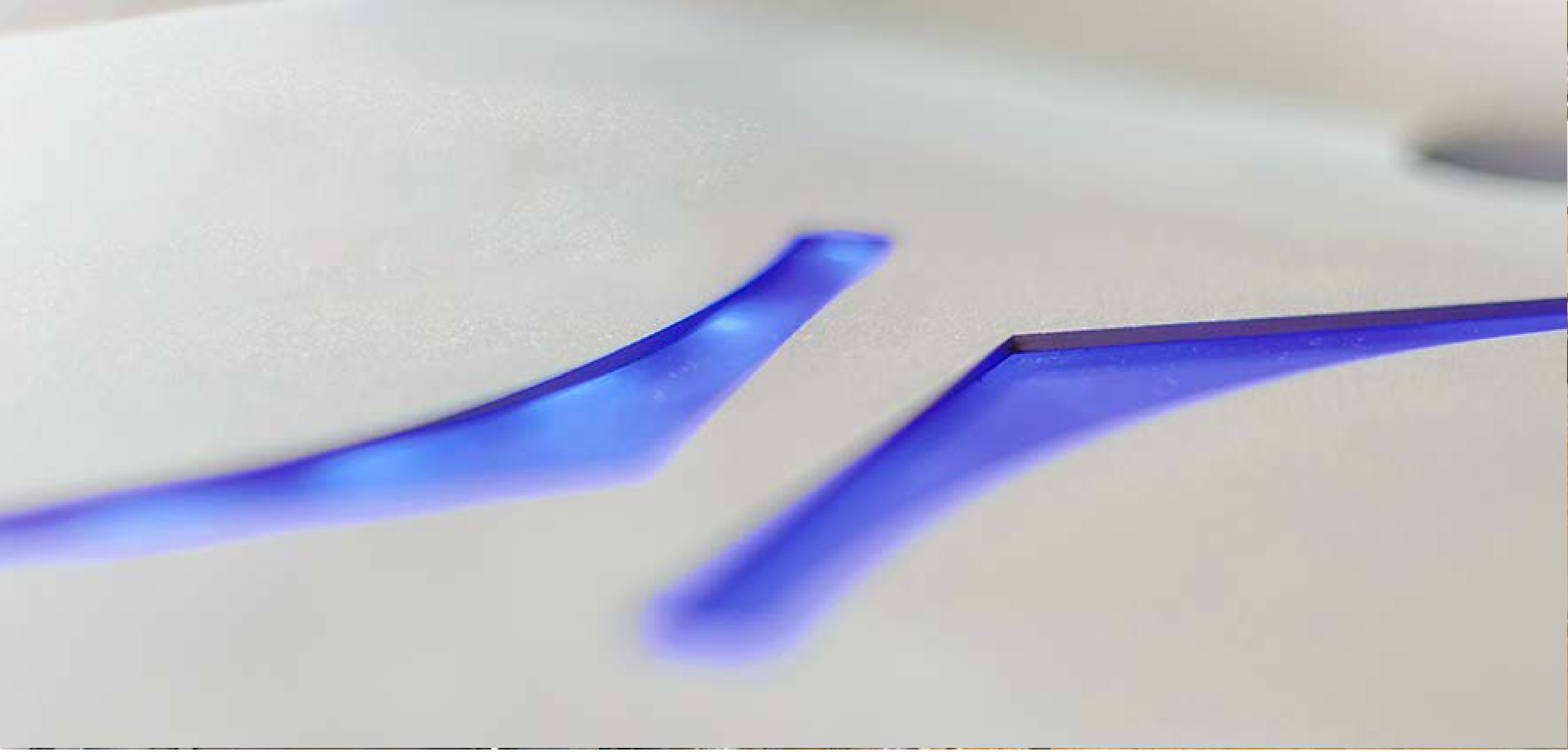

Thermal Process Engineering for Brewers

Basics in Theory and Practice

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Why is a Basic Knowledge important for Brewers?

- Heat exchange can be found everywhere in the brewery!

Heating up the mash and hold the temperature break

Wort boiling

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Why is a Basic Knowledge important for Brewers?

- Heat exchange can be found everywhere in the brewery!

Wort cooling

Heat transfer between a tank and its environment (for instance brewing liquor)

Why is a Basic Knowledge important for Brewers?

- Heat exchange can be found everywhere in the brewery!

Fermentation and beer storage

Flash pasteurization

Why is a Basic Knowledge important for Brewers?

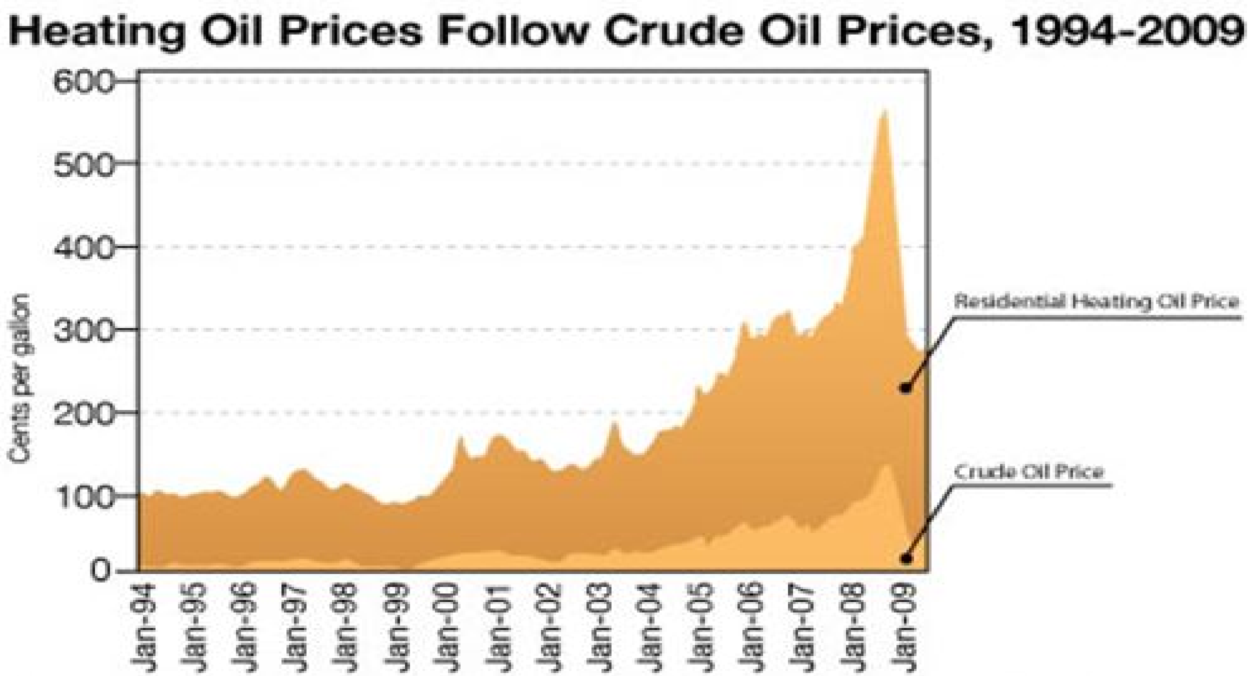
- Average heat/cooling consumption of a 83,000 bbl brewery (100,000 hl)

Heat consumption of the brewhouse:	22.5 kWh/bbl sales beer
Of that mashing (infusion):	3 kWh/bbl sales beer
Of that boiling (10% total evaporation):	13.5 kWh/bbl sales beer
Heat consumption of the whole brewery:	44.1 kWh/bbl sales beer
Cooling consumption of the whole brewery:	7.7 kWh/bbl sales beer

>50% of the total heat are consumed in the brewhouse!

Why is a Basic Knowledge important for Brewers?

- Heating oil price development in the past



Source: Energy Information Administration, *Petroleum Marketing Monthly* (January 1995 to present).

➢ The price for heating oil rose in the past and will be unstable in the future!

Why is a Basic Knowledge important for Brewers?

- Heat transfer is part of many processes during beer production.
- The knowledge about the physics behind is important to ensure high product quality.
- It also offers the opportunity to improve your wort-/beer taste.
- Understanding heat transfer means recognizing potential to save money in the future.
- Saving primary energy means to be more independent of the uncertain development of heating oil prices.
- Additionally, CO_2-Emission may be decreased.

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- Why is a Basic Knowledge important for Brewers?
- Necessary Basics of Thermodynamics
  - Heat and Energy
  - Definition of Thermodynamic Parameters
  - Thermal Energy and Power
  - Heat Transfer
  - How can Brewers improve the k-value and the Heat Transfer?
- Practical Calculations in the Brewery
  - Mashing
  - Wort Boiling
  - Wort Cooling with a Plate Heat Exchanger
  - Importance of Tank Insulation
  - Fermentation
- Final Remarks

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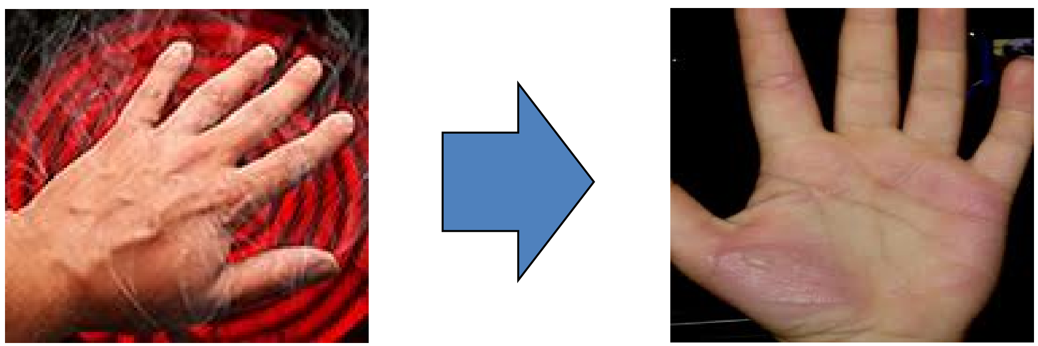
Heat and Energy

- What is heat?

Heat (abbreviation Q) is energy that is being transferred based on a temperature difference of a system and its environment (or between two systems) across the common system boarder.



Heat comes from the higher temperature level to the lower temperature level. The results are often serious.

- Therefore, heat always flows from the system with a higher temperature level to the system with lower temperature level (according to the second law of thermodynamics).

- Heat flow ($\dot{Q}$)is determined as the transferred heat in a certain time interval. It can be considered the same as the thermal power.

Heat and Energy

- Heat is transferred energy. But how is energy defined?
- Example: What contains more energy: a cup of hot soup or a glass of water?

- Obviously, the soup has got more energy because of its higher temperature.

> ➢ Energy is the ability of a system to work or to release heat.

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Definition of Thermodynamic Parameters

- Specific heat capacity c_p (also called specific heat):
  - The specific capacity describes which quantity of heat is required to rise the temperature of 1 kg of a certain substance by 1 Kelvin. The physical unit is $\frac{kJ}{kg \cdot K}$. The c_p value only applies for a certain pressure.

Fluid	c_p $[\frac{kJ}{kg \cdot K}]$ for atmospheric pressure
Water	4.18
Mash (15 °P)	3.73
Mash (20 °P)	3.60
Mash (25 °P)	3.46
Wort	4.0 – 4.1
Air	1.005

- **With increasing density of the mashes, the specific heat decreases.**

Definition of Thermodynamic Parameters

- **Specific Enthalpy h:**

  - Enthalpy means the content of heat of a body. The specific enthalpy is the heat in relation to mass $[\frac{kJ}{kg}]$. For fluids applies:

$$h = c_p \cdot \Delta T$$

T: Temperature

enthalpy = specific heat value X delta Temperature

  - Enthalpy of vaporization/-condensation r $[\frac{kJ}{kg}]$ is the content of heat that is required/released for changing the state of aggregation from liquid to vapor state and vice versa. The amount of enthalpy depends on the pressure level of the system (vapor pressure!). For condensing saturated steam applies:

Pressure of the system (abs.)	r $[\frac{kJ}{kg}]$ for water/vapor transformation
1.0	2,257.9
1.5	2,226.2
2.0	2,201.6
5.0	2,107.4

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Thermal Energy and Power

- How can you calculate the energy of a fluid?

Generally:	$Q = m \cdot h$
For fluids:	$Q = m \cdot c_p \cdot \Delta T$
Saturated steam:	$Q = m \cdot r$

m: Mass of the material

- The required thermal power can be found by considering the time to heat up a body/fluid:

$$\dot{Q} = \frac{Q}{t}$$

t: Time

Further examples concerning brewing in a later chapter

Heat Transfer

- 3 possibilities of transferring heat through a vessel wall:
  - Heat conduction
  - Convection
  - Heat radiation (not considered in this presentation, but in fact has influence on wort boiling and cooling outdoor fermentation tanks)

➢ In reality, there is always a combination of the three types.

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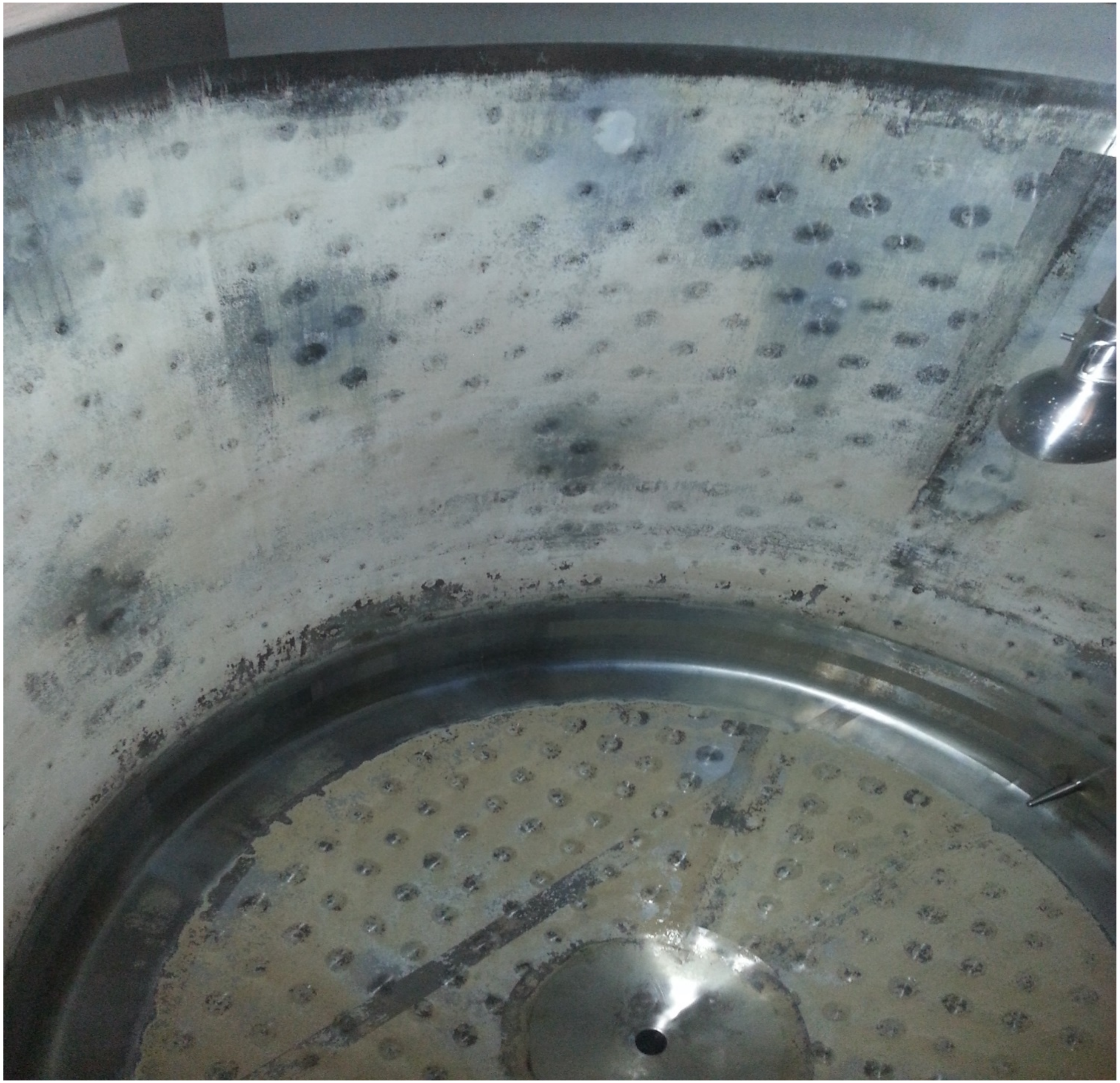
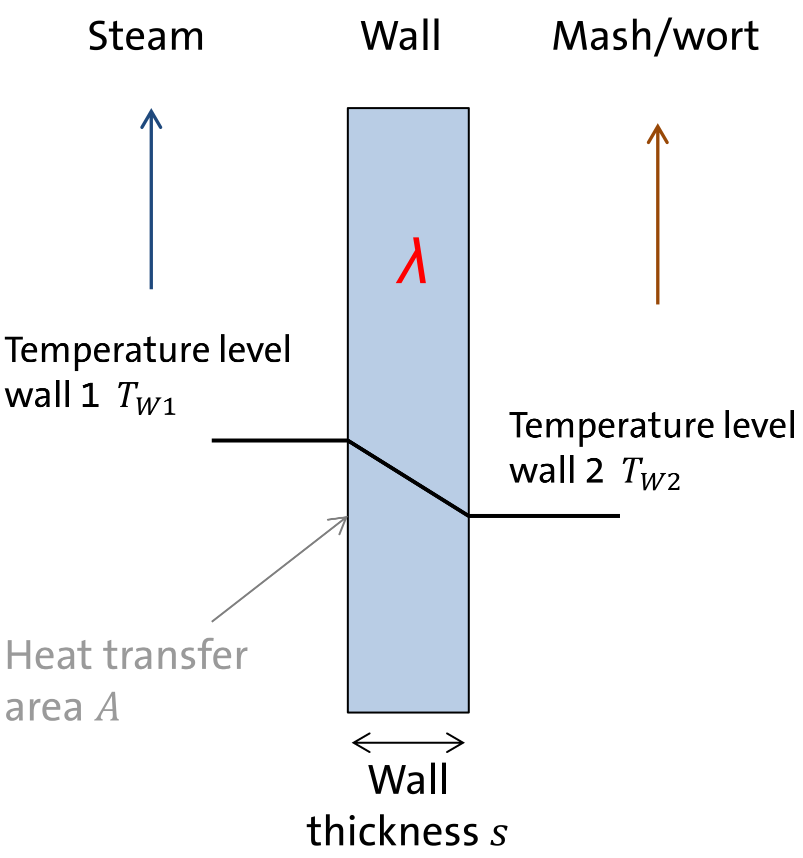


Heat Transfer

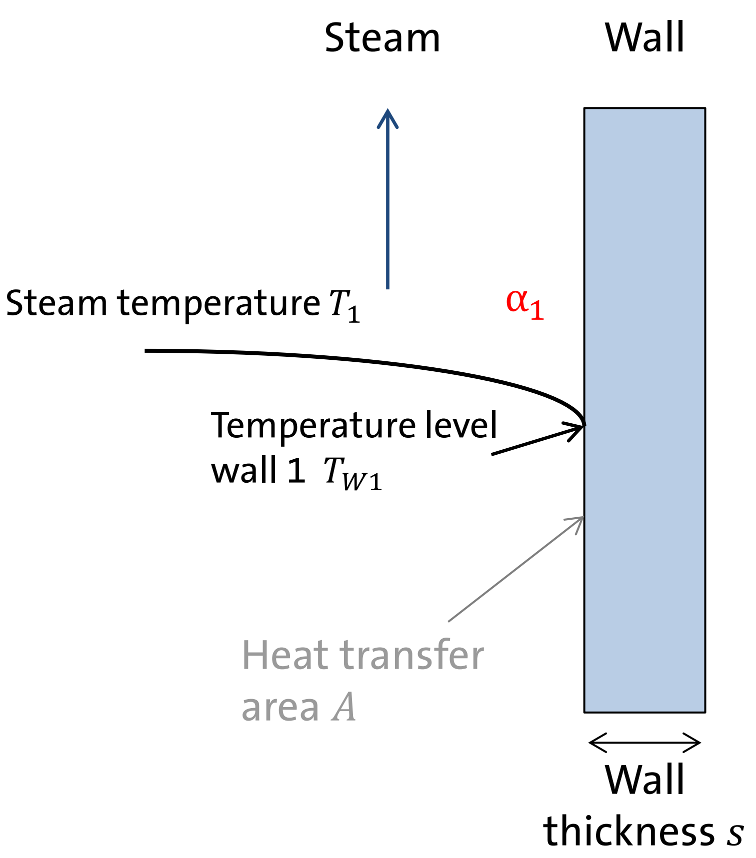
- ***Heat conduction and thermal conductivity λ („lambda“):***
    - Material property that describes how big the temperature difference between the in- and outside of a wall is.
    - $\dot{Q} = \lambda \cdot \frac{A}{s} \cdot (T_{W1} - T_{W2})$

Material	$\lambda [\frac{W}{m \cdot K}]$ for 68 °F
Stainless Steel	15
Copper	380
Aluminum	229
Silver	410



Heat Transfer

- ***Convection***
  - The convection coefficient ***α*** describes the ability of a fluid (gas) to gather / release energy from / to the surface of a wall.
  - $\dot{Q} = \alpha_1 \cdot A \cdot (T_1 - T_{W1})$
  - α (unit $\frac{W}{m^2 \cdot K}$) can be specified by experiments using dimensionless numbers (e.g. Reynold's number).
  - α-value depends on:
    - Material properties (of the wall and of the fluid)
    - Fluid flow near the wall (higher turbulents result in better α)



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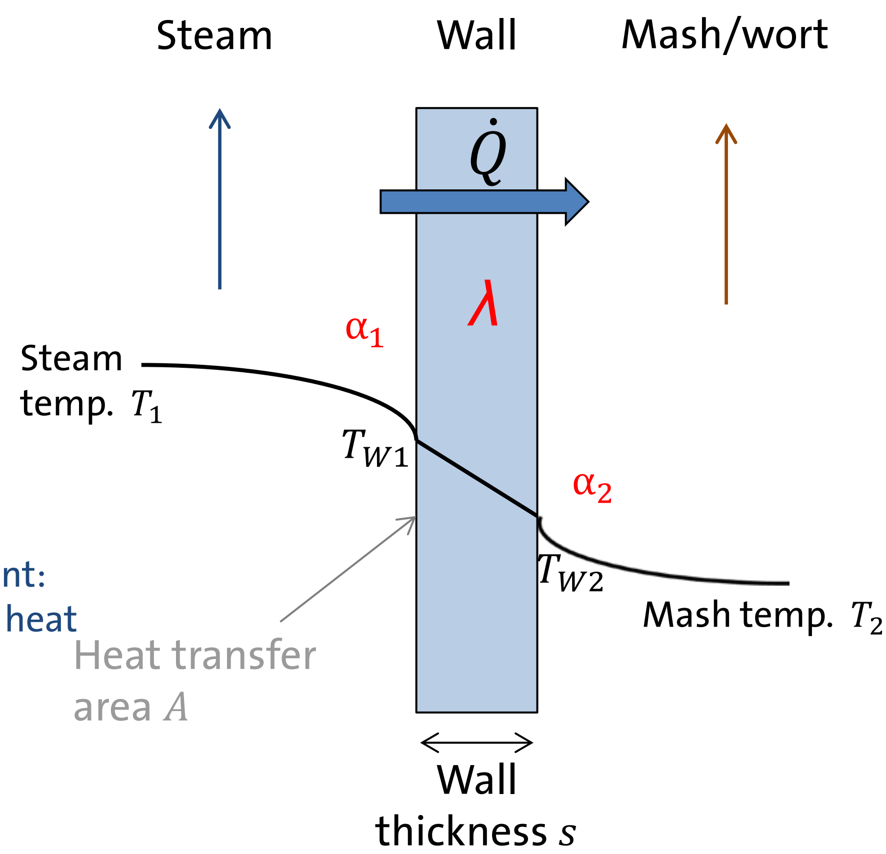
Heat Transfer

- **<u>The real heat transfer</u>:**
  - In real heating (and cooling!) processes, a combination of *conductivity* and *convection* takes place.
  - The whole heat transfer is characterized by the k-value.
  - $k = \frac{1}{\frac{1}{\alpha_1} + \frac{s}{\lambda} + \frac{1}{\alpha_2}}$
  - $\dot{Q} = k \cdot A \cdot (T_1 - T_2)$

Temperature gradient: The driving force of heat transfer

  - Conventional mash tuns obtain a k-value of $1{,}000 - 1{,}500\ \frac{W}{m^2 \cdot K}$

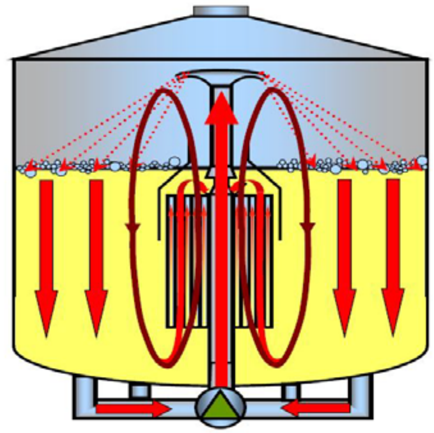


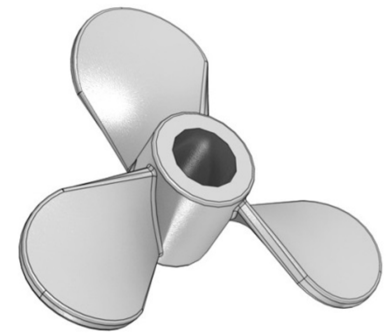
> The k-value is a dimension that estimates whether much or less heat is transferred

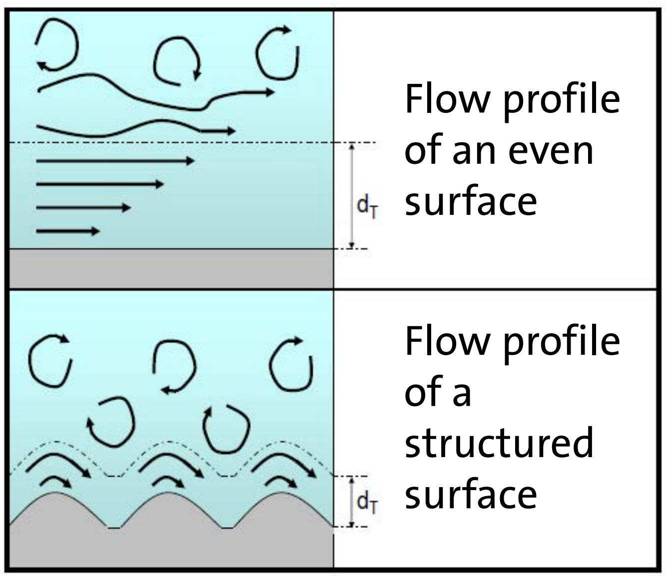
How can Brewers improve the k-value and the Heat Transfer?

- Basically, the higher the turbulences in the product and the heating medium, the better the k-value

- Possibilities for higher turbulences:
  - Proper agitation during mashing, including a fitting agitator shape (propeller mixer)
  - Special surface of the mash tun/kettle
    - Pillow Plates, increasing the heat exchange area (k-value: $2{,}000\,\frac{W}{m^2 \cdot K}$)
  - Using a circulation pump during boiling.
  - Avoid fouling and calcification! Correct and proper cleaning of the tanks is important!
  - Shape of the heating/cooling pipes.
  - Improved shape of the heat exchanger plates of the wort cooler or flash pasteurizer.







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Mashing

- Assumptions
  - Mash volume V: 58 hl or 5,800 l
  - Density of the mash ρ_M: 1.06 kg/l
  - Heat capacity of the mash c_p: $3.6 \frac{kJ}{kg \cdot K}$
  - Mash-in temperature T_{in}: 333 K (140 °F)
  - Transfer mash temperature T_{out}: 351 K (172 °F)
  - Heat transfer losses f_{loss}: 5%
  - Heating rate HR: 1 K/min

Can be decreased by improving the k-value!

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Mashing

- Which amount of heat is required?
  - General equation: $Q = m \cdot h$
  - Considering mash: $Q = m \cdot c_p \cdot \Delta T$
  - Considering $m = \rho \cdot V$: $Q = \rho_M \cdot V \cdot c_p \cdot (T_{out} - T_{in})$
  - Considering f_{loss}: $Q = \rho_M \cdot V \cdot c_p \cdot (T_{out} - T_{in}) \cdot f_{loss}$

$$Q = \rho_M \cdot V \cdot c_p \cdot (T_{out} - T_{in}) \cdot f_{loss} = 1.06\ \frac{kg}{l} \cdot 5{,}800\ l \cdot 3.6\ \frac{kJ}{kg \cdot K} \cdot (351\ K\ - 333\ K) \cdot 1.05 = 418{,}310\ kJ = 116.2\ kWh$$

> This calculation applies for every infusion-mashing. For more precise calculation, you need to know your exact material data and you have to find out you transfer losses

Mashing

- What amount of steam do you need to heat up the mash?

➢ The heat required from the mash must be served by the steam. Assuming we work with a saturated steam over pressure of 1 bar (equals 14.5 psi):

Enthalpy of condensation 2,206.1 kJ/kg

$$Q_{mash} = Q_{steam}$$
$$Q_{mash} = m_{steam} \cdot r_{1\,bar}$$
$$m_{steam} = \frac{Q_{mash}}{r_{1\,bar}} = \frac{418{,}310\ kJ}{2{,}206.1\ kJ/kg} = 189.6\ kg \text{ steam}$$

- The consideration for the thermal power during heating-up from one rest to another are analog.

Heating rate determines the thermal power (and vice versa)

$$\dot{Q}_{mash} = \dot{Q}_{steam}$$
$$\rho_M \cdot V \cdot c_p \cdot HR = \dot{m}_{steam} \cdot r_{1\,bar}$$
$$1.06\ \frac{kg}{l} \cdot 5{,}800\ l \cdot 3.6\ \frac{kJ}{kg \cdot K} \cdot 1\ \frac{K}{60s} = \dot{m}_{steam} \cdot 2{,}206.1\ \frac{kJ}{kg}$$
$$\dot{m}_{steam} = \frac{369\ kW}{2{,}206.1\ kJ/kg} = 0.167\ \frac{kg}{s} = 10\ \frac{kg}{min}$$

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Wort Boiling

- Example: External boiling: How often must the wort circulate to achieve the desired evaporation?

- Assumptions

  - The technology ensures an evaporation rate E of 6%/h
  - Density water ρ_{Water}: 965 kg/m³
  - Density wort ρ_{Wort}: 1,030 kg/m³
  - Specific heat $c_{p,Wort}$: $4.1 \frac{kJ}{kg \cdot K}$
  - Temperature difference ΔT between in- and outlet of the boiler: 5 K
  - Enthalpy of evaporation r: 2,250 kJ/kg

Density of wort at boiling-temperature. With increasing temperature, the density decreases.
=> Boiling-temperature means lower density

Wort Boiling

- Example: External boiling: How often must the wort circulate to achieve the desired evaporation?

- The number of cycles is defined by the wort flow and the cast out wort

$$n = \frac{\dot{V}_{wort}}{V_{cast\ out}}$$

- ***The thermal power of boiling power must be the same as the thermal power for evaporation.***

Must be the same!

$$\dot{Q}_{boiler} = \dot{V}_{wort} \cdot \rho_{Wort} \cdot c_{p,Wort} \cdot \Delta T$$

$$\dot{Q}_{evaporation} = V_{cast\ out} \cdot E \cdot \rho_{Water} \cdot r$$

Heat flow ($\dot{Q}$); Density wort (ρ_{Wort}); Heat capacity ($c_{p,Wort}$); Density water (ρ_{Water})

The evaporation rate always refers to the cast out wort

- Result:

$$n = \frac{E \cdot \rho_{Water} \cdot r}{\rho_{Wort} \cdot c_{p,Wort} \cdot \Delta T} = \frac{0.06\frac{1}{h} \cdot 965\frac{kg}{m^3} \cdot 2{,}250\ kJ/kg}{1{,}030\frac{kg}{m^3} \cdot 4.1\frac{kJ}{kg \cdot K} \cdot 5\ K} = 6.2\frac{1}{h}$$

➢ 7 cycles per hour required!

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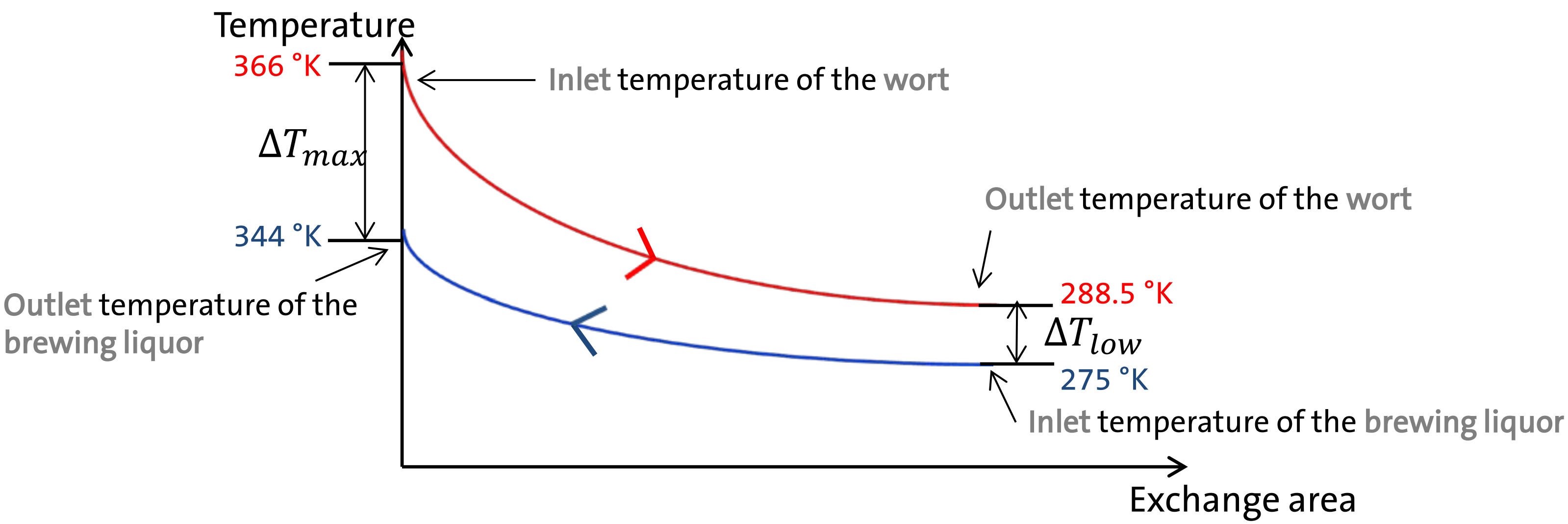
Wort Cooling

- While cooling down the wort, hot brewing liquor will be gained.
- For the configuration of a counter-flow plate exchanger, one has to consider the different temperatures of the water in different parts of the wort cooler.



- For that purpose, the average logarithmic temperature ΔT_{log} is used for calculations:

$$\Delta T_{log} = \frac{\Delta T_{max} - \Delta T_{low}}{\ln\left(\frac{\Delta T_{max}}{\Delta T_{low}}\right)}$$

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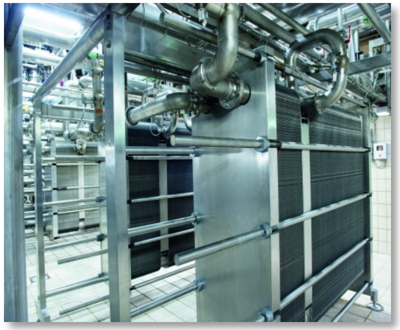

Wort Cooling

- Assumptions:
  - The wort gets chilled down from 200 to 60 °F (equals 366 to 288.5 K)
  - The brewing liquor's temperature rises from 36 to 165 °F (275 to 344 K)

➢ $\Delta T_{high} = 366\ K - 344\ K = 22\ K$

➢ $\Delta T_{low} = 288.5\ K - 275\ K = 13.5\ K$

$$\Delta T_{log} = \frac{\Delta T_{high} - \Delta T_{low}}{\ln\left(\frac{\Delta T_{high}}{\Delta T_{low}}\right)} = \frac{22\ K - 13.5\ K}{\ln\left(\frac{22\ K}{13.5\ K}\right)} = 17.4\ K$$

- Required thermal power:

$$\dot{Q} = \frac{\rho_{wort} \cdot V_{cast\ out} \cdot c_{p,wort} \cdot (T_{wort,inlet} - T_{wort,outlet})}{cooling\ time}$$

$$= \frac{1.03\ \frac{kg}{l} \cdot 5{,}800\ l \cdot 4.1\ \frac{kJ}{kg \cdot K} \cdot (366\ K - 288.5\ K)}{3{,}600\ s} = 527.3\ kW$$

- How much brewing liquor can be gained?

$$\dot{m}_{water} = \frac{\dot{Q}\quad \text{Thermal power}}{c_{p,water} \cdot (t_{water\ outlet} - t_{water\ inlet})} = \frac{527.3\ kW}{4.2\ \frac{kJ}{kg \cdot K} \cdot (344\ K - 275\ K)} = 6{,}550\ \frac{kg}{h}$$

$$= \mathbf{1,730\ \frac{gal}{h}}$$

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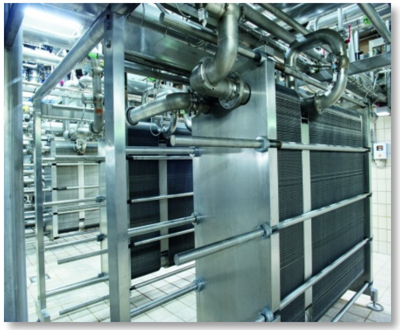
Wort Cooling



- Which exchange area is needed?

Required thermal power

$$A = \frac{\dot{Q}}{k \cdot \Delta T_{log}} = \frac{527.3\ kW}{3.0\ \frac{kW}{m^2 \cdot K} \cdot 17.4\ K} = 10.1\ m^2$$

Delta T log slide 28

Given by supplier

- In case that one plate has $0.4\ m^2$ exchange area:

$$Number\ of\ plates = \frac{10.1\ m^2}{0.4\ m^2} = 25.25 = 26\ plates!$$

> ➢ Those equations apply for any single-stage plate heat exchanger! That means, for example, that a flash pasteurizer can be calculated the same way. A two-stage heat exchanger can also be calculated like this by using other material properties and temperatures.

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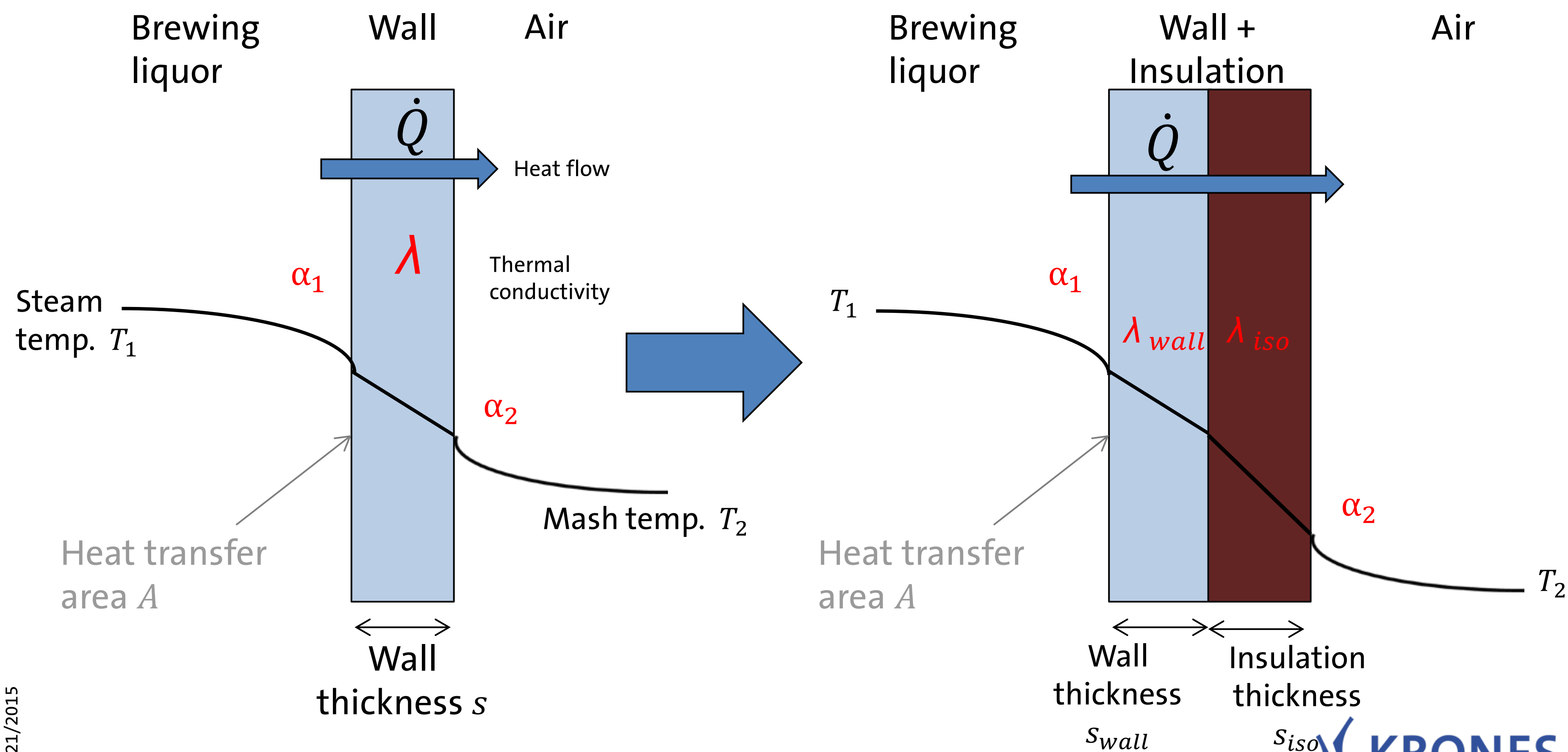
Importance of Tank Insulation

- Remember the situation of heat transfer through a wall (slide 19).
- How does the situation change, when the tank wall is insulated?



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Importance of Tank Insulation

- Without insulation:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{s}{\lambda} + \frac{1}{\alpha_2}} = \frac{1}{\frac{1}{300\,\frac{W}{m^2 \cdot K}} + \frac{0.03\,m}{15\,\frac{W}{m \cdot K}} + \frac{1}{13\,\frac{W}{m^2 \cdot K}}} = 12.16\,\frac{W}{m^2 \cdot K}$$

Convection coefficient (α_1); Thermal conductivity (λ)

- With insulation:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{s_{wall}}{\lambda_{wall}} + \frac{s_{iso}}{\lambda_{iso}} + \frac{1}{\alpha_2}} = \frac{1}{\frac{1}{300\,\frac{W}{m^2 \cdot K}} + \frac{0.03\,m}{15\,\frac{W}{m \cdot K}} + \frac{0.1\,m}{0.05\,\frac{W}{m \cdot K}} + \frac{1}{13\,\frac{W}{m^2 \cdot K}}}$$

$$= 0.48\,\frac{W}{m^2 \cdot K}$$

➢ About 25 times less heat loss due to insulation!

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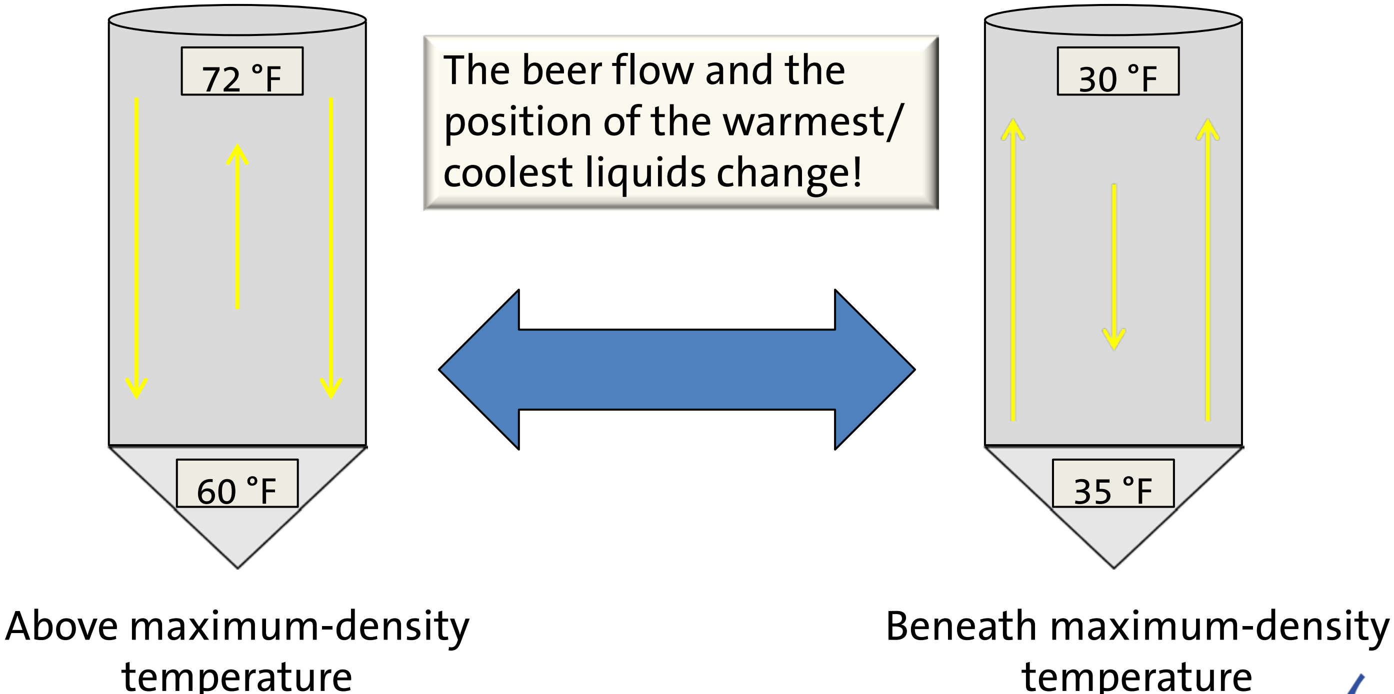
Fermentation

- Basic knowledge about circulation in the fermentation tanks
  - Beer has its highest density at about 37 °F (3 °C)
  - Due to different density-levels, there is a natural convection (circulation) in a fermentation tank
  - So, what happens during primary fermentation (>37 °F) and maturation (<37 °F) in the tank?



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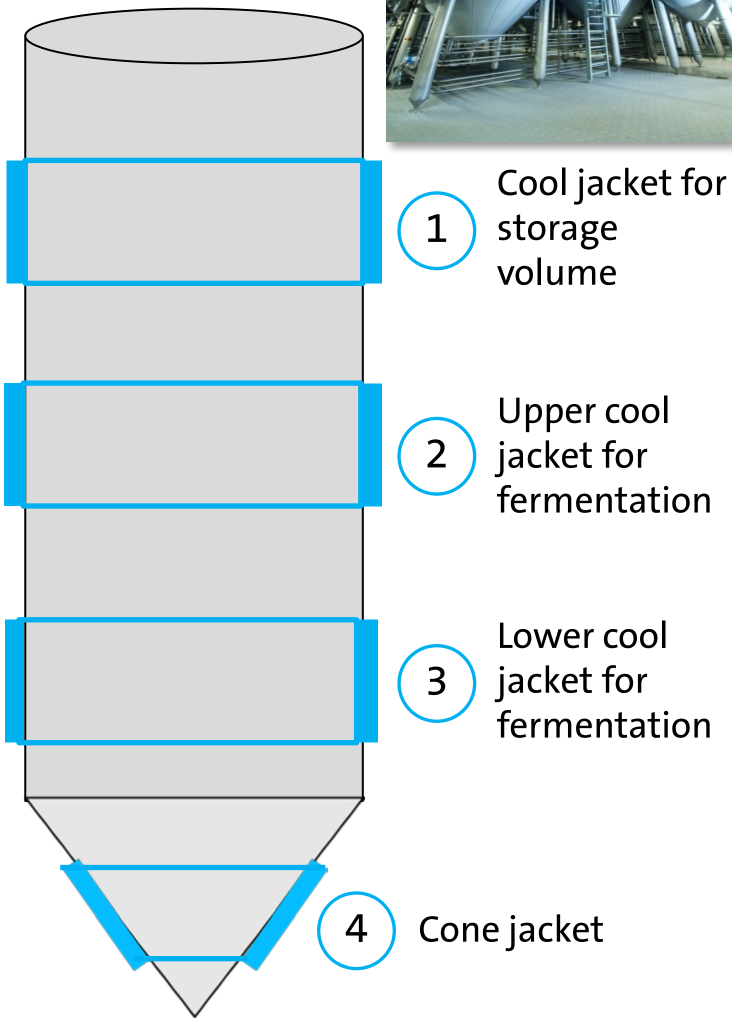
Fermentation

- During primary fermentation, the coolest liquid is at the bottom of the tank.
- During maturation, the warmest beer is at the bottom of the tank.
  - ➢ Cone jackets necessary!
- That fact is important to understand when the cooling jackets are switched on or off.
- During primary fermentation, the upper cool jacket has to be switched on (area 2).
- When the green beer gets chilled to maturating temperature, all cooling jackets have to be activated (1+2+3+4)
- After reaching maturation temperature, cooling the cone is sufficient (4).



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Fermentation

- Knowing the principles about cooling beer can prevent you from ice layers on fermentation tanks.
- Having thick ice layers does not mean your beer has got its must temperature.
- In fact, it is an evidence for erratic cooling and uneven temperature distribution is in the tank.
- This results in quality deviations of the beer. The fermentation and the beer taste is unsatisfying.
- Furthermore, formation of ice layers means a too high consumption of energy.
- Other reasons for ice layer formation might be:
  - Location of the cooling jackets
  - Placement of the temperature probe
  - False control of the flow of the coolant

Good idea

Bad idea

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Fermentation

- Which refrigerating energy and power is required from the refrigerating plant?

- Assumptions for calculating:
  - Fermentation and maturation temperatures.
  - Real density of the wort in the beginning: 12 °P (12%)
  - Real density of the wort after fermentation: 3 °P (3%)

    ΔE = 9%
  - Volume of green beer: 50 bbl
  - Radiation and heat insertion from environment neglected.
  - Material properties supposed (c_p, ρ)
  - $e = 587 \frac{kJ}{kg}$

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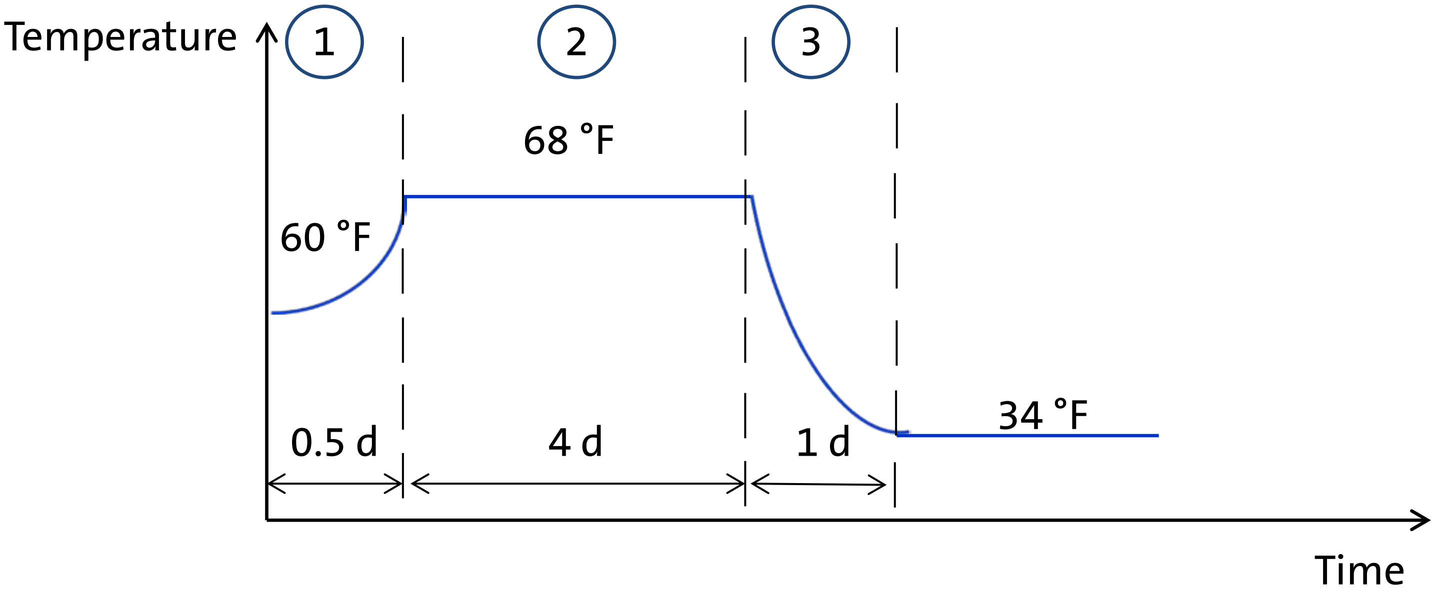
Fermentation



(1) No cooling energy required! During respiration and fermentation, yeast releases heat that helps to reach the primary fermentation temperature within a day.

(2) Primary fermentation temperature is reached and fermentation heat has to be discharged. The yeast produces $e = 587$ kJ per kg fermentable sugar.

(3) Cooling down the green beer to maturation temperature determines the necessary power of the refrigerating plant.

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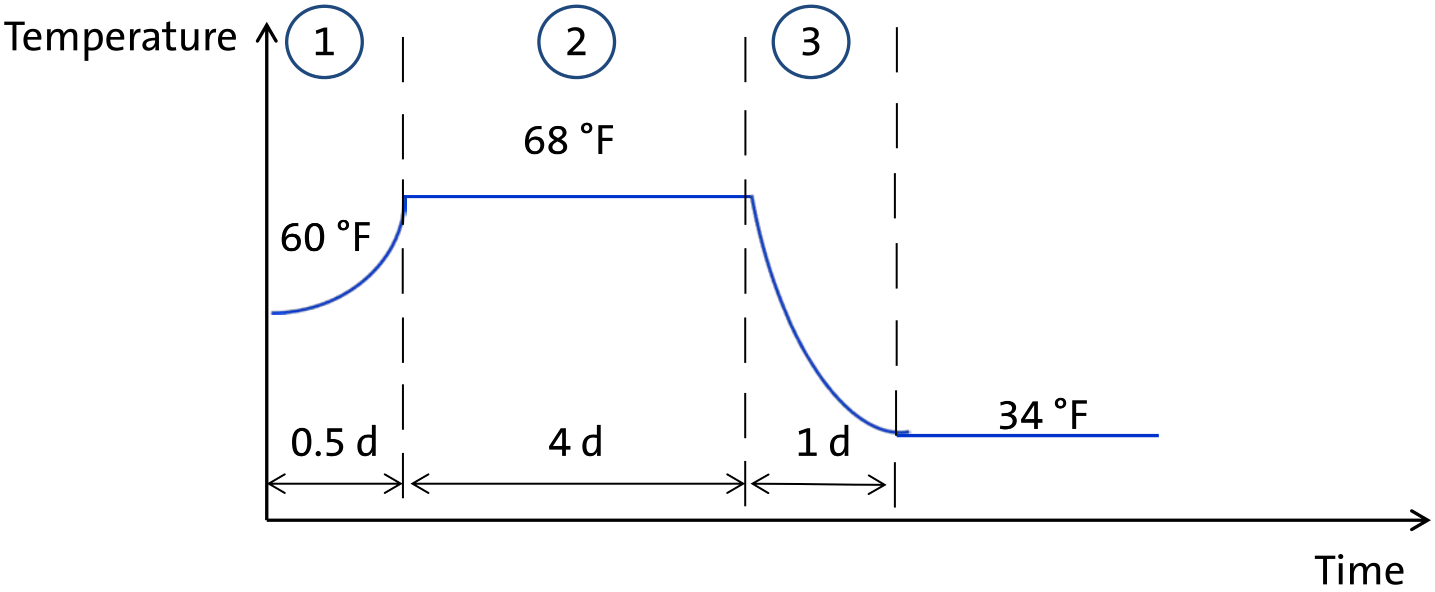
Fermentation



1 No cooling energy required! During respiration and fermentation, yeast releases heat that helps to reach the primary fermentation temperature within a day.

Fermentation

- Energy gained while heating up to primary fermentation temperature:

1

$$\boldsymbol{Q_1 = \rho_{wort} \cdot V \cdot c_{p,wort} \cdot \left(T_{start} - T_{fermentation}\right)}$$

$$= 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 4.04\,\frac{kJ}{kg \cdot K} \cdot (288.5\,K - 293\,K) = -108{,}607 = -30\,kWh$$

Negative because that is no energy we have to insert!

- Energy, that has to be discharged during primary fermentation:

2

$$\boldsymbol{Q_2 = \underbrace{\rho_{wort} \cdot V}_{m} \cdot \underbrace{\Delta E \cdot e}_{h}} = 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 0.09 \cdot 587\,\frac{kJ}{kg} = 315{,}606\,kJ = 87.7\,kWh$$

- Energy needed to cool down to maturation temperature:

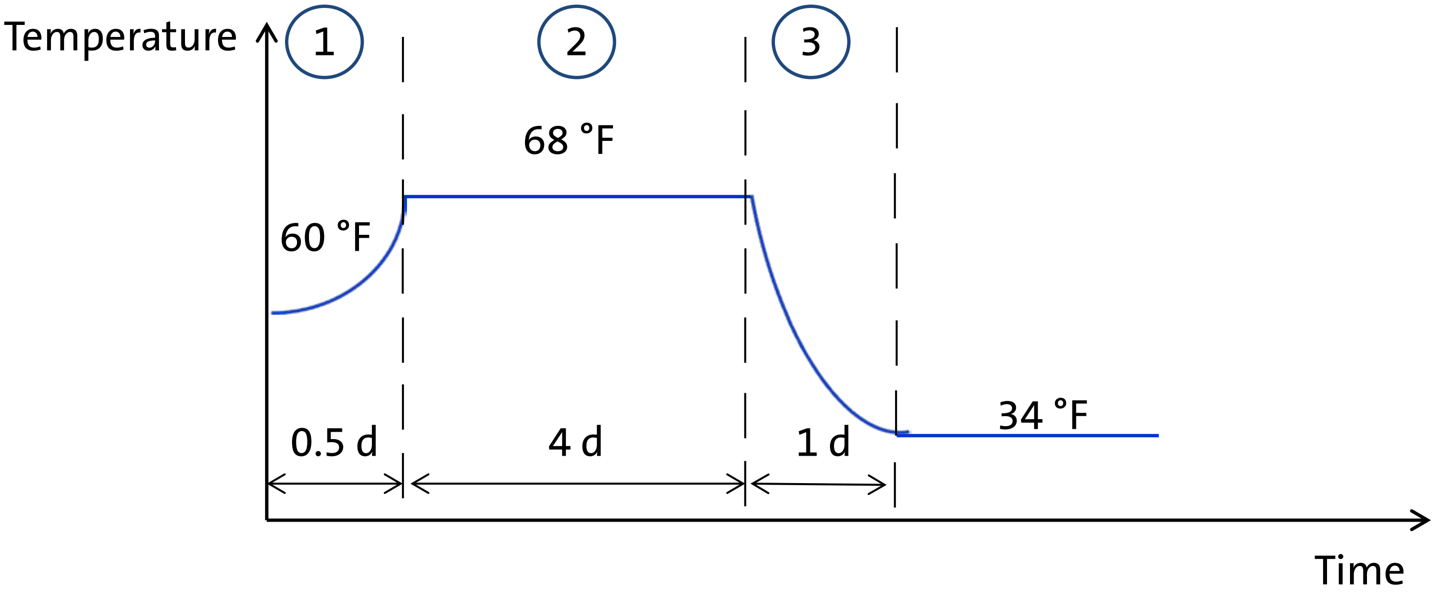
$$\boldsymbol{Q_3 = \rho_{wort} \cdot V \cdot c_{p,wort} \cdot \left(T_{fermentation} - T_{maturation}\right)}$$

3

$$= 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 4.04\,\frac{kJ}{kg \cdot K} \cdot (293\,K - 274\,K) = 458{,}564\,kJ = 127.4\,kWh$$

> Note: In reality, the density and the specific heat would change during the whole process. But the differences are very small, so they can be ignored. The values can be considered as constant. Additionally, we must not forget the temperature difference between the environment and the tank content during the real process!

Fermentation



2

Cooling down the green beer to maturation temperature determines the necessary power of the refrigerating plant.

Fermentation

- Energy gained while heating up to primary fermentation temperature:

(1)

$$\boldsymbol{Q_1 = \rho_{wort} \cdot V \cdot c_{p,wort} \cdot \left(T_{start} - T_{fermentation}\right)}$$

$$= 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 4.04\,\frac{kJ}{kg \cdot K} \cdot (288.5\,K - 293\,K) = -108{,}607 = -30\,kWh$$

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- Energy, that has to be discharged during primary fermentation:

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$$\boldsymbol{Q_2 = \underbrace{\rho_{wort} \cdot V}_{m} \cdot \underbrace{\Delta E \cdot e}_{h}} = 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 0.09 \cdot 587\,\frac{kJ}{kg} = 315{,}606\,kJ = 87.7\,kWh$$

- Energy needed to cool down to maturation temperature:

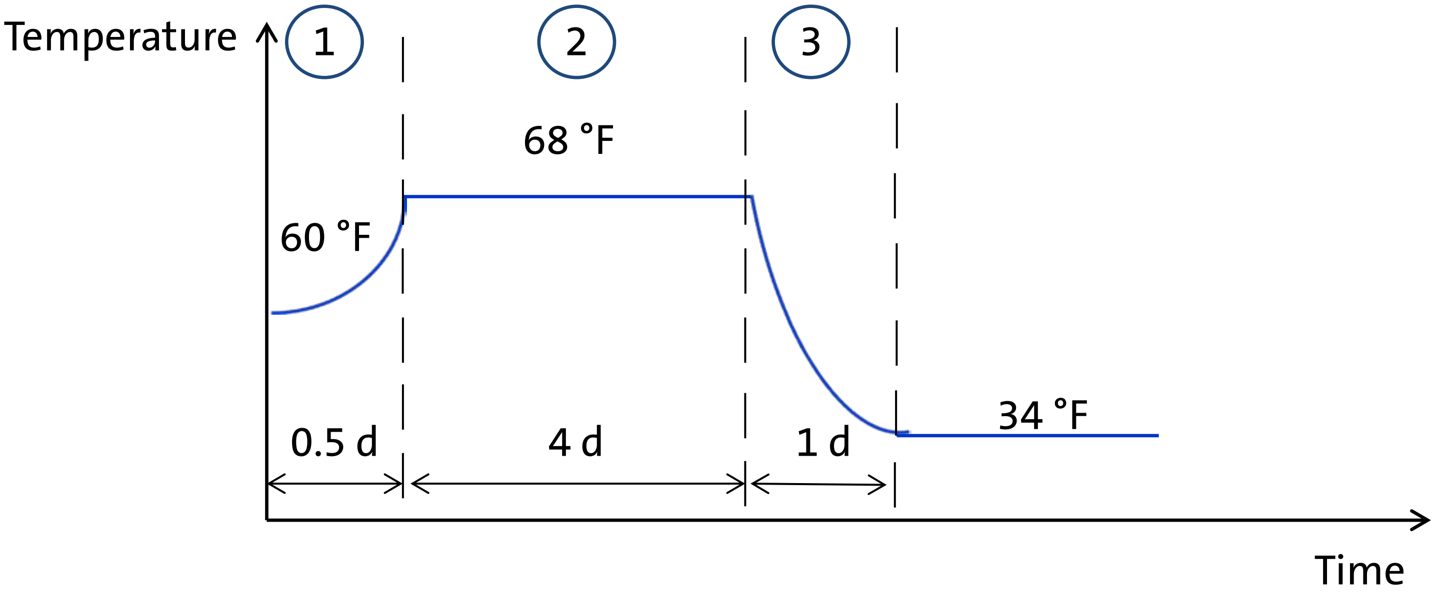
(3)

$$\boldsymbol{Q_3 = \rho_{wort} \cdot V \cdot c_{p,wort} \cdot \left(T_{fermentation} - T_{maturation}\right)}$$

$$= 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 4.04\,\frac{kJ}{kg \cdot K} \cdot (293\,K - 274\,K) = 458{,}564\,kJ = 127.4\,kWh$$

> ➢ Note: In reality, the density and the specific heat would change during the whole process. But the differences are very small, so they can be ignored. The values can be considered as constant. Additionally, we must not forget the temperature difference between the environment and the tank content during the real process!

Fermentation



3 Cooling down the green beer to maturation temperature determines the necessary power of the refrigerating plant.

Fermentation

- Energy gained while heating up to primary fermentation temperature:

(1)

$$\boldsymbol{Q_1 = \rho_{wort} \cdot V \cdot c_{p,wort} \cdot \left(T_{start} - T_{fermentation}\right)}$$

$$= 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 4.04\,\frac{kJ}{kg \cdot K} \cdot (288.5\,K - 293\,K) = -108{,}607 = -30\,kWh$$

Negative because that is no energy we have to insert!

- Energy, that has to be discharged during primary fermentation:

(2)

$$\boldsymbol{Q_2 = \underbrace{\rho_{wort} \cdot V}_{m} \cdot \underbrace{\Delta E \cdot e}_{h}} = 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 0.09 \cdot 587\,\frac{kJ}{kg} = 315{,}606\,kJ = 87.7\,kWh$$

- Energy needed to cool down to maturation temperature:

(3)

$$\boldsymbol{Q_3 = \rho_{wort} \cdot V \cdot c_{p,wort} \cdot \left(T_{fermentation} - T_{maturation}\right)}$$

$$= 1.03\,\frac{kg}{l} \cdot 5800\,l \cdot 4.04\,\frac{kJ}{kg \cdot K} \cdot (293\,K - 274\,K) = 458{,}564\,kJ = 127.4\,kWh$$

> Note: In reality, the density and the specific heat would change during the whole process. But the differences are very small, so they can be ignored. The values can be considered as constant. Additionally, we must not forget the temperature difference between the environment and the tank content during the real process!

Fermentation

- **Combining the three equations delivers the total amount of cooling energy:**

$$Q_{total} = Q_1 + Q_2 + Q_3 = -30\ kWh + 87.7\ kWh + 127.4\ kWh = 185.1\ kWh$$

- **The required refrigeration power is determined by maturation temperature and the desired time to reach this temperature.**

$$\dot{Q}_{refrigeration} = \frac{Q_3}{time} = \frac{127.4\ kWh}{24\ h} = 5.3\ kW$$

- **Assuming we use direct vaporization to cool the fermenter, which amount of ammonia do we need? (Using indirect cooling with water: same calculation as shown in section "Mashing")**

$$\dot{Q}_{refrigeration} = \dot{m}_{ammonia} \cdot r_{ammonia} \Rightarrow \dot{m}_{ammonia} = \frac{\dot{Q}_{refrigeration}}{r_{ammonia}} = \frac{5.3\ kW}{1{,}300\ \frac{kJ}{kg}} = 0.004\ \frac{kg}{s} = 14.7\ kg/h$$

> ➢ Note: The calculations were made for ONE fermentation tank. If there are more tanks that have to be cooled down at once you need times more refrigeration power and ammonia flow.

Table of Content

KRONES

Final Remarks

- As we can find heat transfer everywhere in the brewery, brewers should know about the basics of thermodynamics.
- Those basics lead to equations to calculate the required heat/cold and thermal power of a process.
- That not only helps you to appraise energy consumption, but also to recognize potential for savings.
- We discussed practical applications for the main operations during the brewing process.
- The calculations should not be seen as total but they give you a close idea in which regions you operate. Include a safety factor in your calculations (5-10%)!

Thanks for your attention!

KRONES