4. Heat exchangers; Steam, steam processes

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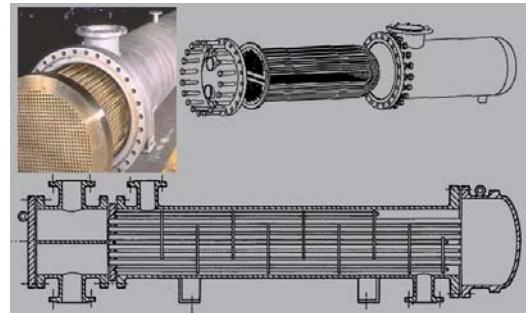
4.1 Heat exchangers

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)
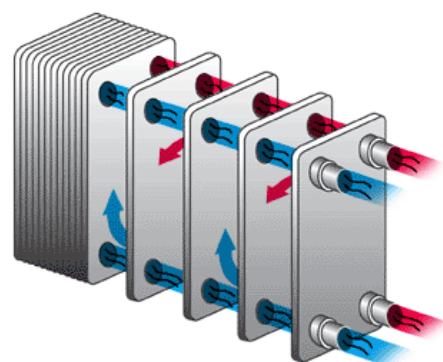

A shell-and-plate heat exchanger; widely used in power plants, oil refineries and chemical process plants.

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).

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

- Typical every-day-life examples:
  - Cooking equipment
 - Refrigerators
  - Car radiator
  - Air conditioning systems

picture: http://www.heatexchangers.org/

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

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.
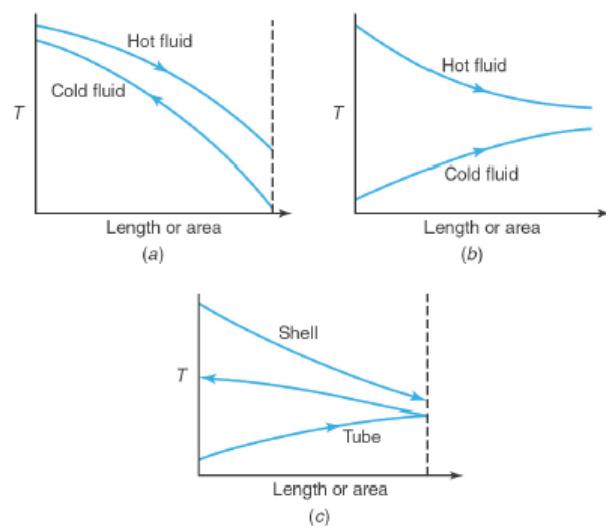
pictures: KJ05
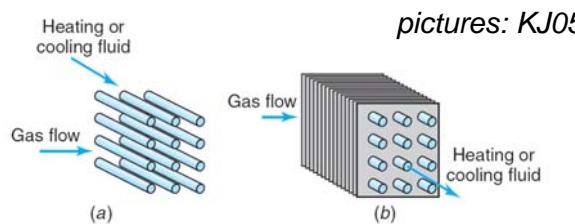
Heat exchangers: Geometries /3
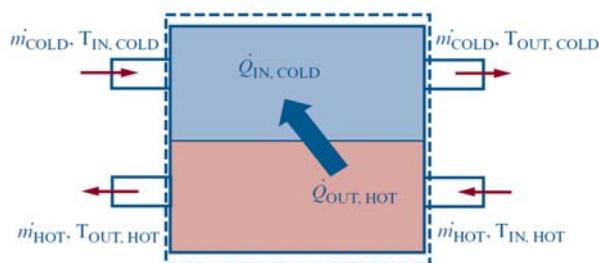
Temperature distribution in a **counter-flow heat exchanger**.

<u>Note:</u> 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

Heat exchangers: energy balance

Heat exchanger schematic with open system boundary around both streams.

Picture: SEHB06

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 = ΔH

$$\dot{Q}_{cold} = \Delta\dot{H}_{cold} = -\Delta\dot{H}_{hot} = -\dot{Q}_{hot}$$
$$\Delta\dot{H}_{cold} = \dot{m}_{cold} \cdot (h_{cold,out} - h_{cold,in}) = \dot{m}_{hot} \cdot (h_{hot,in} - h_{hot,out}) = -\Delta\dot{H}_{hot}$$

Often (modest temperature differences) it can be simplified to

$$\dot{m}_{cold} \cdot c_{p,cold} \cdot (T_{cold,out} - T_{cold,in}) = \dot{m}_{hot} \cdot c_{p,hot} \cdot (T_{hot,in} - T_{hot,out})$$
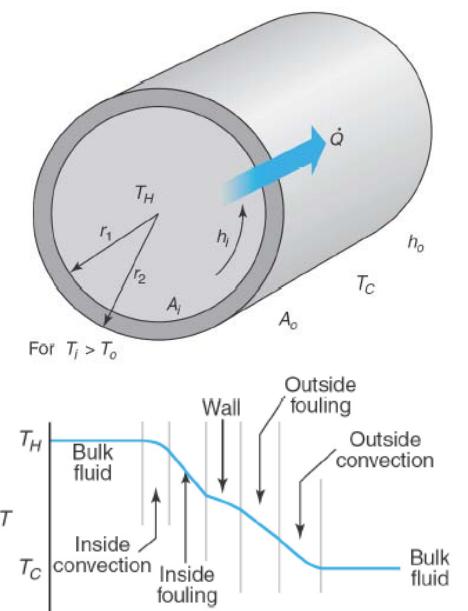
Overall heat transfer coefficient

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

  $\dot{Q} = U \cdot A \cdot \Delta T$ for temperature diffence ΔT (°C), heat exchange area A (m²) and **overall heat transfer coefficient U** (W/(m²·K))

  (sv: värmegenomgångskoefficient)

- U is a combination of several heat transfer resistances

For $T_i > T_o$

Resistances contributing to the overall heat transfer coefficient U
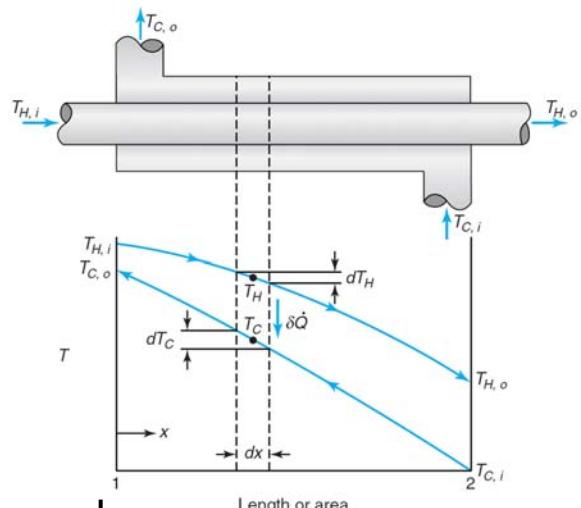
pictures: KJ05

Heat exchanger analysis /1
The LMTD method

- Heat exchanger performance depends on how much heat exchange area A (in m²) 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!

picture: KJ05

Heat exchanger analysis /2
The LMTD method

- With average temperature difference $\langle \Delta T \rangle = \langle T_H - T_C \rangle$ for the heat exchanger length, the heat rate can be expressed as
  $$\dot{Q} = \langle U \rangle \cdot A \cdot \langle \Delta T \rangle$$

- If it can be assumed that $U \approx$ 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":
  $$T_H - T_C = \Delta T = \Delta T(x) = \Delta T_1 + \frac{\int_{"1"}^{x} \delta \dot{Q}}{\dot{Q}} (\Delta T_2 - \Delta T_1)$$

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

  this integrates to

$$\boxed{\dot{Q} = U \cdot A \cdot \frac{(\Delta T_2 - \Delta T_1)}{\ln\left(\dfrac{\Delta T_2}{\Delta T_1}\right)} = U \cdot A \cdot \Delta T_{lm}}$$

  *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 $\dot{Q} = \langle U \rangle \cdot A \cdot F \cdot \Delta T_{lm}$ in the analysis given above for a single-pass counter-flow heat exchanger: $U \cdot A = \dot{Q} / (F \cdot \Delta T_{lm})$
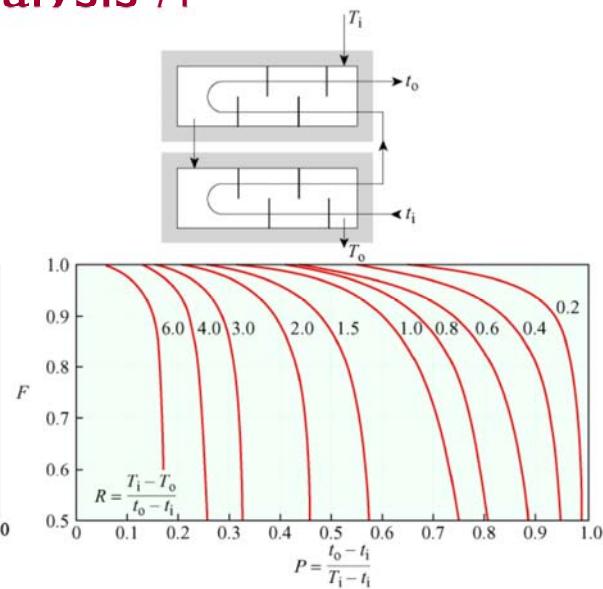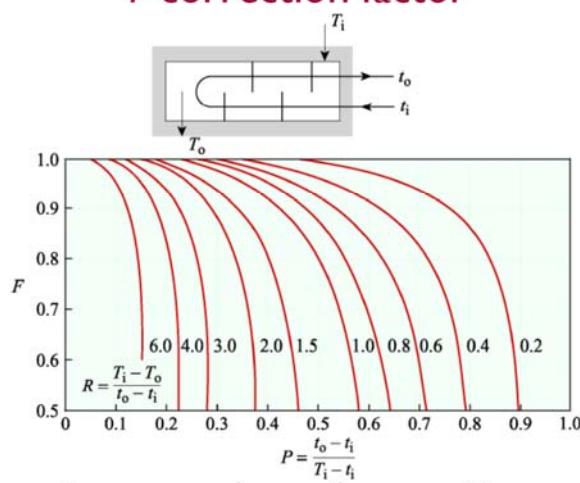
- **The F correction factor is found from design graphs: _see for example next slide_**

- For an economically feasible design $F > 0.75$

Heat exchanger analysis /4

The LMTD method:
F correction factor

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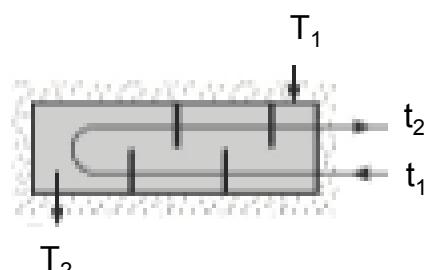
Right: Shell-and-tube with two shell passes and any multiple of four tube passes (four, eight, etc. tube passes).

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 $t_2 = 115 °C$

  <u>Calculate</u> ΔT_{lm} and the *F* correction factor.

4.2 Evaporators and condensers

Condensers

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

- Usually "plate-and-shell" condensors 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.)
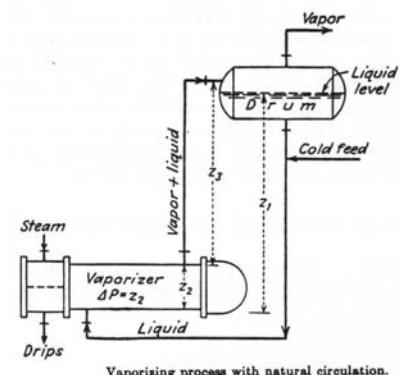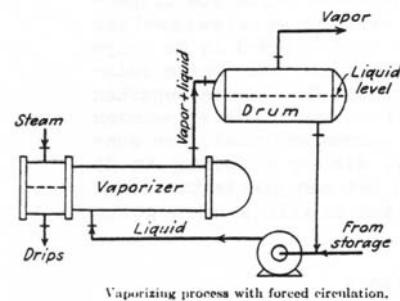
- Also used are contact condensors where coolant and vapor are mixed and leave the condenser as a single stream.

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.

pictures: TUD86
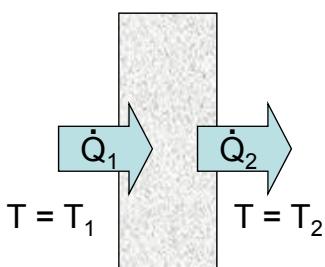
4.3 Heat exchanger efficiency; "effectiveness"; remarks on selection

Heat exchanger efficiency vS91

- 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 $T_1 > T_2$

$\dot{Q}_1$ → $\dot{Q}_2$ →

$T = T_1$ $T = T_2$

- Thermodynamic analysis

Energy balance

$$\dot{Q}_1 = \dot{Q}_2$$

Entropy balance

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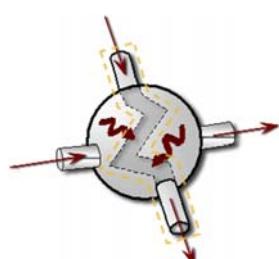
$$\dot{S}_{gen} = \dot{Q}_1 \left(\frac{1}{T_2} - \frac{1}{T_1} \right) = \dot{Q}_1 . \frac{T_1 - T_2}{T_1 T_2} > 0$$

- This shows that S_{gen} is large for large temperature differences (T_1-T_2) and low temperatures T_1 and T_2
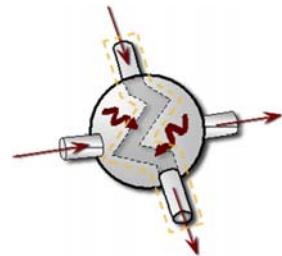
Heat exchanger effective performance / 1

- Heat exhanger 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 ΔT requires much surface A!).

- This shows that counter-current heat exchangers perform much better than co-current heat exchangers.

Picture : http://www.learnthermo.com/T1-tutorial/ch05/lesson-C/pg10.php

Heat exchanger effective performance /2

- Ideally, the flows aquire each others temperature: the exergy losses will then be zero. For this, the heat capacity rates $\dot{m} \cdot c_p$ 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")

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

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_{min} and C_{max} as

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

and since ΔT is largest for small $C = \dot{m} \cdot c_p$ (see next slide)
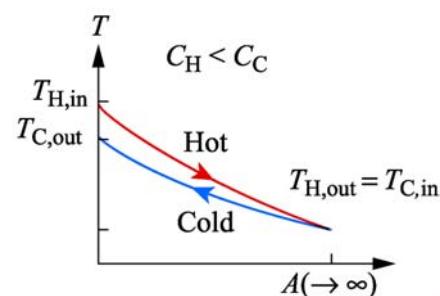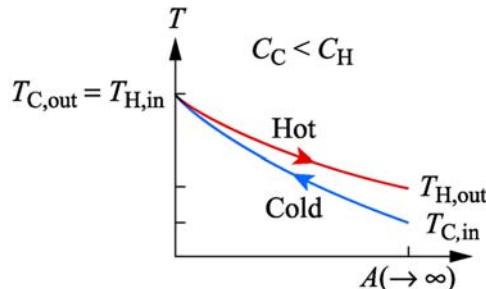
$$\dot{Q}_{max} = C_{min} \cdot (T_{H,in} - T_{C,in})$$

Heat exchanger effectiveness /2

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

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 $T_{C,out} = T_{H,in}$ (top). If the hot fluid is the minimum ($C_H < C_C$), then the maximum possible heat transfer occurs when $T_{H,out} = T_{C,in}$.

picture: T06

Heat exchanger effectiveness /3

- The ε-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:
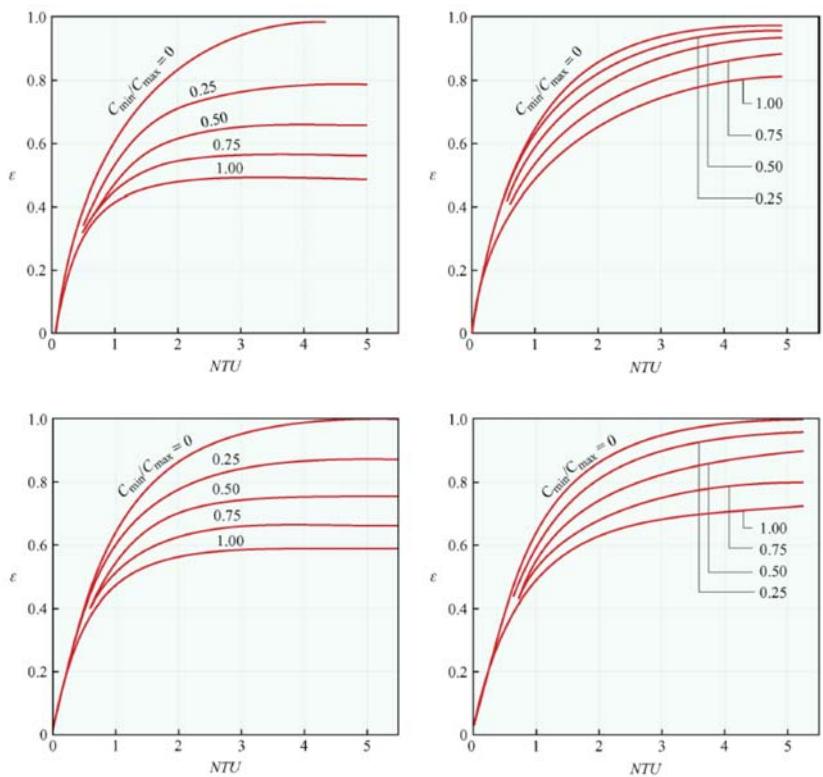
$$NTU = \frac{U \cdot A}{C_{min}} \quad and \quad C^* = \frac{C_{min}}{C_{max}}$$

- A transfer unit ~ distance ΔL 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 ε =f(NTU, C_{min}, geometry *etc.*) can be found in tables, or diagrams can be used; see →:

Heat exchanger effective-ness /4

- *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

Heat exchanger effectiveness /5a

Type of Heat Exchanger	Effectiveness relations	NTU relations
All exchangers with $C^* = 0$	$\varepsilon = 1 - \exp(-NTU)$	$NTU = -\ln(1 - \varepsilon)$
Double pipe Counter flow	$\varepsilon = \dfrac{1 - \exp[-NTU(1 - C^*)]}{1 - C^* \exp[-NTU(1 - C^*)]}$	$NTU = \dfrac{1}{C^* - 1} \ln\left(\dfrac{\varepsilon - 1}{C^* \varepsilon - 1}\right)$
Parallel flow	$\varepsilon = \dfrac{1 - \exp[-NTU(1 + C^*)]}{1 + C^*}$	$NTU = -\dfrac{\ln[1 - \varepsilon(1 + C^*)]}{1 + C^*}$

table: KJ05

- Common equations for effectiveness and NTU

Heat exchanger effectiveness /5b
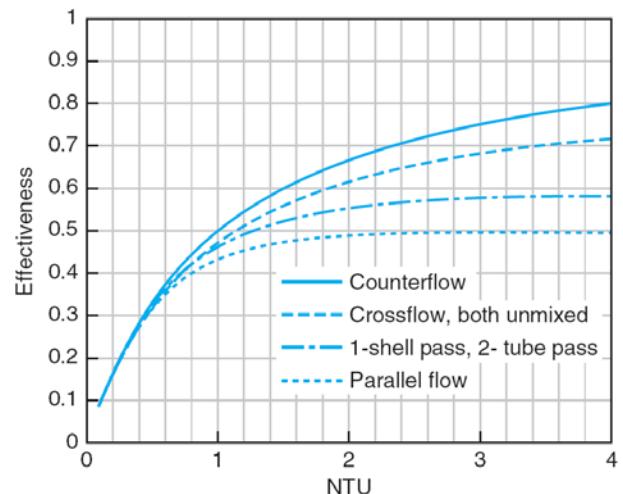
Type of Heat Exchanger	Effectiveness relations	NTU relations
Shell-and-tube One-shell pass; 2, 4, 6, ... tube passes (TEMA E shell)	$$\varepsilon_1 = \frac{2}{(1 + C^*) + (1 + C^{*2})^{0.5}\dfrac{(1 + \exp[-NTU\sqrt{1 + C^{*2}}])}{(1 - \exp[-NTU\sqrt{1 + C^{*2}}])}}$$	$$NTU = -\frac{1}{(1 + C^{*2})^{0.5}}\ln\left(\frac{E - 1}{E + 1}\right)$$ $$E = \frac{2/\varepsilon_2 - (1 + C^*)}{(1 + C^{*2})^{0.5}}$$
n-shell passes; $2n$, $4n$, $6n$, ... tube passes	$$\varepsilon = \left[\left(\frac{1 - \varepsilon_1 C^*}{1 - \varepsilon_1}\right)^n - 1\right]\left[\left(\frac{1 - \varepsilon_1 C^*}{1 - \varepsilon_1}\right)^n - C^*\right]^{-1}$$	Use above two equations with ε_1 $$\varepsilon_2 = \frac{F - 1}{F - C^*} \qquad F = \left(\frac{\varepsilon C^* - 1}{\varepsilon - 1}\right)^{1/n}$$

table: KJ05

- Common equations for effectiveness and NTU

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

picture: KJO5

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
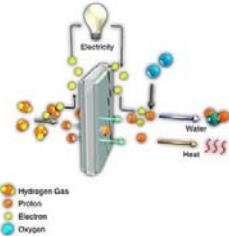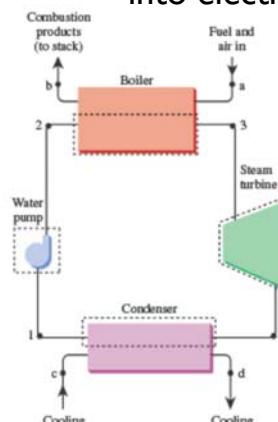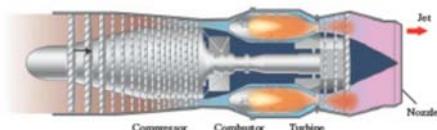
4.4 Power production*

* Often by mistake referred to as "energy production"
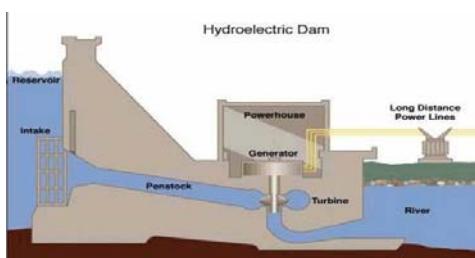
Power (+ heat) production /1

- **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 /2
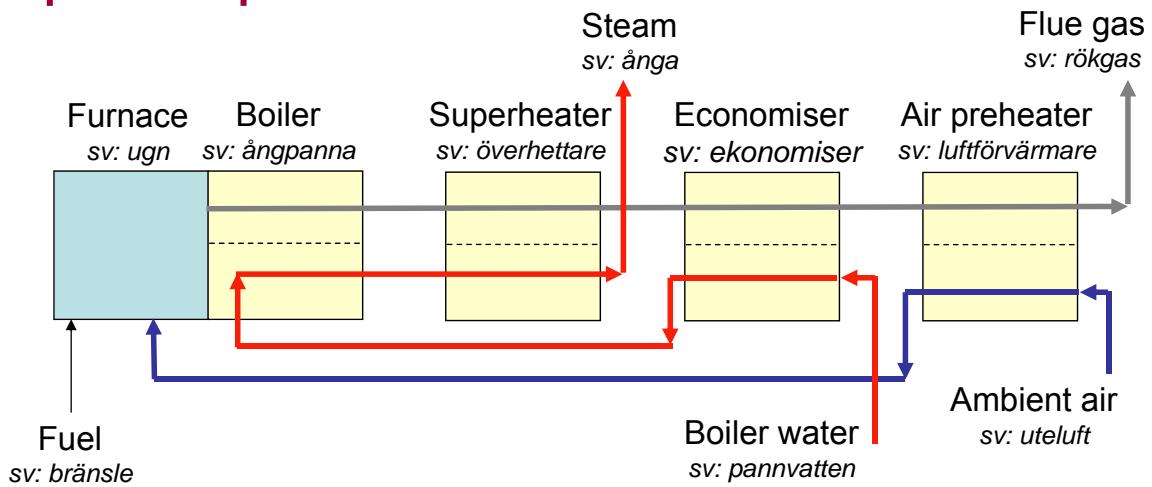
- **Using height differences in (large) rivers or between lakes in a hydropower station** → production of electricity in a turbine + generator
- **Solar radiation energy** → conversion into heat (→ hot water) and/or electricity using a photovoltaic convertor

- **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
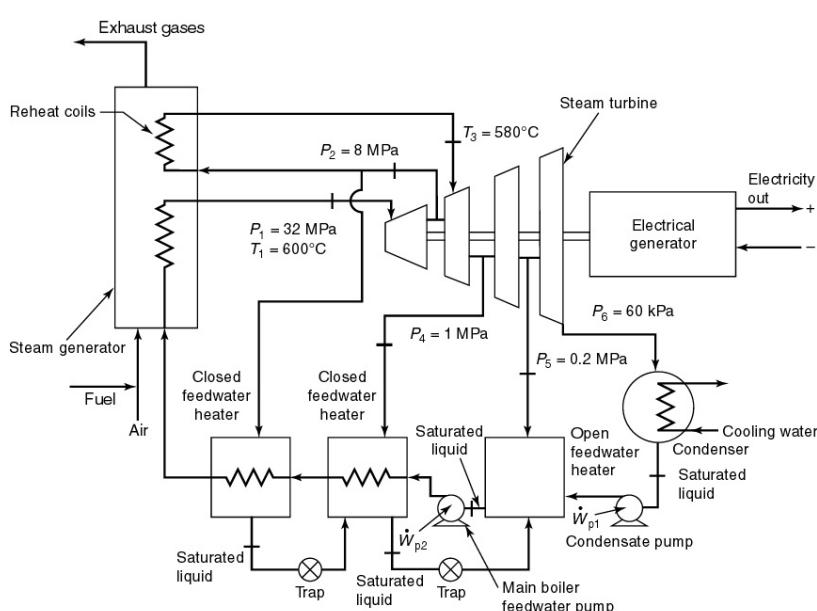
Heat exchangers in a condensing power plant

Steam
sv: ånga

Flue gas
sv: rökgas

| Furnace sv: ugn | Boiler sv: ångpanna | Superheater sv: överhettare | Economiser sv: ekonomiser | Air preheater sv: luftförvärmare |

Fuel
sv: bränsle

Boiler water
sv: pannvatten

Ambient air
sv: uteluft
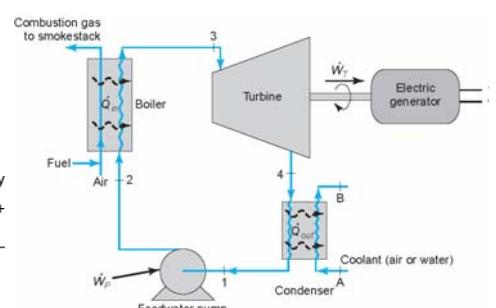
*Picture after ÖS96
p. 30 (note correction!)*
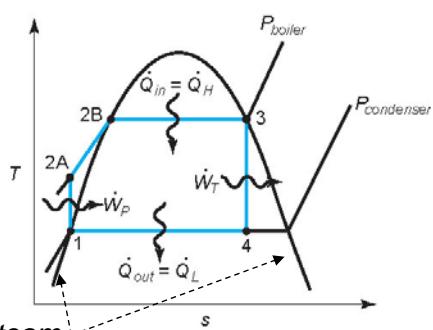
A typical condensing power plant

Exhaust gases

Reheat coils

$T_3 = 580°C$

$P_2 = 8$ MPa

Steam turbine

Electricity out

$P_1 = 32$ MPa
$T_1 = 600°C$

Electrical generator

Steam generator

Fuel

Air

$P_4 = 1$ MPa

$P_6 = 60$ kPa

$P_5 = 0.2$ MPa

Closed feedwater heater

Closed feedwater heater

Saturated liquid

Open feedwater heater

Cooling water
Condenser

Saturated liquid

Saturated liquid

$\dot{W}_{p2}$

$\dot{W}_{p1}$
Condensate pump

Saturated liquid

Trap

Saturated liquid

Trap

Main boiler feedwater pump

Schematic of a Rankine power cycle

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

Simplified Rankine power cycle

pictures: KJ05

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 = 4.19 kJ/kgK

$\dot{Q}_{OUT,1} = \dot{Q}_{STACK\ LOSS} = 500\ MW$

Power plant

$\dot{Q}_{IN} = \dot{Q}_{FUEL} = 5000\ MW$

$\dot{W}_{OUT} = \dot{W}_{ELECT} = 3000\ MW$

$T_2 = 16\ °C$

$T_2 = 30\ °C$

Cooling water from river

$P_1 = P_2 = 0.1013\ MPa$

Cooling water return
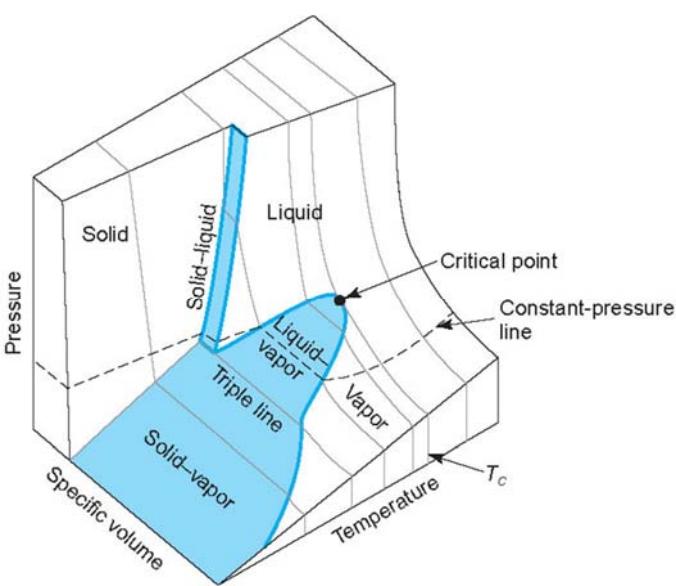
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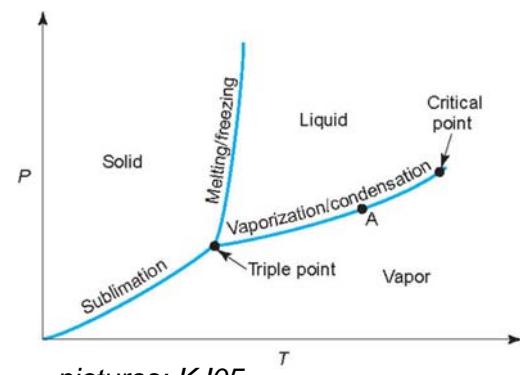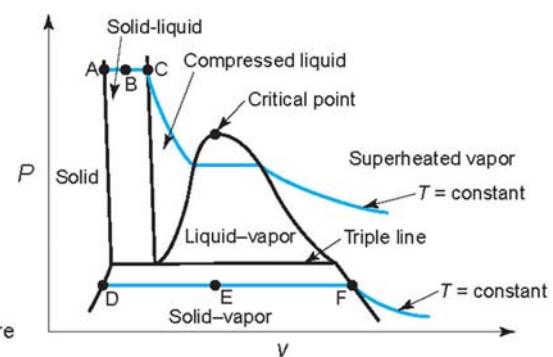
4.5 Steam properties; Steam processes

Properties of pure substances /1
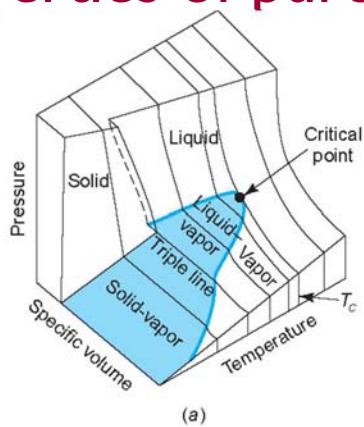
Solid, liquid and vapour states
in a p,V,T surface
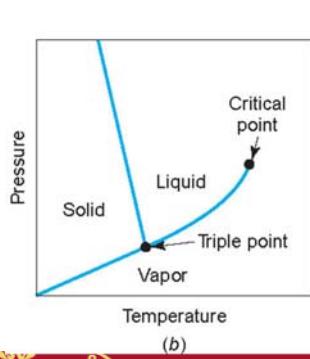
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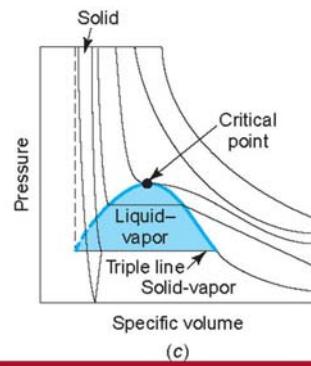
Properties of pure substances /2

p,V,T diagram, p,T
diagram and p,V diagram
of a substance that
expands on freezing,
such as water
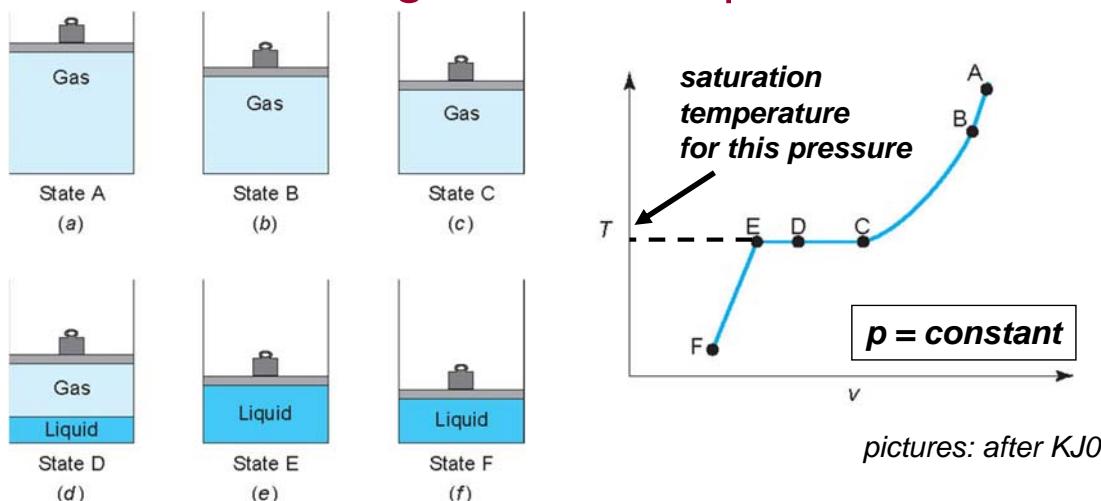
Water:
critical point
+374.15°C, 22.12 MPa
Triple point
+0.01°C, 0.6112 kPa

pictures: KJ05

Properties of pure substances /3
Condensation of a gas at constant pressure
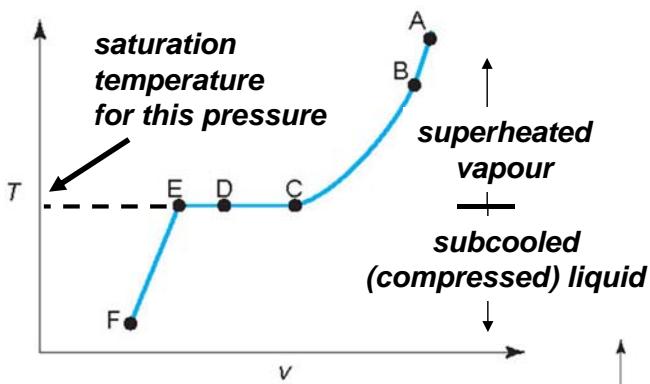
pictures: after KJ05

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.
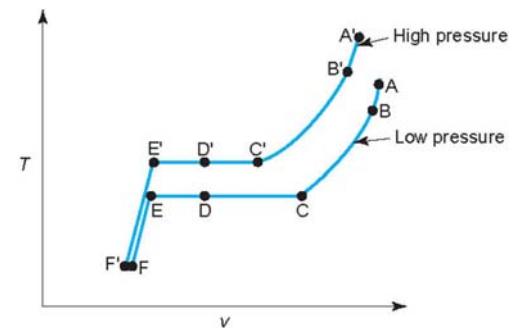
Properties of pure substances /4
Condensation of a gas at constant pressure

At higher pressures, saturation occurs at higher temperatures (C' versus C) and smaller specific volumes (*i.e.* higher density)
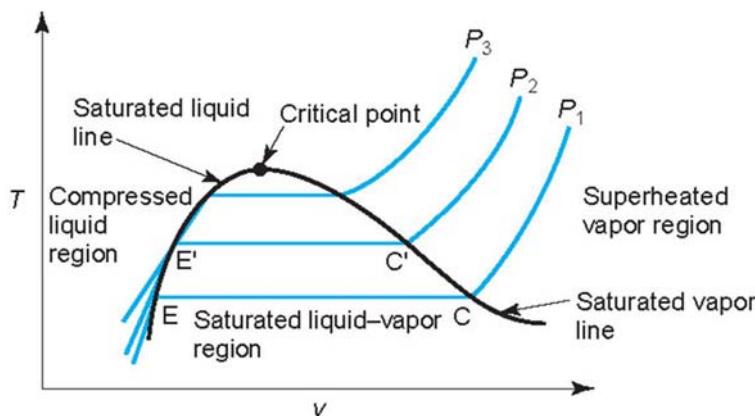
pictures: after KJ05

Properties of pure substances /5
Condensation of a gas at constant pressure
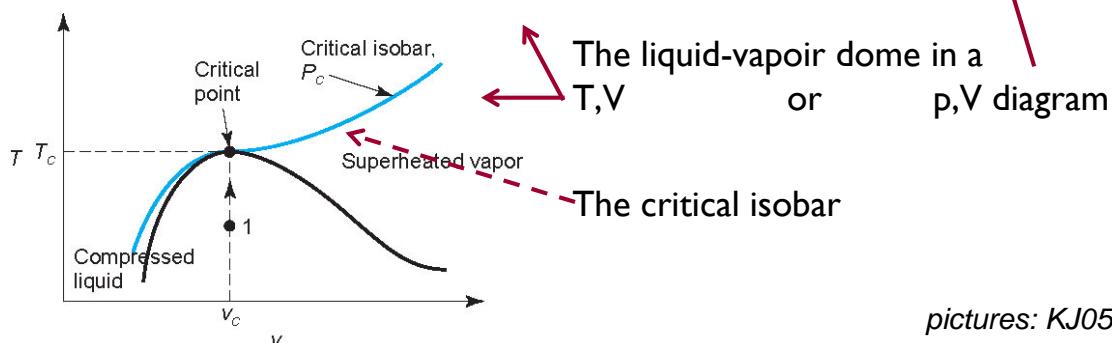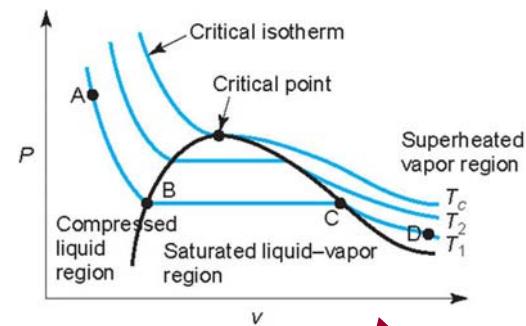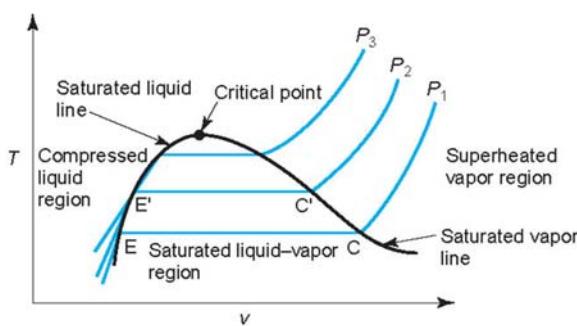
picture: KJ05

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 /6
Condensation of a gas
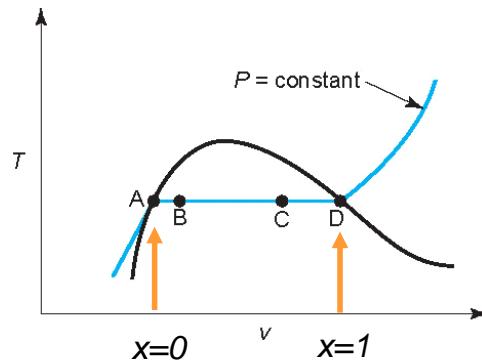
The liquid-vapoir dome in a T,V   or   p,V diagram

The critical isobar

pictures: KJ05

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, 0x,** of this mixture is defined as the mass fraction vapor in the mixture:

picture: KJ05

$$X = \frac{m_{gas}}{m_{gas} + m_{liquid}} = \frac{m_V}{m_V + m_L}$$

$$= \frac{m_g}{m_g + m_f} \quad \text{(with "f" from german "flüssig")}$$

Note that x is a thermodynamic property, like p,T,v, u, h, s

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 x,   0 ≤ x ≤ 1,** of this mixture is defined as the mass fraction vapor in the mixture:

picture: KJ05

$$X = \frac{m_{gas}}{m_{gas} + m_{liquid}} = \frac{m_V}{m_V + m_L}$$

$$= \frac{m_g}{m_g + m_f} \quad \text{(with "f" from german "flüssig")}$$

Note that x is a thermodynamic property, like p,T,v, u, h, s
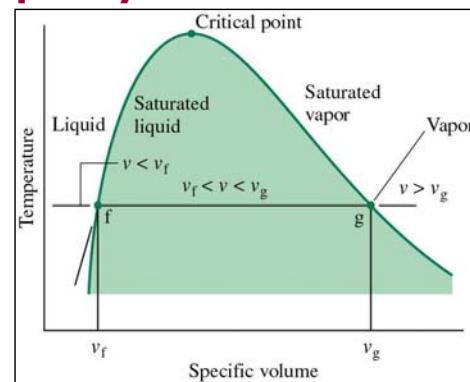
Condensation of a gas : **mixture quality**

$$x = \frac{m_{gas}}{m_{gas} + m_{liquid}} = \frac{m_V}{m_V + m_L}$$

$$x = \frac{m_g}{m_g + m_f} \quad \text{(with "f" from german "flüssig")}$$

With specific volume $v = V/m$ (m³/kg)
(= 1/density !) this gives for x:

$$v = \frac{V_{total}}{m_{total}} \;;\; v_L = \frac{V_L}{m_L} \;;\; v_V = \frac{V_V}{m_V} \text{ and } V_{total} = V_L + V_V$$

$$v \cdot m_{total} = v_L \cdot m_L + v_V \cdot m_V \;\Rightarrow\; v = v_L \frac{m_L}{m_{total}} + v_V \frac{m_V}{m_{total}}$$

$$v = (1-x) \cdot v_L + x \cdot v_V \quad \text{or} \quad x = \frac{v - v_L}{v_V - v_L} = \frac{v - v_L}{v_{LV}}$$

or with other notation $\quad v = (1-x) \cdot v_f + x \cdot v_g \quad$ or $\quad x = \frac{v - v_f}{v_g - v_f} = \frac{v - v_f}{v_{fg}}$

http://www2.cemr.wvu.edu/~smirnov/mae320/figs/F3-8.jpg

- 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:

$$u = (1\text{-}x) \cdot u_L + x \cdot u_v \qquad \text{or} \qquad u = (1\text{-}x) \cdot u_f + x \cdot u_g$$

$$h = (1\text{-}x) \cdot h_L + x \cdot h_v \qquad \text{or} \qquad h = (1\text{-}x) \cdot h_f + x \cdot h_g$$

$$s = (1\text{-}x) \cdot s_L + x \cdot s_v \qquad \text{or} \qquad s = (1\text{-}x) \cdot s_f + x \cdot s_g$$

$$x = \frac{m_g}{m_f + m_g} = \frac{v - v_L}{v_V - v_L} = \frac{u - u_L}{u_V - u_L} = \frac{h - h_L}{h_V - h_L} = \frac{s - s_L}{s_V - s_L}$$

$$\text{or alternatively}: x = \frac{v - v_f}{v_g - v_f} = \frac{u - u_f}{u_g - u_f} = \frac{h - h_f}{h_g - h_f} = \frac{s - s_f}{s_g - s_f}$$

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):

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

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

Saturation (boiling) pressure of water at various temperatures

Temperature, T °C	Saturation pressure, P_{sat} kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

Table: ÇB98

Steam tables: saturation pressure

Saturated water (H2O)--Pressure table									
kPa	deg-C	Spec. Volume m^3/kg		Internal energy kJ/kg		Enthalpy kJ/kg		Entropy kJ/kg*K	
Press.	Sat. temp.	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor
p kPa	Tsat@p	v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g
0.6113	0.01	0.001000	206.14	0	2375.3	0.01	2501.4	0.0000	9.1562
1.0	6.98	0.001000	129.21	29.3	2385.0	29.30	2514.2	0.1059	8.9756
1.5	13.03	0.001001	87.98	54.71	2393.3	54.71	2525.3	0.1957	8.8279
2.0	17.50	0.001001	67.00	73.48	2399.5	73.48	2533.5	0.2607	8.7237
2.5	21.08	0.001002	54.25	88.48	2404.4	88.49	2540.0	0.3120	8.6432
3.0	24.08	0.001003	45.67	101.04	2408.5	101.05	2545.5	0.3545	8.5776
4.0	28.96	0.001004	34.80	121.45	2415.2	121.46	2554.4	0.4226	8.4746
5.0	32.88	0.001005	28.19	137.81	2420.5	137.82	2561.5	0.4764	8.3951
7.5	40.29	0.001008	19.24	168.78	2430.5	168.79	2574.8	0.5764	8.2515
10	45.81	0.001010	14.67	191.82	2437.9	191.83	2584.7	0.6493	8.1502
15	53.97	0.001014	10.02	225.92	2448.7	225.94	2599.1	0.7549	8.0085
20	60.06	0.001017	7.649	251.38	2456.7	251.40	2609.7	0.8320	7.9085
25	64.97	0.001020	6.204	271.9	2463.1	271.93	2618.2	0.8931	7.8314
30	69.10	0.001022	5.229	289.2	2468.4	289.23	2625.3	0.9439	7.7686
40	75.87	0.001027	3.993	317.53	2477.0	317.58	2636.8	1.0259	7.67
50	81.33	0.001030	3.240	340.44	2483.9	340.49	2645.9	1.0910	7.5939
75	91.78	0.001037	2.217	384.31	2496.7	384.39	2663.0	1.2130	7.4564
p MPa	Tsat@p	v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g
0.1	99.63	0.001043	1.694	417.36	2506.1	417.46	2675.5	1.3026	7.3594
0.125	105.99	0.001048	1.3749	444.19	2513.5	444.32	2685.4	1.374	7.2844
0.150	111.37	0.001053	1.1593	466.94	2519.7	467.11	2693.6	1.4336	7.2233

22 MPa

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

Steam tables: saturation temperature

deg-C	kPa	Spec. Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg		Entropy kJ/kg*K	
Temp.	Sat. press.	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor
$T\,^0C$	$p\_sat@T$	v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g
0.01	0.6113	0.001000	206.14	0.00	2375.3	0.01	2501.4	0.0000	9.1562
5	0.8721	0.001000	147.12	20.97	2382.3	20.98	2510.6	0.0761	9.0257
10	1.2276	0.001000	106.38	42.00	2389.2	42.01	2519.8	0.1510	8.9008
15	1.7051	0.001001	77.93	62.99	2396.1	62.99	2528.9	0.2245	8.7814
20	2.339	0.001002	57.79	83.95	2402.9	83.96	2538.1	0.2966	8.6672
25	3.169	0.001003	43.36	104.88	2409.8	104.89	2547.2	0.3674	8.5580
30	4.246	0.001004	32.89	125.78	2416.6	125.79	2556.3	0.4369	8.4533
35	5.628	0.001006	25.22	146.67	2423.4	146.68	2565.3	0.5053	8.3531
40	7.384	0.001008	19.52	167.56	2430.1	167.57	2574.3	0.5725	8.2570
45	9.593	0.001010	15.26	188.44	2436.8	188.45	2583.2	0.6387	8.1648
50	12.349	0.001012	12.03	209.32	2443.5	209.33	2592.1	0.7038	8.0763
55	15.758	0.001015	9.568	230.21	2450.1	230.23	2600.9	0.7679	7.9913
60	19.940	0.001017	7.671	251.11	2456.6	251.13	2609.6	0.8312	7.9096
65	25.03	0.001020	6.197	272.02	2463.1	272.06	2618.3	0.8935	7.8310
70	31.19	0.001023	5.042	292.95	2469.6	292.98	2626.8	0.9549	7.7553
75	38.58	0.001026	4.131	313.90	2475.9	313.93	2643.7	1.0155	7.6824
80	47.39	0.001029	3.407	334.86	2482.2	334.91	2635.3	1.0753	7.6122
85	57.83	0.001033	2.828	355.84	2488.4	355.90	2651.9	1.1343	7.5445
90	70.14	0.001036	2.361	376.85	2494.5	376.92	2660.1	1.1925	7.4791
95	84.55	0.001040	1.982	397.88	2500.6	397.96	2668.1	1.2500	7.4159
$T\,^0C$	$p\_sat@T$ MPa	v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g
100	0.10135	0.001044	1.6729	418.94	2506.5	419.04	2676.1	1.3069	7.3549
105	0.12082	0.001048	1.4194	440.02	2512.4	440.15	2683.8	1.3630	7.2958
110	0.14327	0.001052	1.2102	461.14	2518.1	461.30	2691.5	1.4185	7.2387
115	0.16906	0.001056	1.0366	482.30	2523.7	482.48	2699.0	1.4734	7.1833
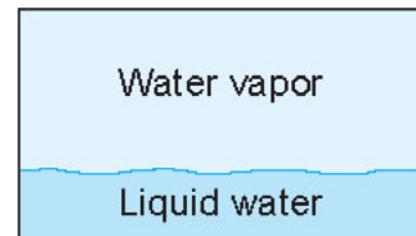
374°C

Source: http://energy.sdsu.edu/testcenter/testhome/Test/solve/basics/tables/tablesPC/TSatH2O.html
see also: http://users.abo.fi/rzevenho/ThermodynamicPropertyTableforsaturatedwater-temperature.pdf

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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.

picture: KJ05

Steam tables: data superheated

Superheated Water (H2O) Table

deg-C	m^3/kg	kJ/kg	kJ/kg	kJ/kg K	m^3/kg	kJ/kg	kJ/kg	kJ/kg K	m^3/kg	kJ/kg	kJ/kg	kJ/kg K
T	p = 0.01 MPa (45.81 C)				p = 0.05 MPa (81.33 C)				p = 0.10 MPa (99.63 C)			
	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	14.674	2437.9	2584.7	8.1502	3.24	2483.9	2645.9	7.5939	1.694	2506.1	2675.5	7.3594
50	14.869	2443.9	2592.6	8.1749								
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947	1.6958	2506.7	2676.2	7.3614
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401	1.9364	2582.8	2776.4	7.6143
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580	2.172	2658.1	2875.3	7.8343
250	24.136	2736.0	2977.3	9.1002	4.82	2735.0	2976.0	8.3556	2.406	2733.7	2974.3	8.0333
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373	2.639	2810.4	3074.3	8.2158
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642	3.103	2967.9	3278.2	8.5435
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546	3.565	3131.6	3488.1	8.8342
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178	4.028	3301.9	3704.4	9.0976
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599	4.49	3479.2	3928.2	9.3398
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852	4.952	3663.5	4158.6	9.5652
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967	5.414	3854.8	4396.1	9.7767
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964	5.875	4052.8	4640.3	9.9764
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859	6.337	4257.3	4891.0	10.1659
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662	6.799	4467.7	5147.6	10.3463
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382	7.26	4683.5	5409.5	10.5183
T	p = 0.2 MPa (120.23 C)				p = 0.30 MPa (133.55 C)				p = 0.40 MPa (143.63 C)			
	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987

60 MPa ↓

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

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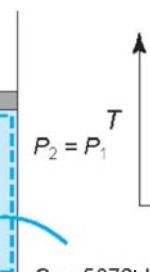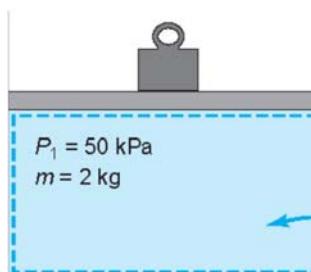
Example: heating water at constant pressure

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

$P_1 = 50$ kPa
$m = 2$ kg

$Q = 5876$ kJ

$P_2 = P_1$

Where is the final state?
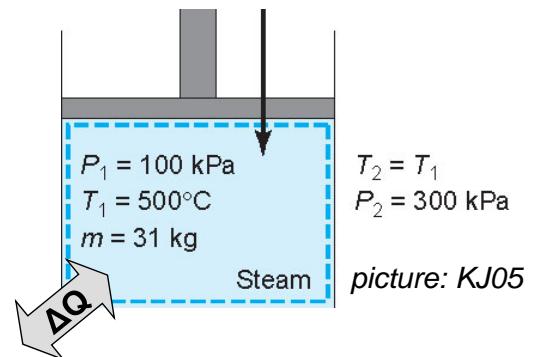
Isobar

pictures: KJ05

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, <u>calculate</u> the heat transfer ΔQ.

$P_1 = 100$ kPa
$T_1 = 500$°C
$m = 31$ kg

$T_2 = T_1$
$P_2 = 300$ kPa

Steam

picture: KJ05

ΔQ
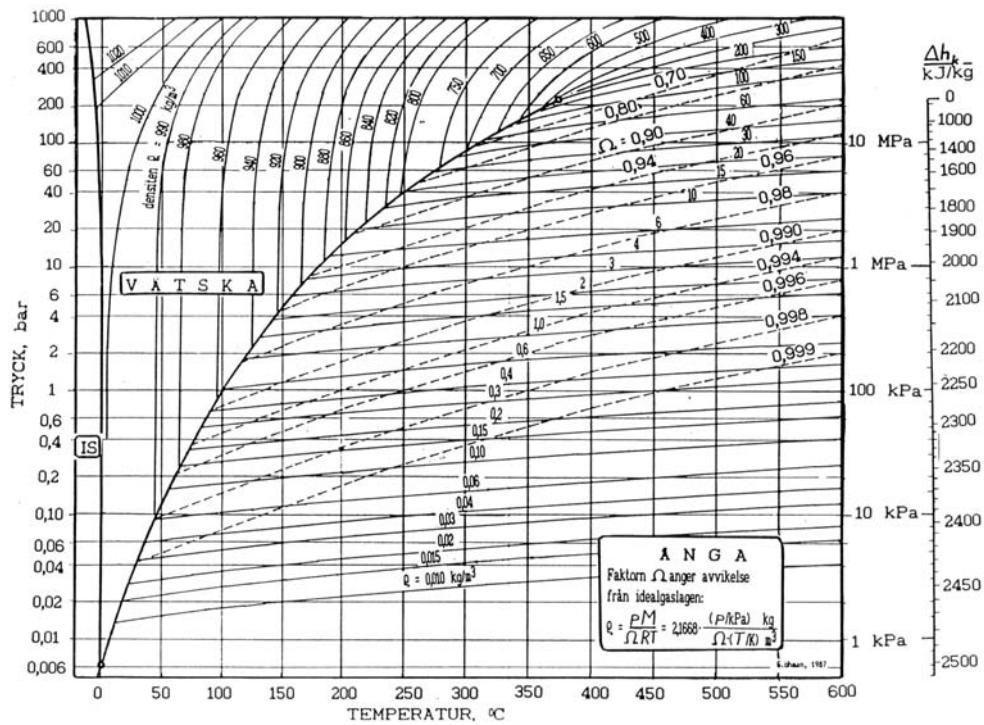
4.6 Water/steam p,T; p,h diagrams; T,s and h,s diagrams

Water/steam p,T diagram /1

p,T: **not** common diagram
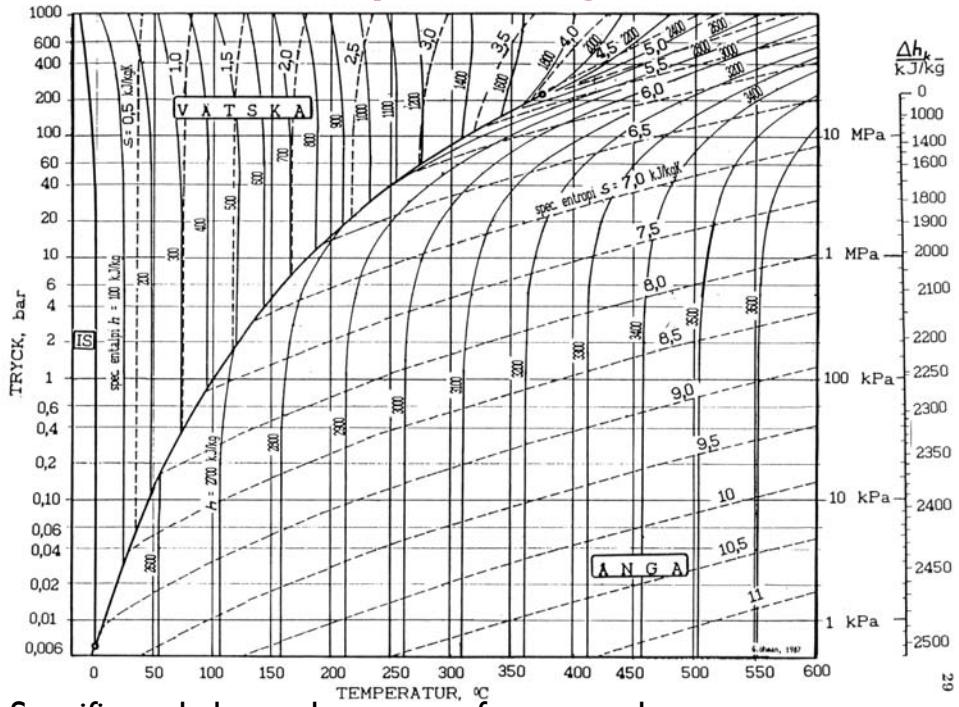
Density of water and steam   source: ÖS96, Fig. 3.5

Water/steam p,T diagram /2

p,T: **not** common diagram
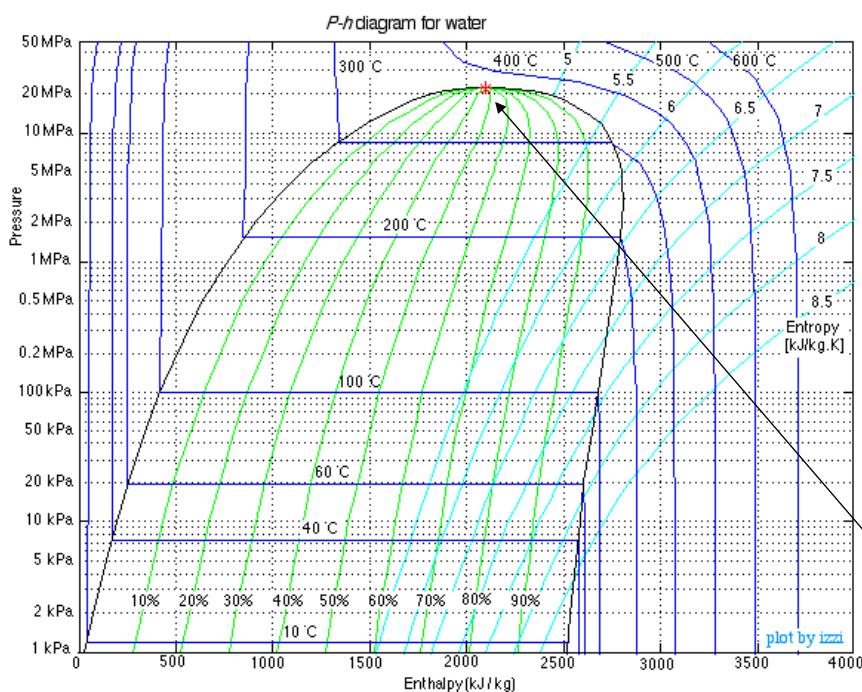
Specific enthalpy and entropy of water and steam
enthalphy h=0 kJ/kg for liquid water at 0°C source: ÖS96, Fig. 3.6

Water/steem h,p diagram

P-h diagram for water

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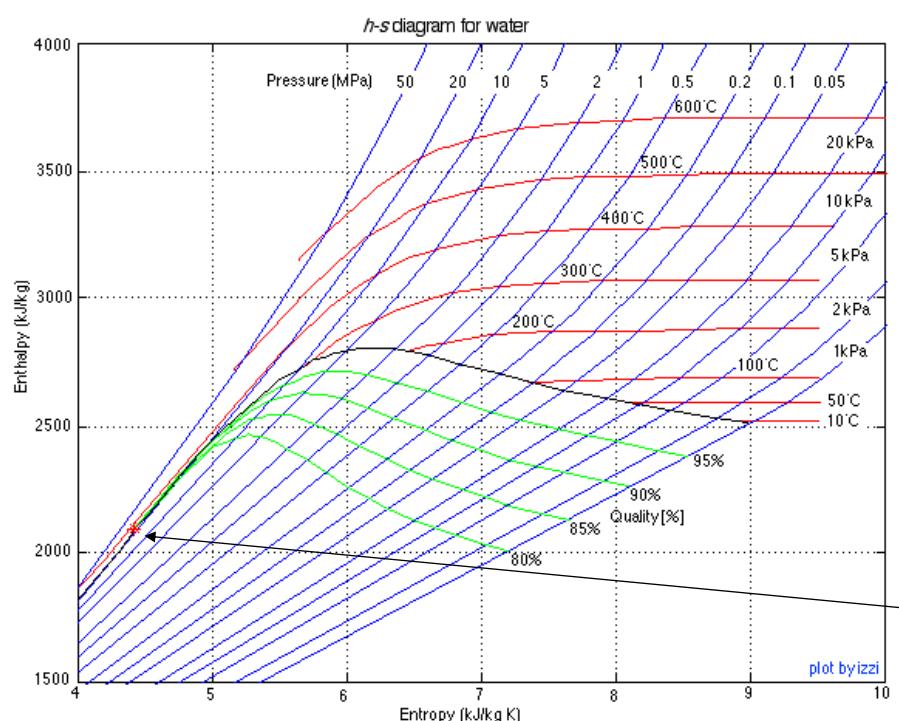
Source: http://www.ent.ohiou.edu/~thermo/property_tables/H2O/ph_water.html

Water/steam h,s diagram

h-s diagram for water

critical point
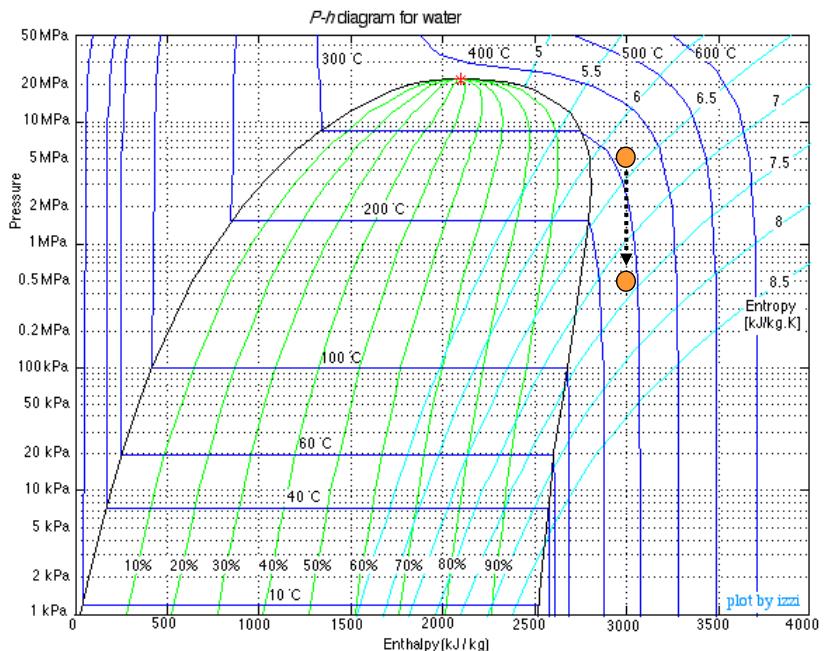
Source: http://www.ent.ohiou.edu/~thermo/property_tables/H2O/hs_water.html
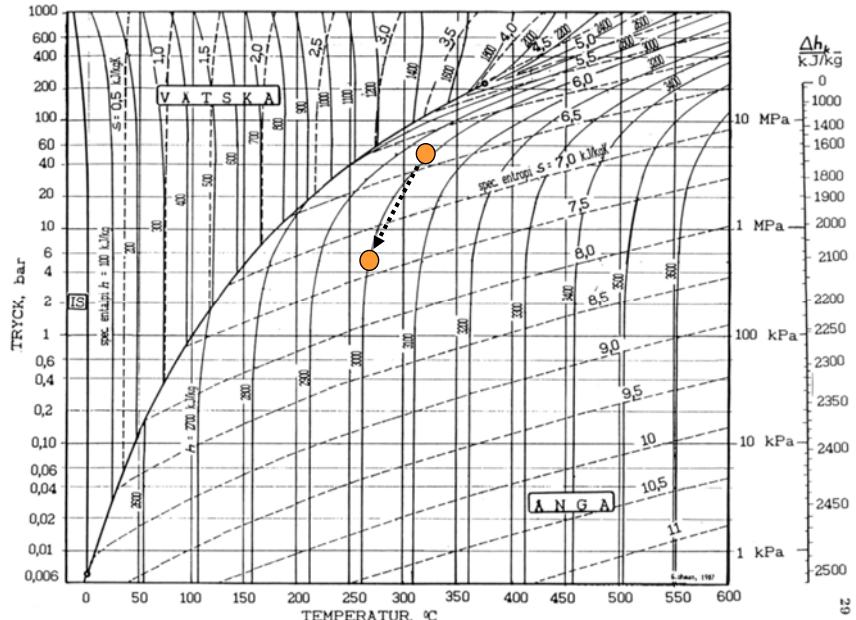
Example: h,p diagrams

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
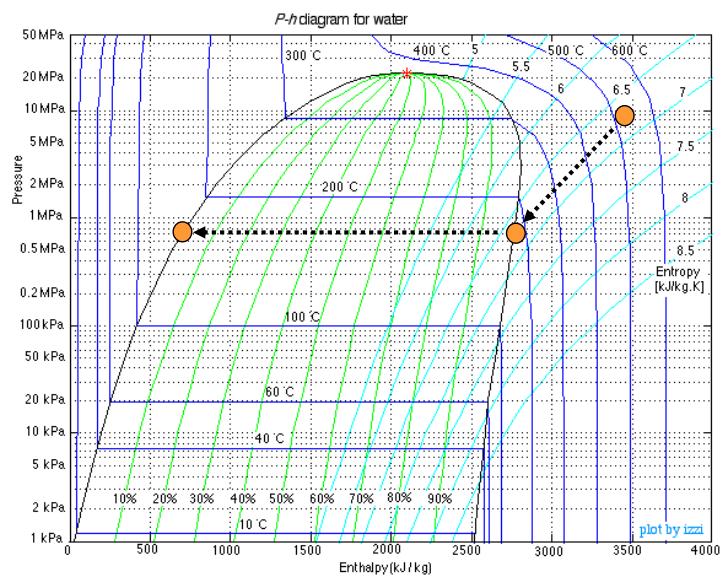
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(ÖS96-3.5a)

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.
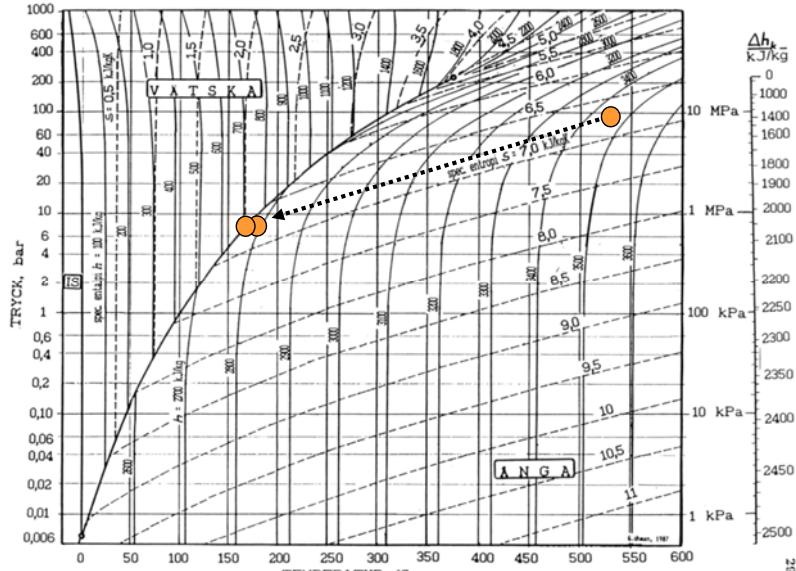
(ÖS96-3.10)

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.
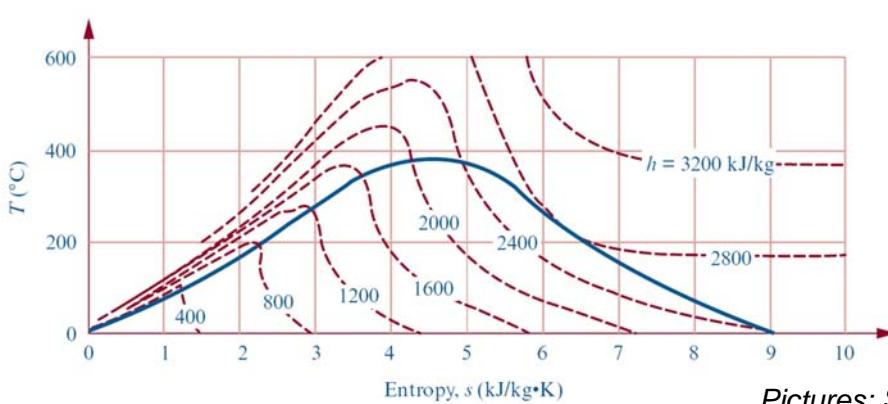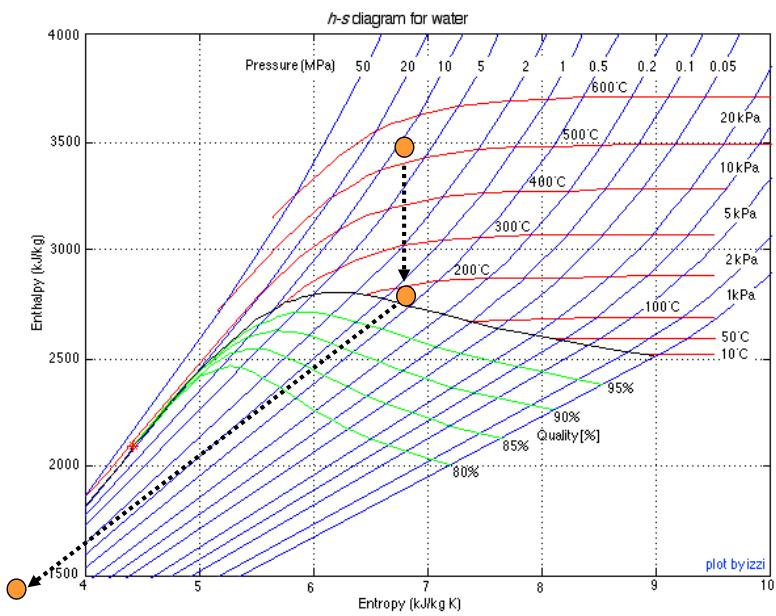
(ÖS96-3.10)

Example: h,s diagrams
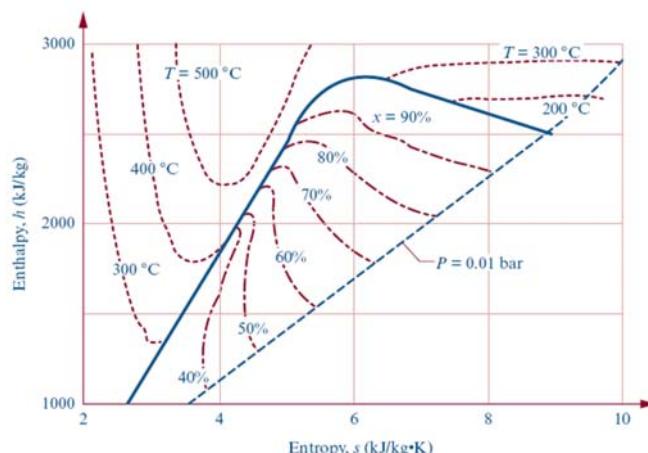
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(ÖS96-3.10)

Pictures: SEHB06

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

4.7 Combustion; Fuels

See also courses FPK1, FPK2 @ OOK

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
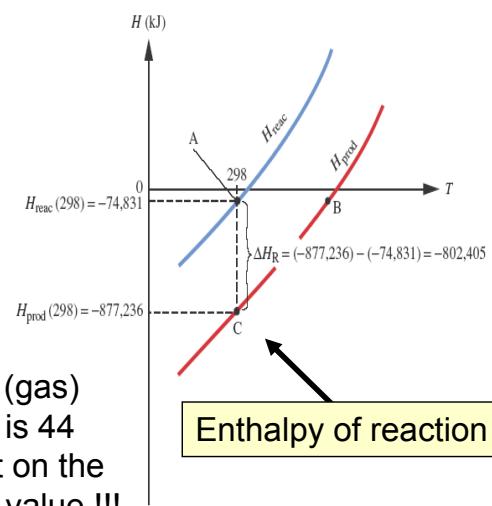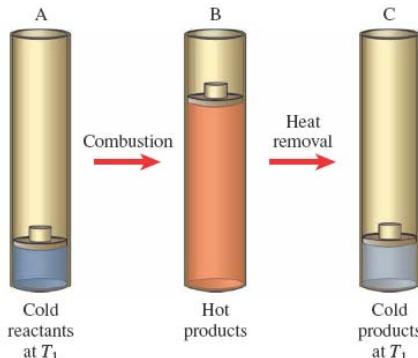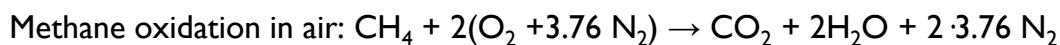
Methane, the largest component of natural gas, has a higher heating value of 55,528 kJ/kg.

Picture: T06

Enthalpy of combustion

Methane oxidation in air: $CH_4 + 2(O_2 + 3.76\,N_2) \rightarrow CO_2 + 2H_2O + 2 \cdot 3.76\,N_2$

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 H_2O(gas) product, or **higher heating value** (HHV) for H_2O(liquid) product. For example, for methane, LHV = 802 kg/mol, HHV = 890 kg/mol.

Pictures: T06

Enthalpy of reaction

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
- CO_2 / kWh power or CO_2 / km for vehicles

Fuels /2 some typical solid fuel data

	C *	H *	N *	O *	S *	Cl *	Mois-ture **	Vola-tiles **	Char **	Ash **	LHV ***	HHV ***	Stoichio-metric air need ****
Polish coal	71	4.3	1.2	11	1.3	0.07	3	35	51	11	27.4	29.3	10.0
Illinois coal	61	4.1	1.2	13	3.6	0.04	6	37	41	16	23.5	25.3	9.4
Petroleum coke	89	3.1	1.7	1.2	4.0	0	2	10	88	< 1	33.7	35.0	11.1
Finnish peat	54	5.9	1.1	34	0.15	0	9	70	17	4	21.1	23.7	8.2
Wood birch	48	6.0	0.13	46	0.03	0	5	88	7	< 1	16.9	19.5	5.3
Wood pine	49	6.0	0.17	44	0.06	0	5	85	10	0.5	17.9	20.4	5.6
Solid recovered fuel (from waste)	48	7.0	0.84	24	0.12	1.0	20	60	8	12	19.1	22.2	8.6
Sewage sludge	25	4.1	3.4	19	1.2	0.06	68	10	7	15	10.0	11.8	6.5
Meat & bone meal	42	5.8	7.5	16	0.38	0.2	7	61	6	26	16.2	18.8	7.4
Packaging waste	49	6.5	0.94	29	0.32	1.12	1	73	3	13	20.8	23.7	7.7
PVC	40	5.1	0	1	0	53.8	0	93	7	0	19.8	22.0	6.2
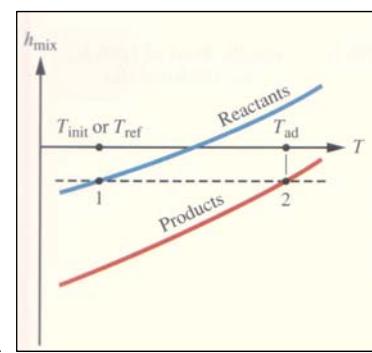
*%-wt dry; ** %-wt "as received"; *** MJ/kg; **** kg dry air / kg dry fuel

Adiabatic flame temperature /1

- Important information on fuel quality is found from the so-called **adiabatic flame temperature**, which for a <u>constant pressure</u> 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 $H_{reactants}$ at the initial temperature T_{init}, the adiabatic reaction temperature T_{ad} for the products is defined as

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

$$\Sigma_i (H_i^o + \int_{T^o}^T c_{p,i} dT)_{products} = \Sigma_i (H_i^o + \int_{T^o}^T c_{p,i} dT)_{reactants}$$

$$@ \; T = T_{r,adiabatic}$$

Picture T06

Adiabatic flame temperature /2

- The adiabatic temperature occurs at **stochiometric conditions**; excess air will lower the temperature

- 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)

- In <u>constant volume</u> combustion the adiabatic reaction temperature T_{ad} for the products is defined by internal energy U

  $U_{products}(T_{ad}) = U_{reactants}(T_{init})$

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Steam tables: pressure table
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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
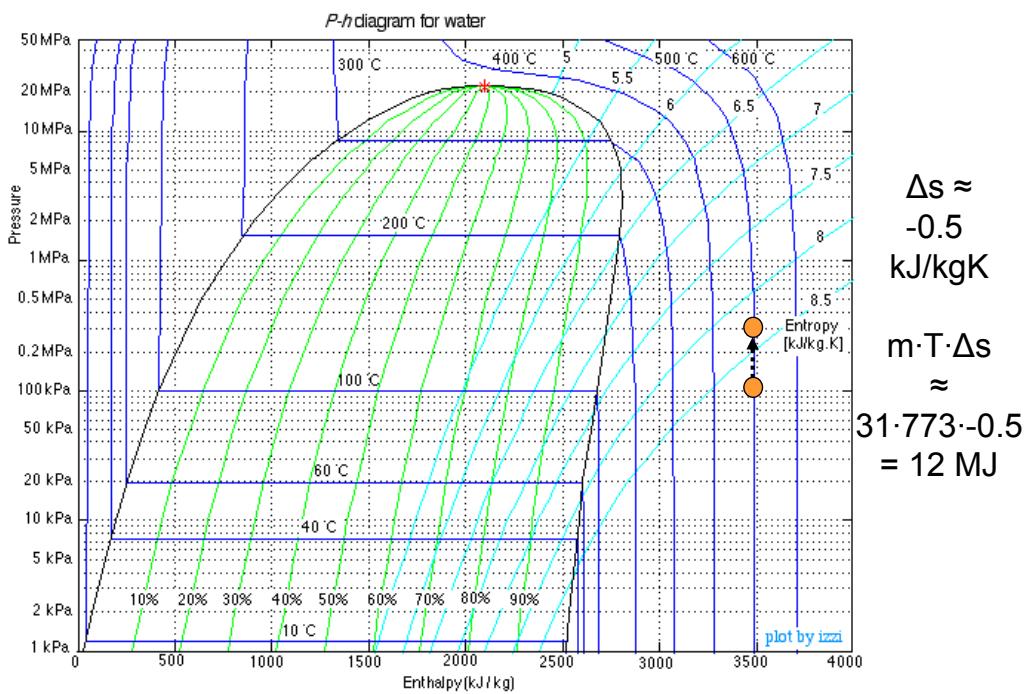
Appendix: case slide 51 h,p diagram

Δs ≈ -0.5 kJ/kgK

m·T·Δs ≈ 31·773·-0.5 = 12 MJ

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