4. Heat exchangers;
Steam, steam processes

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4.1 Heat exchangers
Heat exchangers: General /1

- In a heat exchanger heat is transferred from one (hotter) material or material flow to another (cooler) one.
- In most applications operated under steady-state conditions, for heat exchange between fluid flows.
- External walls are well insulated to avoid heat losses to the environment (except for most air cooling systems).

A shell-and-plate heat exchanger; widely used in power plants, oil refineries and chemical process plants.

picture: http://www.secshellandtube.com/model-info.html

Heat exchangers: General /2

- Also batch heat exchangers are widely used.
- Phase transitions are possible, for example in evaporators or condensors (and some applications involving solids).
- Typical every-day-life examples:
  - Cooking equipment
  - Refrigerators
  - Car radiator
  - Air conditioning systems

A plate-and-frame heat exchanger; also widely used in food-processing industry.

picture: http://www.heatexchangers.org/
Heat exchangers: Geometries /1

Schematics for
(a) counterflow,
(b) parallel flow,
(c) crossflow,
(d) 1 shell and 2
tube passes, and
(e) 2 shell and 4
tube passes.

pictures: KJ05

Heat exchangers: Geometries /2

Temperature distributions
of fluid in
(a) counterflow,
(b) parallel flow, and
(c) 1 shell pass and 2 tubes
passes.

Schematic of mixed and unmixed
flow heat exchangers:
(a) One fluid mixed, one fluid
unmixed, (b) both fluids unmixed.

pictures: KJ05
Heat exchangers: Geometries

Temperature distribution in a counter-flow heat exchanger.

Note: the exit temperature \( T_{C,o} \) of the cold stream can be higher than the exit temperature \( T_{H,o} \) of the hot stream!

picture: KJ05

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Heat exchangers: energy balance

If energy losses to the environment are avoided, the energy balance for both the cold and the hot stream are, (noting that no work is done,) using enthalpy \( h \) to include pV-effects ("flow work"), \( Q = \Delta H \)

\[
\dot{Q}_{\text{cold}} = \dot{\Delta}H_{\text{cold}} = - \dot{\Delta}H_{\text{hot}} = - \dot{Q}_{\text{hot}}
\]

\[
\dot{\Delta}H_{\text{cold}} = \dot{m}_{\text{cold}} \cdot (h_{\text{cold, out}} - h_{\text{cold, in}}) = \dot{m}_{\text{hot}} \cdot (h_{\text{hot, in}} - h_{\text{hot, out}}) = - \dot{\Delta}H_{\text{hot}}
\]

Often (modest temperature differences) it can be simplified to

\[
\dot{m}_{\text{cold}} \cdot c_{p,\text{cold}} \cdot (T_{\text{cold, out}} - T_{\text{cold, in}}) = \dot{m}_{\text{hot}} \cdot c_{p,\text{hot}} \cdot (T_{\text{hot, in}} - T_{\text{hot, out}})
\]

Picture: SEHB06
Overall heat transfer coefficient

- The heat transfer process* may be described by a simple expression

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

for temperature difference \( \Delta T \) (°C), heat exchange area \( A \) (m\(^2\)) and **overall heat transfer coefficient** \( U \) (W/(m\(^2\)·K))

- \( U \) is a combination of several heat transfer resistances

* see also Chapter 5

pictures: KJ05

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Heat exchanger analysis /1

The LMTD method

- Heat exchanger performance depends on how much heat exchange area \( A \) (in m\(^2\)) is needed to transfer a certain heat rate \( \dot{Q} \) (J/s = W)

- For a small section \( dx \) of the tube (with diameter \( D \)), the heat transfer \( \delta \dot{Q} \) equals

\[ \delta \dot{Q} = U \cdot (T_H - T_C) \cdot dA, \]

with \( dA = \pi D \cdot dx \) for this geometry and overall heat transfer coefficient \( U \)

- \( (T_H - T_C) \) may vary!
Heat exchanger analysis /2
The LMTD method

- With average temperature difference \( \Delta T = <T_H - T_C> \) for the heat exchanger length, the heat rate can be expressed as
  \[
  \dot{Q} = <U> \cdot A \cdot \Delta T
  \]

- If it can be assumed that \( U \approx \text{constant} \), a linearisation may be used, with \( \Delta T_1 = (T_{H,i} - T_{C,o}) \) at position "1" and \( \Delta T_2 = (T_{H,o} - T_{C,i}) \) at position "2":
  \[
  T_H - T_C = \Delta T = \Delta T(x) = \Delta T_1 + \frac{x}{L} (\Delta T_2 - \Delta T_1)
  \]

  With \( \delta \dot{Q} = U \cdot (T_H - T_C) \cdot dA \rightarrow A = \int_0^L \frac{\delta \dot{Q}}{U \cdot (T_C - T_H)} \),

  this integrates to
  \[
  \dot{Q} = U \cdot A \cdot \frac{(\Delta T_2 - \Delta T_1)}{\ln \left( \frac{\Delta T_2}{\Delta T_1} \right)} = U \cdot A \cdot \Delta T_{lm}
  \]
  with "lm" short for "logarithmic mean".

Heat exchanger analysis /3
The LMTD method

- For a single-pass counter-flow heat exchanger the design value \( U \cdot A \) follows from \( U \cdot A = \dot{Q} / \Delta T_{lm} \)

- However, in process engineering practice most heat exchangers are NOT of this type, having several "shell passes" and "tube passes".

- For these designs a correction factor \( F \) is applied, using the heat balance \( Q = <U> \cdot A \cdot F \cdot \Delta T_{lm} \) in the analysis given above for a single-pass counter-flow heat exchanger: \( U \cdot A = \dot{Q} / (F \cdot \Delta T_{lm}) \)

- The \( F \) correction factor is found from design graphs: see for example next slide

- For an economically feasible design \( F > 0.75 \)
Heat exchanger analysis

The LMTD method:

*F* correction factor

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F correction factors for several heat exchanger types:

**Left:** Shell-and-tube with one shell pass and any multiple of two tube passes (two, four, etc. tubes passes)

**Right:** Shell-and-tube with two shell passes and any multiple of four tube passes (four, eight, etc. tube passes).

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**Example: LMTD method**

- A 1 shell pass, 2 tube pass heat exchanger is operated with hot fluid in/out temperatures \( T_1 = 182°C \), \( T_2 = 99°C \) and cold fluid (inside the tubes) in/out temperatures \( t_1 = 10°C \) and \( t_2 = 115 °C \)

  Calculate \( \Delta T_{lm} \) and the *F* correction factor.
4.2 Evaporators and condensers

Condensers

- Condensers are used to liquify vapors; the condensation heat (or "latent heat") is absorbed by a coolant (often water).

- Usually "plate-and-shell" condensers are used ("plate-and-frame" units may show vapor leakage), with four main types:
  1. **Horizontal** / condensation on the **outside** of the tubes
  2. **Vertical** / condensation on the **outside** of the tubes
  3. **Horizontal** / condensation on the **inside** of the tubes
  4. **Vertical** / condensation on the **inside** of the tubes

Most used is 1.; for condensing a high pressure or temperature or corrosive vapor type 4. is used. (Types 2. and 3. are more typically used in evaporators.)

- Also used are contact condensers where coolant and vapor are mixed and leave the condenser as a single stream.
Evaporators

- Evaporators are used to concentrate a solution of a non-volatile solute and a volatile solvent (in most cases the solvent is water). One application is to produce a slurry of crystals in a saturated mother liquid. Another very important application is as reboiler for partial evaporation of distillation column bottom liquid.

- Most common are (low pressure) steam-heated vertical-tube evaporators, with the boiling liquid inside the tubes under a moderate vacuum. The boiling liquid may run upwards or downwards.

- To reduce equipment size, often a drum is added for vapor / liquid separation.

4.3 Heat exchanger efficiency; "effectiveness"; remarks on selection

pictures: TUD86
Heat exchanger efficiency

- A simple steady-state heat transfer process; heat is transported from medium 1 to medium 2 by conduction through a material that separates them.
- Temperature $T_1 > T_2$

Thermodynamic analysis

- Energy balance
  $$\dot{Q}_1 = \dot{Q}_2$$
- Entropy balance
  $$\frac{\dot{Q}_1}{T_1} + \dot{S}_{\text{gen}} = \frac{\dot{Q}_2}{T_2} \Rightarrow \dot{S}_{\text{gen}} = \dot{Q}_1 \left( \frac{1}{T_2} - \frac{1}{T_1} \right) = \dot{Q}_1 \frac{T_1 - T_2}{T_1 T_2} > 0$$

- This shows that $S_{\text{gen}}$ is large for large temperature differences $(T_1 - T_2)$ and low temperatures $T_1$ and $T_2$

Heat exchanger effective performance

- Heat exchanger efficiency (2nd Law) analysis shows that the temperature difference between the flows (or with the flow, for only on medium flow) should be as small as possible (but too small $\Delta T$ requires much surface $A$!).

- This shows that counter-current heat exchangers perform much better than co-current heat exchangers.
Heat exchanger effective performance /2

- Ideally, the flows acquire each other's temperature: the exergy losses will then be zero. For this, the heat capacity rates $\dot{m}_C \cdot c_p$ for the hot (H) and cold (C) streams should be equal: $\dot{m}_C \cdot c_{pC} = \dot{m}_H \cdot c_{pH}$.

- This is anyhow a requirement for a high "effectiveness" of the heat exchanger, which depends on the ratio $(\dot{m}_C \cdot c_{pC}) / (\dot{m}_H \cdot c_{pH})$.

Heat exchanger effectiveness /1

- The effectiveness of a given heat exchanger can be defined as (for cold stream "C" and hot stream "H")

  $$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\text{max}}} \quad \text{where} \quad \dot{Q} = C_C \cdot \Delta T_C = C_H \cdot \Delta T_H$$

  with heat capacity rates $C_C = \dot{m}_C \cdot c_{pC}$ and $C_H = \dot{m}_H \cdot c_{pH}$

  comparing the actual heat transfer with the maximum possible for the given geometry and material flows.

- Defining the minimum and maximum heat capacity rates $C_{\text{min}}$ and $C_{\text{max}}$ as

  $$C_{\text{min}} = \min\{\dot{m}_C \cdot c_{pC} , \dot{m}_H \cdot c_{pH}\} \quad \text{and} \quad C_{\text{max}} = \max\{\dot{m}_C \cdot c_{pC} , \dot{m}_H \cdot c_{pH}\}$$

  and since $\Delta T$ is largest for small $C = \dot{m} \cdot c_p$ (see next slide)

  $$\dot{Q}_{\text{max}} = C_{\text{min}} \cdot (T_{\text{H,in}} - T_{\text{C,in}})$$
Heat exchanger effectiveness /2

- The maximum possible temperature change in any of the fluid flows would be \((T_{H,\text{in}} - T_{C,\text{in}})\): 

In a counterflow heat exchanger, the minimum fluid undergoes the greater temperature change from inlet to outlet. If the cold fluid is the minimum \((C_C < C_H)\), the maximum possible heat exchange occurs when \(T_{C,\text{out}} = T_{H,\text{in}}\) (top). If the hot fluid is the minimum \((C_H < C_C)\), then the maximum possible heat transfer occurs when \(T_{H,\text{out}} = T_{C,\text{in}}\).

Heat exchanger effectiveness /3

- The \(\varepsilon\)-NTU method relates the effectiveness to the number of transfer units \(NTU\) of the heat transfer process and the ratio of the heat capacity rates \(C^*\), defined as:

\[
NTU = \frac{U \cdot A}{C_{\text{min}}} \quad \text{and} \quad C^* = \frac{C_{\text{min}}}{C_{\text{max}}}
\]

- A transfer unit ~ distance \(\Delta L\) of the heat exchanger tubings where \(T_C(x+\Delta L) = T_H(x)\) along axis \(x\).

(Total heat exchange surface \(A \approx \pi \cdot D \cdot \Delta L \cdot NTU\) for round tubes.)

- For an existing heat exchanger the geometry, flows and specific heats of the flows give the effectiveness.

- Relations that give \(\varepsilon = f(NTU, C_{\text{min}}, \text{geometry etc.})\) can be found in tables, or diagrams can be used; see \(\rightarrow\):
Heat exchanger effectiveness

- **Top:** parallel flow (left) and counter flow (right) single tube HEs
- **Bottom:** one (left) and many (right) (2, 4, 6,...) shell-passes and multiple of 2 tube passes

*pictures: T06*

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Heat exchanger effectiveness

<table>
<thead>
<tr>
<th>Type of Heat Exchanger</th>
<th>Effectiveness relations</th>
<th>NTU relations</th>
</tr>
</thead>
<tbody>
<tr>
<td>All exchangers</td>
<td>$\varepsilon = 1 - \exp(-\text{NTU})$</td>
<td>$\text{NTU} = -\ln(1 - \varepsilon)$</td>
</tr>
<tr>
<td>Double pipe Counter flow</td>
<td>$\varepsilon = \frac{1 - \exp[-\text{NTU}(1 + C^<em>)]}{1 - C^</em> \exp[-\text{NTU}(1 + C^*)]}$</td>
<td>$\text{NTU} = \frac{1}{C^* - 1} \ln\left(\frac{\varepsilon - 1}{C^* - 1}\right)$</td>
</tr>
<tr>
<td>Parallel flow</td>
<td>$\varepsilon = \frac{1 - \exp[-\text{NTU}(1 + C^<em>)]}{1 + C^</em>}$</td>
<td>$\text{NTU} = -\ln\left[1 - \varepsilon(1 + C^<em>)\right] \frac{1}{1 + C^</em>}$</td>
</tr>
</tbody>
</table>

*table: KJ05*

- Common equations for effectiveness and NTU
Heat exchanger effectiveness /5b

<table>
<thead>
<tr>
<th>Type of Heat Exchanger</th>
<th>Effectiveness relations</th>
<th>NTU relations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell-and-tube</td>
<td>$\varepsilon_1 = \frac{2}{(1 + C^<em>) + (1 + C^</em>)^{0.5}} \left(1 - \exp[-NTU \sqrt{1 + C^*}] \right)$</td>
<td>$NTU = \frac{1}{(1 + C^*)^{0.5}} \ln \left( \frac{E - 1}{E + 1} \right)$</td>
</tr>
<tr>
<td>One-shell pass;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2, 4, 6, ... tube</td>
<td></td>
<td></td>
</tr>
<tr>
<td>passes; (TEMA E shell)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$-shell passes;</td>
<td>$\varepsilon = \left[ \left( \frac{1 - \varepsilon_1 C^<em>}{1 - \varepsilon_1} \right)^x \right] \left[ \left( \frac{1 - C^</em>}{1 - \varepsilon_1} \right)^y - C^* \right]^{-1}$</td>
<td>Use above two equations with $\varepsilon_2 = \frac{F - 1}{F - C^<em>} F = \left( \frac{C^</em> - 1}{\varepsilon - 1} \right)^{1/n}$</td>
</tr>
<tr>
<td>2$n$, 4$n$, 6$n$, ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tube passes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Common equations for effectiveness and NTU

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Heat exchanger effectiveness /6

- Comparison of effectiveness for counterflow, crossflow, multipass, and parallel flow heat exchangers (for $C^* = 1.0$).
- This comparison shows that a counter-flow HE always has the highest effectiveness while a parallel flow HE always gives the lowest.

![Graph showing effectiveness vs NTU for different flow configurations](image: KJ05)
Heat exchanger selection

- The heat effects of phase transitions (boiling/condensing) can be quite large and for a pure substance take place at a constant temperature.

- The choice for a certain design is based on 3 things:
  - The value $U \cdot A$; for a given value for the overall heat transfer coefficient $U$, the heat exchange area $A$ determines the diameter $d$, length $L$ and number $n$ of tubes needed.
  - The pressure drop of the flows through the device (which means an energy penalty).
  - The economics of material costs, footprint, heat losses, .....

- Note that fouling has an effect not only on $U$ but also on operation and maintenance costs.

4.4 Power production*

* Often by mistake referred to as "energy production"
Power (+ heat) production

- **Combustion of fuel (or waste) in a furnace** → production of steam in a boiler → production of electricity in a steam turbine + generator
- **Combustion of fuel in an engine** → production of electricity in a steam turbine + generator OR motion of a vehicle
- **Combustion of fuel in a gas turbine** → production of electricity in generator
- **Nuclear reaction in nuclear reactor** → steam production → production of electricity in a steam turbine + generator
- **Combustion (oxidation) of fuel in a fuel cell** → direct conversion of chemical energy into electricity

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Power (+ heat) production

- **Using height differences in (large) rivers or between lakes in a hydropower station** → production of electricity in a turbine + generator
- **Solar radiation energy** → conversion into heat (→ hot water) and/or electricity using a photovoltaic convertor
- **Kinetic energy in wind** → production of electricity in a wind power generator
- **Kinetic energy in tides and strong water currents** → production of electricity in a wave or tide power generator
Heat exchangers in a condensing power plant

Furnace  
Boiler  
Superheater  
Economiser  
Air preheater  
Ambient air

Fuel  
Boiler water

Steam  
Flue gas

Schematic of a Rankine power cycle

A typical condensing power plant

Liquid-vapor dome for water/steam to be discussed in next section

Picture after ÖS96  
p. 30 (note correction!)
**Example:** power plant cooling process

- A power plant is cooled using river water. **Calculate** the required mass flow rate $\dot{m}$ of the cooling water.

  specific heat river water $c_p = 4.19 \text{ kJ/kgK}$

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4.5 Steam properties; Steam processes
Properties of pure substances /1

Solid, liquid and vapour states in a p,V,T surface

Properties of pure substances /2

p,V,T diagram, p,T diagram and p,V diagram of a substance that expands on freezing, such as water

Water:
critical point
+374.15°C, 22.12 MPa
Triple point
+0.01°C, 0.6112 kPa
pictures: KJ05
Condensation of a gas at constant pressure

When cooled to low enough temperatures, gases condense into liquids. In the cooling process above, liquid droplets start to form at point C where a saturated (sv: mättad) vapour exists. Further cooling along CDE gives a two-phase mixture (droplets in gas) until at point E a saturated liquid is obtained.

At higher pressures, saturation occurs at higher temperatures (C' versus C) and smaller specific volumes (i.e. higher density).
Connecting, for different pressures, the saturation points for the gas (C, C', C'', ...) gives the **saturated vapour line**; similarly the saturation points for the liquid (E, E', E'', ...) gives the **saturated liquid line**. These lines come together at the **critical point**, on what is called the **liquid-vapour dome** (sv: kupol).
Properties of pure substances /7
Condensation of a gas: mixture quality

Under the liquid-vapour dome, a two-phase (liquid-vapour) mixture exists; the quality, \(0 \leq x \leq 1\), of this mixture is defined as the mass fraction vapor in the mixture:

\[
x = \frac{m_{\text{gas}}}{m_{\text{gas}} + m_{\text{liquid}}} = \frac{m_v}{m_v + m_L} \\
= \frac{m_g}{m_g + m_f}
\]

(with "f" from German "flüssig")

Note that \(x\) is a thermodynamic property, like \(p, T, v, u, h, s\)
Properties of pure substances /8

Condensation of a gas: mixture quality

\[ x = \frac{m_{\text{gas}}}{m_{\text{gas}} + m_{\text{liquid}}} = \frac{m_{V}}{m_{V} + m_{L}} \]

\[ x = \frac{m_{g}}{m_{g} + m_{f}} \] (with "f" from german "flüssig")

With specific volume \( v = V/m \) \((= 1/density !)\) this gives for \( x \):

\[ v = \frac{V_{\text{total}}}{m_{\text{total}}} \; ; \; v_{L} = \frac{V_{L}}{m_{L}} \; ; \; v_{V} = \frac{V_{V}}{m_{V}} \; \text{and} \; V_{\text{total}} = V_{L} + V_{V} \]

\[ v \cdot m_{\text{total}} = v_{L} \cdot m_{L} + v_{V} \cdot m_{V} \; \Rightarrow \; v = v_{L} \cdot \frac{m_{L}}{m_{\text{total}}} + v_{V} \cdot \frac{m_{V}}{m_{\text{total}}} \]

\[ v = (1-x) \cdot v_{L} + x \cdot v_{V} \; \text{or} \; x = \frac{v - v_{L}}{v_{V} - v_{L}} = \frac{v - v_{L}}{v_{LV}} \]

or with other notation \( v = (1-x) \cdot v_{f} + x \cdot v_{g} \) or \( x = \frac{v - v_{f}}{v_{g} - v_{f}} = \frac{v - v_{f}}{v_{fg}} \)

Properties of pure substances /9

- For a system with total mass \( m \) with internal energy \( u = U/m \), enthalpy \( h = H/m \), entropy \( s = S/m \) the value for the mixture in the two phase region can be calculated the same way:

\[ u = (1-x) \cdot u_{L} + x \cdot u_{V} \; \text{or} \; u = (1-x) \cdot u_{f} + x \cdot u_{g} \]

\[ h = (1-x) \cdot h_{L} + x \cdot h_{V} \; \text{or} \; h = (1-x) \cdot h_{f} + x \cdot h_{g} \]

\[ s = (1-x) \cdot s_{L} + x \cdot s_{V} \; \text{or} \; s = (1-x) \cdot s_{f} + x \cdot s_{g} \]

\[ x = \frac{m_{g}}{m_{f} + m_{g}} = \frac{v - v_{L}}{v_{V} - v_{L}} = \frac{u - u_{L}}{u_{V} - u_{L}} = \frac{h - h_{L}}{h_{V} - h_{L}} = \frac{s - s_{L}}{s_{V} - s_{L}} \]

or alternatively: \( x = \frac{v - v_{f}}{v_{g} - v_{f}} = \frac{u - u_{f}}{u_{g} - u_{f}} = \frac{h - h_{f}}{h_{g} - h_{f}} = \frac{s - s_{f}}{s_{g} - s_{f}} \)
Water/steam saturation points

Saturation curves for water/steam can be approximated within 1% error in pressure $p$ (kPa) and temperature $T$ (°C) using (source: ÖS96):

$$p_{\text{sat}}(\text{kPa}) = 100 \cdot \exp \left( \frac{11.78 \cdot (T(\text{°C}) - 99.64)}{(T(\text{°C}) + 230)} \right)$$

$$T_{\text{sat}}(\text{°C}) = \frac{3883.16}{16.3852 - \ln p (\text{kPa})} - 230$$

Table: ÇB98

Steam tables: saturation pressure

Source: http://energy.sdsu.edu/testcenter/testhome/Test/solve/basics/tables/tablesPC/pSatH2O.html
see also: http://users.abo.fi/rzevenho/ThermodynamicPropertyTable/saturatedwater-pressure.pdf
Steam tables: saturation temperature

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<tr>
<th>Temp. (°C)</th>
<th>Sat. press. (kPa)</th>
<th>Sat. liquid</th>
<th>Sat. vapor</th>
<th>Internal Energy (kJ/kg)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ/kgK)</th>
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<td>188.54</td>
<td>2334.6</td>
<td>188.54</td>
<td>0.010000</td>
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</tbody>
</table>

374°C

Example: quality of a two-phase mixture

- A two-phase mixture of steam and water at 7 bar occupies a volume of 0.2 m³, with mass 20 kg. Calculate the quality, and estimate temperature.
Steam tables: data superheated

Source: http://energy.sdsu.edu/testcenter/testhome/Test/solve/basics/tables/tablesPC/superH2O.html
see also: http://users.abo.fi/rzevenho/ThermodynamicPropertyTableforSuperheatedVaporofWater.pdf

Example: heating water at constant pressure

- Two kg of saturated liquid water at 50 kPa are heated at constant pressure, adding 5876 kJ of heat. Calculate the final temperature.
Example: Isothermal compression of steam

- Thirty-one (31) kg of (superheated) steam in a piston-cylinder assembly are compressed slowly (i.e. reversibly) and isothermally at 500°C from 100 kPa to 300 kPa. Making use of entropy data, calculate the heat transfer $\Delta Q$.

\begin{align*}
P_1 &= 100 \text{ kPa} \\
T_1 &= 500^\circ\text{C} \\
m &= 31 \text{ kg} \\
T_2 &= T_1 \\
P_2 &= 300 \text{ kPa}
\end{align*}

\[ \text{picture: KJ05} \]

4.6 Water/steam $p,T$; $p,h$ diagrams; $T,s$ and $h,s$ diagrams
Density of water and steam  

Specific enthalpy and entropy of water and steam

enthalpy $h = 0$ kJ/kg for liquid water at $0^\circ$C

source: ÖS96, Fig. 3.5

source: ÖS96, Fig. 3.6
Water/steam h,p diagram

Source: http://www.ent.ohiou.edu/~thermo/property_tables/H2O/ph_water.html

Critical point

Water/steam h,s diagram

Source: http://www.ent.ohiou.edu/~thermo/property_tables/H2O/hs_water.html

Critical point
Example: h,p diagrams

If 1 kg/s steam at 330°C, 50 bar is led through a throttling valve (sv: strypventil) in which pressure is reduced to 5 bar, what will be the final temperature? (ÖS96-3.5a)

Example: p,T diagrams

If 1 kg/s steam at 330°C, 50 bar is led through a throttling valve (sv: strypventil) in which pressure is reduced to 5 bar, what will be the final temperature? (ÖS96-3.5a)
Example: **h,p diagrams**

- How much turbine power can be obtained if 50 kg/s steam at 530°C and 90 bar expands against 7.2 bar. Compare this with the heat release from this steam if it would condense at 7.2 bar.

(ÖS96-3.10)

---

Example: **p,T diagrams**

- How much turbine power can be obtained if 50 kg/s steam at 530°C and 90 bar expands against 7.2 bar. Compare this with the heat release from this steam if it would condense at 7.2 bar.

(ÖS96-3.10)
Example: h,s diagrams

- How much turbine power can be obtained if 50 kg/s steam at 530°C and 90 bar expands against 7.2 bar. Compare this with the heat release from this steam if it would condense at 7.2 bar.

(ÖS96-3.10)

T,s diagram and h,s (Mollier) diagrams for water/steam
Combustion processes

- "Combustion or burning is a complex sequence of chemical reactions between a fuel and an oxidant accompanied by the production of heat or both heat and light in the form of either a glow or flames."
- "Since not every oxidation process results in the production of heat (for example, corrosion), the term combustion can only be applied to exothermic processes that occur at a rate fast enough to produce heat." (Source: wikipedia)

- Two types of combustion cases can be distinguished:
  - Constant pressure combustion, in furnaces and boilers
  - Constant volume combustion, in internal combustion engines

Picture: T06

See also courses FPK1, FPK2 @ OOK
**Enthalpy of combustion**

Methane oxidation in air: \( \text{CH}_4 + 2(\text{O}_2 + 3.76 \text{ N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 2 \cdot 3.76 \text{ N}_2 \)

**Note:** the water product can be as steam (gas) or as liquid water; the enthalpy difference is 44 J/mol = \( \Delta_h \) _vaporisation, H2O. This has an effect on the calculated heat of combustion, or heating value !!! Therefore **lower heating value** (LHV) is defined for H2O(gas) product, or **higher heating value** (HHV) for H2O(liquid) product. For example, for methane, LHV = 802 kg/mol, HHV = 890 kg/mol.

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**Fuels /1**

- **Important properties of fuels are:**
  - calorific heating value
  - air demand (kg air / kg fuel)
  - moisture and ash-forming matter content
  - combustible volatiles and char content and the ratio of these ("fuel ratio")
  - availability and costs, and stability of these
  - pollution-producing species content
  - CO2 / kWh power or CO2 / km for vehicles
### Fuels / some typical solid fuel data

<table>
<thead>
<tr>
<th></th>
<th>C *</th>
<th>H *</th>
<th>N *</th>
<th>O *</th>
<th>S *</th>
<th>Moisture *</th>
<th>Volatiles *</th>
<th>Char *</th>
<th>Ash *</th>
<th>LHV ***</th>
<th>HHV ***</th>
<th>Stoichiometric air need ****</th>
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<tbody>
<tr>
<td>Polish coal</td>
<td>71</td>
<td>4.3</td>
<td>1.2</td>
<td>11</td>
<td>1.3</td>
<td>0.07</td>
<td>3</td>
<td>35</td>
<td>51</td>
<td>11</td>
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<td>29.3</td>
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<td>Illinois coal</td>
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<td>13</td>
<td>3.6</td>
<td>0.04</td>
<td>6</td>
<td>37</td>
<td>41</td>
<td>16</td>
<td>23.5</td>
<td>25.3</td>
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<td>Petroleum coke</td>
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<td>3.1</td>
<td>1.7</td>
<td>1.2</td>
<td>4.0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>88</td>
<td>&lt;1</td>
<td>33.7</td>
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<tr>
<td>Finnish peat</td>
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<td>5.9</td>
<td>1.1</td>
<td>34</td>
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<td>0</td>
<td>9</td>
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<td>17</td>
<td>4</td>
<td>21.1</td>
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<td>46</td>
<td>0.03</td>
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<td>5</td>
<td>88</td>
<td>7</td>
<td>&lt;1</td>
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<td>19.5</td>
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<td>60</td>
<td>8</td>
<td>12</td>
<td>19.1</td>
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<td>(from waste)</td>
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<td>3.4</td>
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<td>10</td>
<td>7</td>
<td>15</td>
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<td>61</td>
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<td>93</td>
<td>7</td>
<td>0</td>
<td>19.8</td>
<td>22.0</td>
</tr>
</tbody>
</table>

* %-wt dry; ** %-wt "as received"; *** MJ/kg; **** kg dry air / kg dry fuel

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### Adiabatic flame temperature /1

- Important information on fuel quality is found from the so-called **adiabatic flame temperature**, which for a **constant pressure** process is the maximum temperature that can be reached.

- No heat losses from the system → all reaction enthalpy is used to raise the temperature of the product mixture.

- Based on the enthalpy of reactants $H_{\text{reactants}}$ at the initial temperature $T_{\text{init}}$, the adiabatic reaction temperature $T_{\text{ad}}$ for the products is defined as

$$H_{\text{products}}(T_{\text{ad}}) = H_{\text{reactants}}(T_{\text{init}})$$

$$\sum_i (H_i^p + \int_{T_i}^{T_{\text{ad}}} c_{p,i} dT)_{\text{products}} = \sum_i (H_i^r + \int_{T_i}^{T_{\text{ad}}} c_{p,i} dT)_{\text{reactants}}$$

@ $T = T_{r, \text{adiabatic}}$
Adiabatic flame temperature /2

- The adiabatic temperature occurs at stoichiometric conditions; excess air will lower the temperature.
- In constant volume combustion the adiabatic reaction temperature $T_{ad}$ for the products is defined by internal energy $U$
  \[ U_{products}(T_{ad}) = U_{reactants}(T_{init}) \]

- At high temperatures dissociation becomes important, and relations for product equilibrium composition must be included; for example
  \[ N_2 \leftrightarrow 2N, \ H_2O \leftrightarrow H_2 + \frac{1}{2}O_2 \]
  (ignoring these gives errors of hundreds of degrees)

Sources

KJ05: D. Kaminski, M. Jensen ”Introduction to Thermal and Fluids Engineering”, Wiley (2005)
TUD86: ”Apparaten voor de procesindustrie / Apparaten voor warmteoverdracht”, (ST42/i20) Delft University of Technology (1986) (in Dutch)
Steam tables: pressure table
for example: http://users.abo.fi/rzevenho/ThermodynamicPropertyTableforsaturatedwater-pressure.pdf
Steam tables: temperature table
for example: http://users.abo.fi/rzevenho/ThermodynamicPropertyTableforsaturatedwater-temperature.pdf
Steam tables: superheated vapour table
for example: http://users.abo.fi/rzevenho/ThermodynamicPropertyTableforsuperheatedvaporofwater.pdf
Appendix: case slide 51 h,p diagram

\[ \Delta s \approx -0.5 \text{ kJ/kgK} \]

\[ m \cdot T \cdot \Delta s \approx 31 \cdot 773 \cdot -0.5 = 12 \text{ MJ} \]