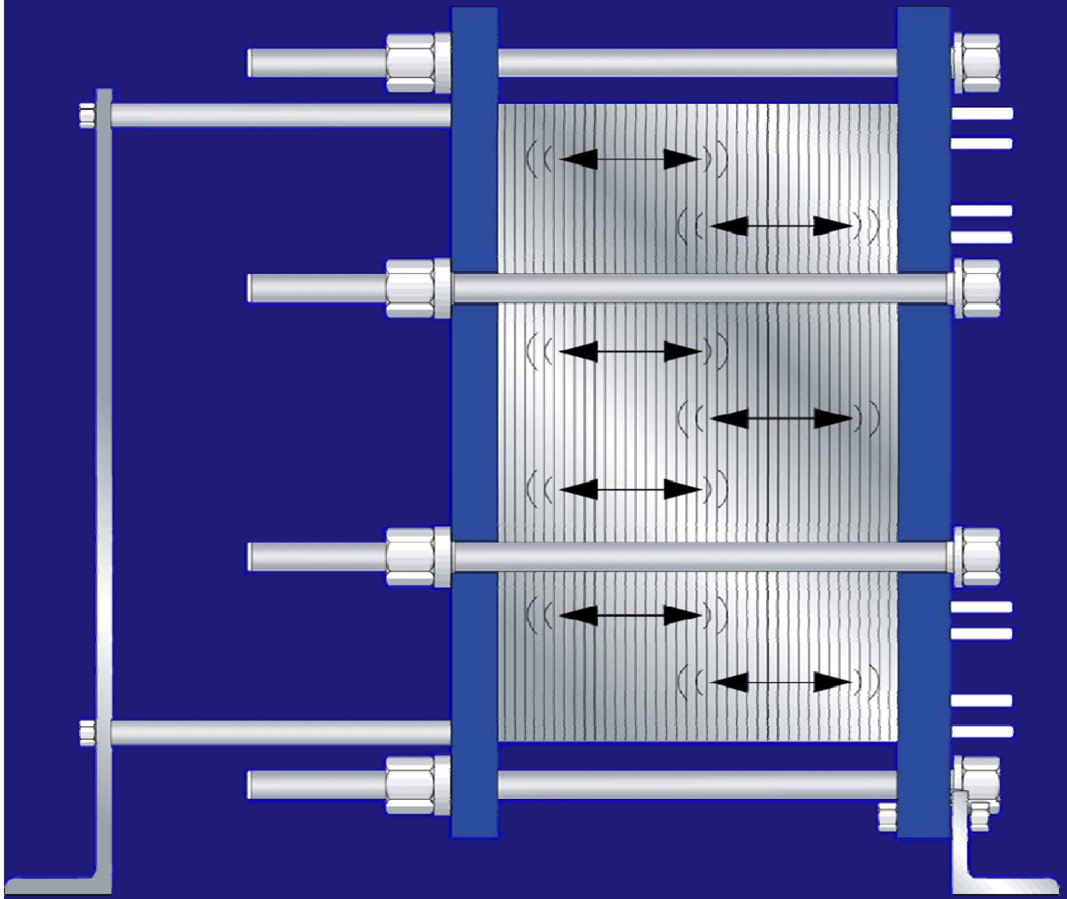
Size and weight

- PHE requires less floor area
- PHE weighs less
- Easy installation
- Low PxV
  - For small heat exchangers pressure vessel certificates and regular inspection are unnecessary



	PHE	S&T
Weight ratio	1	6
Space ratio	1	7
Hold-up volume ratio	1	6

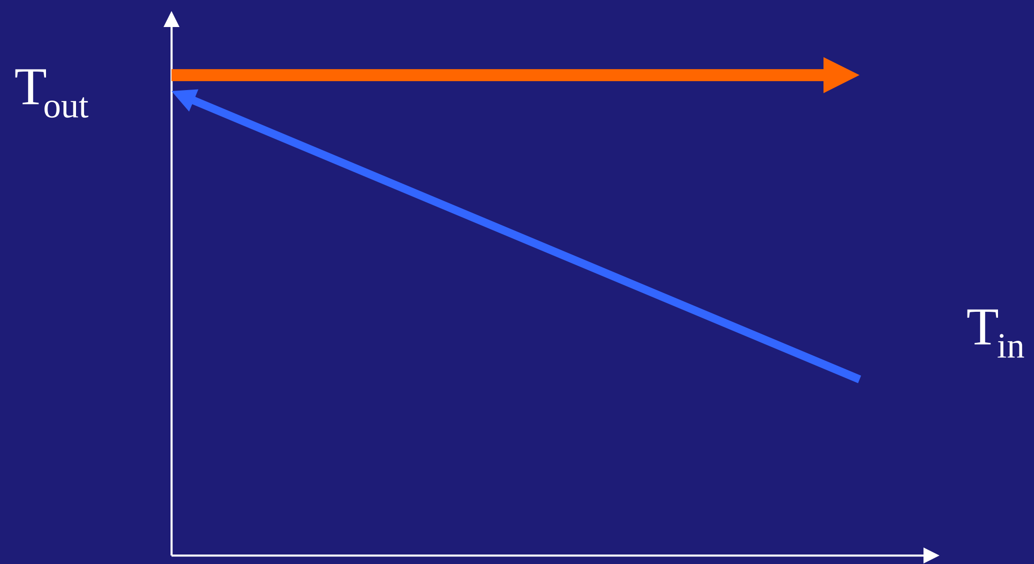
Fatigue



- Thanks to the elasticity of the gaskets, there will be no thermal fatigue problems in the PHE plate pack

Thermal efficiency

- A close temperature approach is possible in a PHE
- PHE higher k-value

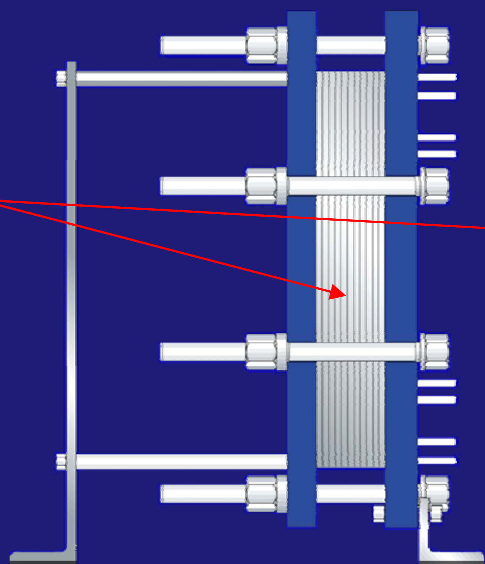


A lower condensation temperature

Condensation at 150 °C

Load: 1 MW, 60 - 80 ºC

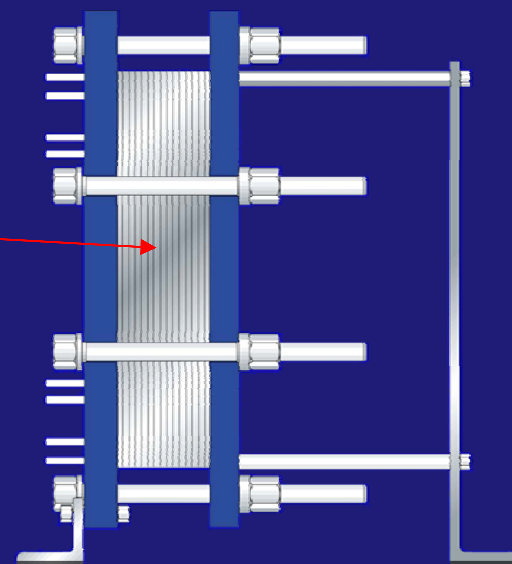
TS6-M with 20 plates



Condensation at 120 °C

Load: 1 MW, 60 - 80 ºC

TS6-M with 28 plates



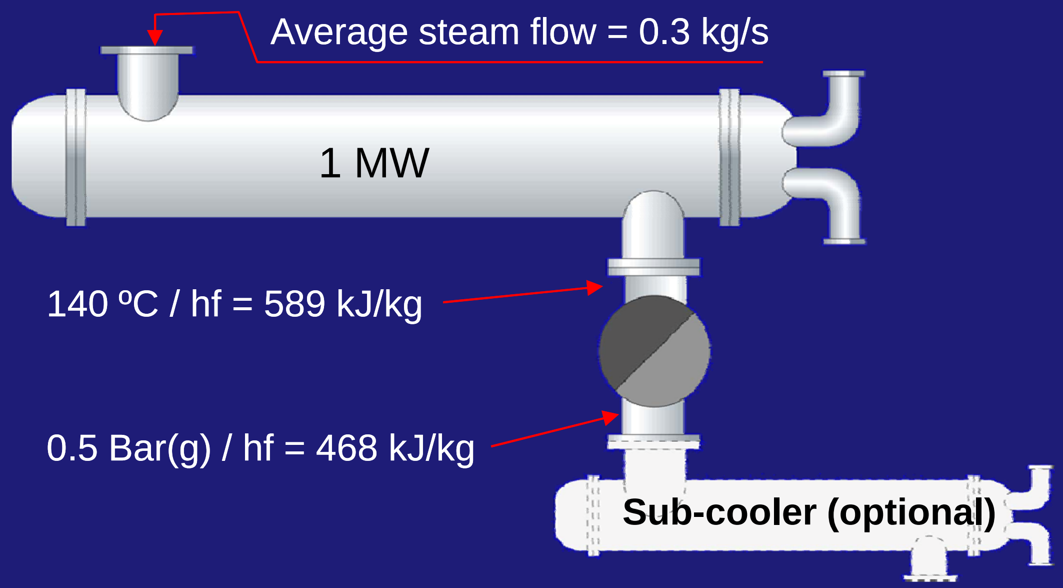
Very small difference in no of plates

Why design with a low condensation temperature ?

- Minimise flash steam
- Reduce scaling
- No pressure build up in the condensate system

PHE provides minimum of flash steam

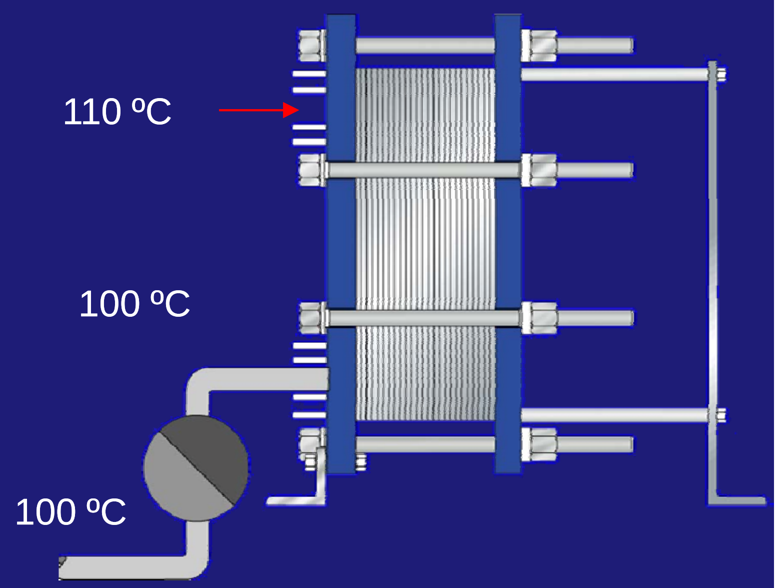
Max condensation temp. 160 ºC
Average condensation temp. 140 ºC



Average operation time; 6,000 hr/year
Energy cost; 25 Euro / MWh

Q = m*(hfin-hfout)*time =
0.3*(589-486)*6,000 = 185,400 kWh
Energy cost = 25* 185.4 = 4635 EURO / Year

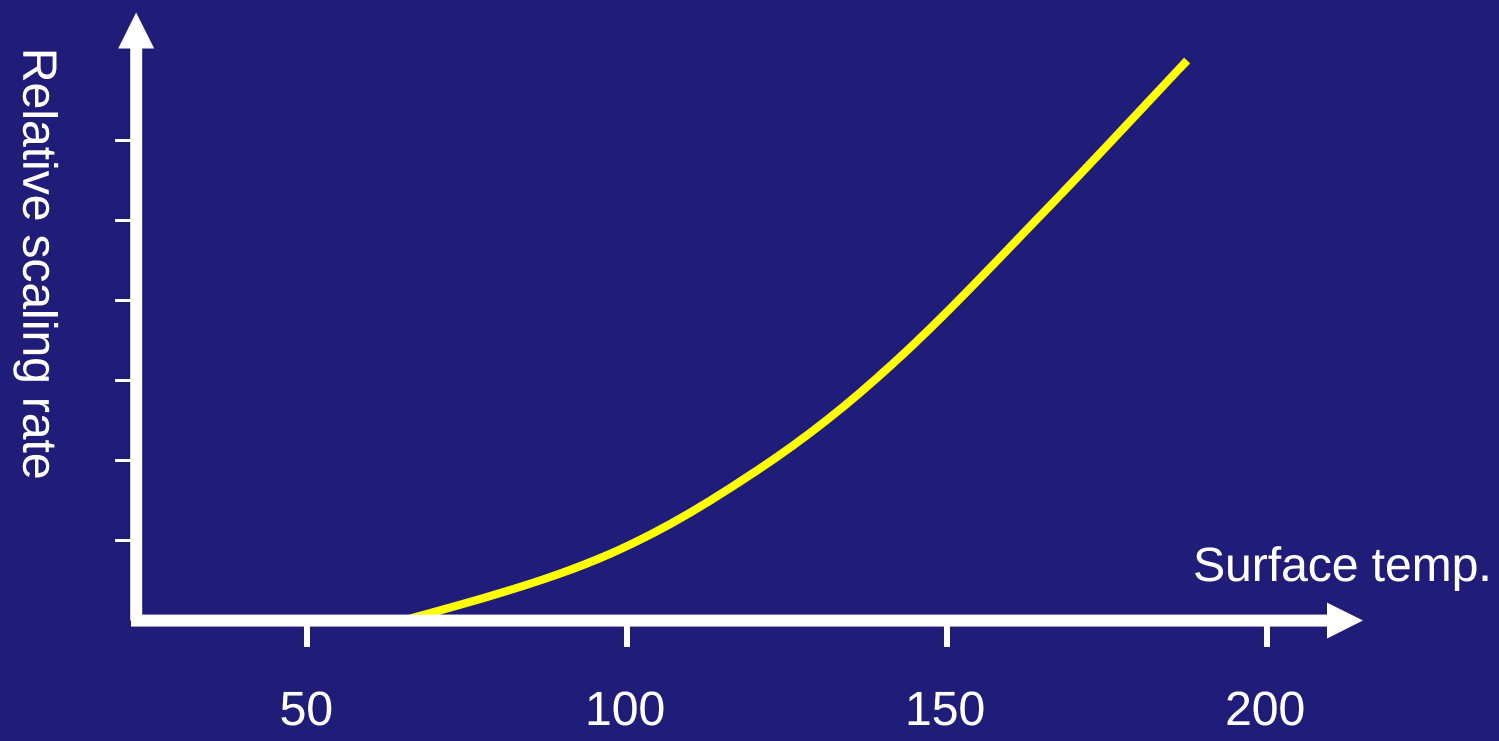
Max condensation temp. 120 ºC
Average condensation temp. 110 ºC



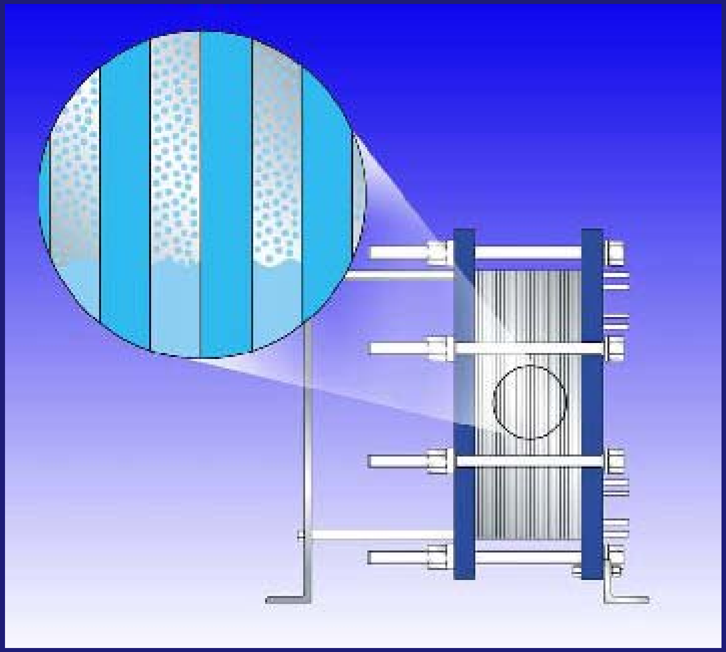
- No losses
- Minimum scaling
- No need to sub cool the condensate
- No pressure build up in the condensate system

Benefits compared to S&T

Minimised condensation temperature reduce scaling

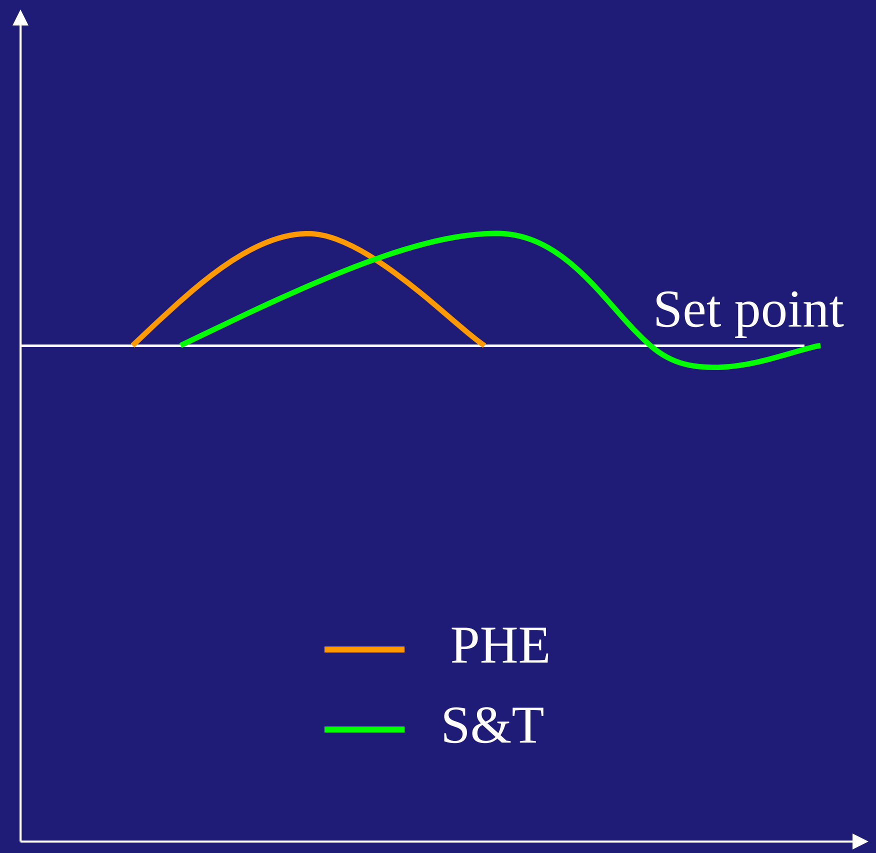


Subcooling of condensate



- Possibility of introducing condensate level control and utilising the lower part as a subcooler
- Vertical orientation of the plates makes drainage easy in a PHE

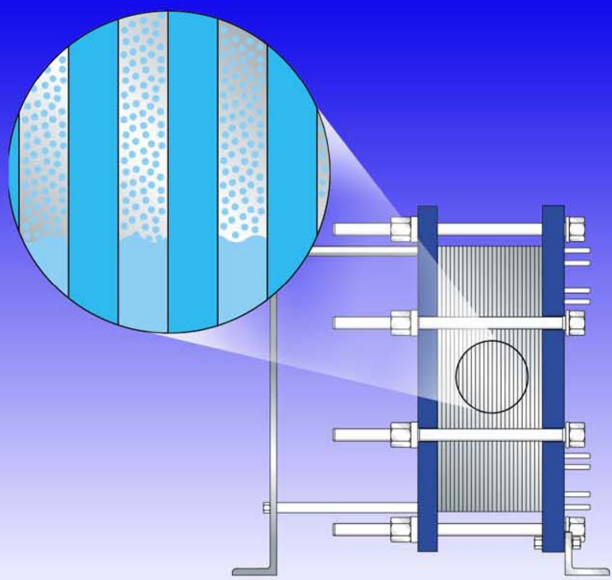
Temperature control accuracy

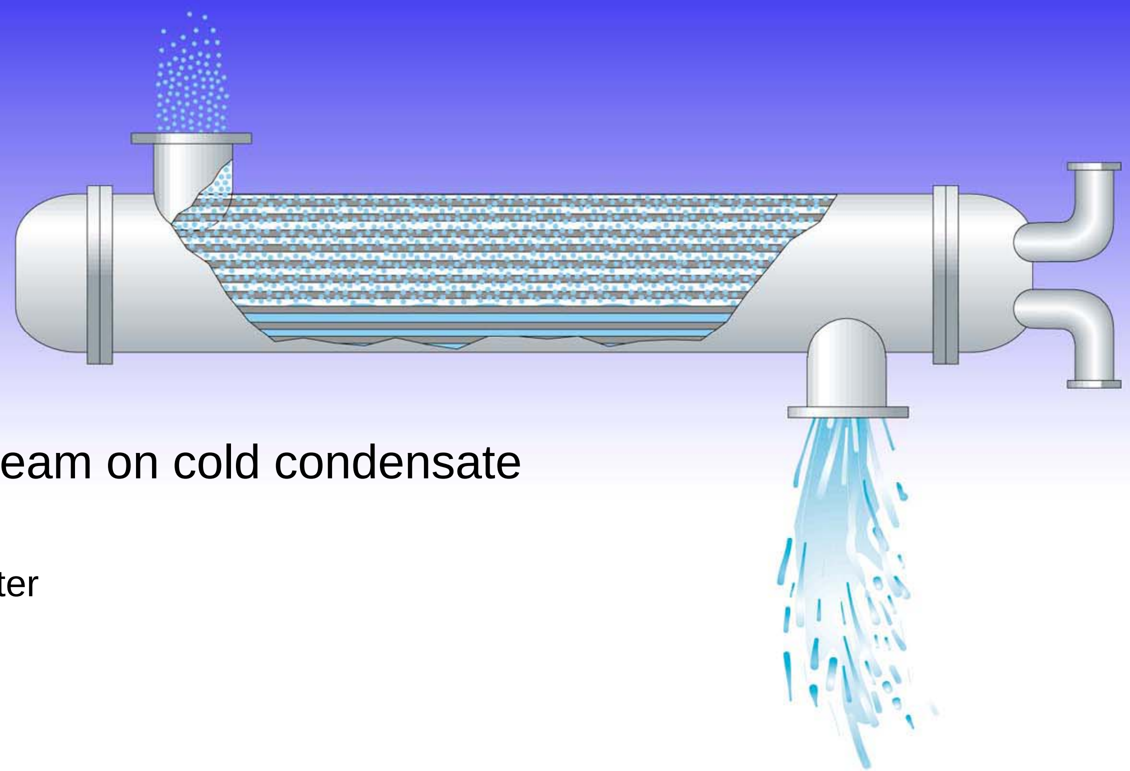


- Low hold-up volume, high thermal efficiency and low weight provides a short response time and an accurate temperature control

PHE can handle stall conditions

Large contact area between steam and water
- Implosions, Noise
- Water hammer
- Poor temperature control





Hot steam on cold condensate

Small contact area between steam and water
- No implosions
- No noise
- Acceptable temperature control

Summary PHE versus S&T

- PHE compact and easily extendable
- Temperature control accuracy
  - PHE short response time
- Low condensation temperature minimises scaling and flash steam
- *PxV*

Alfa Laval