ENERESE Training course

Lecture #2

Renewable and low-ex technologies for energy supply in high energy efficient buildings

BAT (best available technologies) for heat generation

Lecturers prof. dr. Sašo Medved

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Heat for space heating, tap water heating and air-conditioning of the buildings is dominant in final energy consumption in most of EU countries. 50% of final energy use is needed in form of heat. Moreover, advance systems for cooling can convert the heat into the coldness, reducing the use of electricity.

Heat is generated in buildings mainly by combustion of fuel in heat generator called furnace or boiler. Combustion is exothermal chemical reaction where chemical energy of fuel is transformed into heat by oxidation. Solid, liquid or gas fossil fuels or solid fuels made from biomass are used as energy carriers.

Different technologies of furnaces and boilers regarding to the fuel type will be presented in the lecture.

Flue gases are by products of the heat. Flue gasses consists substances dangerous to the environment, especially to the atmosphere. There are several technologies for improving heat generator efficiency and reduction of harmful substances in flue gasses, for example condensation boilers or low-NOx burners.
Types of heat generators: combustion of FF, RES

- **Furnaces without or with chimney**

  ![Diagram of Furnace without or with chimney]

  - Fuel
  - Air
  - Heat exchanger
  - Combustion chamber
  - Flue gases (draft driven)
  - Indoor air
  - Solid residuals (manual withdraw)

- **Boilers**

  ![Diagram of Boiler]

  - Fuel (solid, liquid, gasous)
  - Air
  - Combustion chamber
  - Heat exchanger
  - Flue gases (draft, fan driven)
  - Heat transfer fluid (steam, air, water)
  - Solid residuals (manual, mechanical withdraw)
Burning of (solid) fuels is very complex. Four phase should follow one after other:

- fuel drying phase (1); dehydration of wet fuel like wood biomass fuels occurs at temperatures up to 100 °C;
- pyrolysis phase (2); process of thermochemical decomposition where 70% to 80% of fuel decomposed into volatile compounds like \( \text{H}_2, \text{CH}_4, \) tars and the char at temperatures 200 to 300 °C and below stehiometric amount of combustion air (5); this phase is called primary combustion;
- combustion phase; volatile gasses containing carbon and hydrogen react with oxygen (6) and heat is produced; this phase is called secondary combustion;
- gasification of char (3); char reacts with oxygen and water vapour and combustible gases like \( \text{H}_2 \) and \( \text{CO} \) occurs; non-combustible residuals of char must be removed from the boiler.

Solid fuels like wood biomass burning is composed of four phases – dehydration (1), pyrolyses (2), combustion (4) and gasification of the char (3); primary (5) and secondary (6) air is needed for this thermochemical reaction.

Source: FEMOPET Slovenija
Efficiency of heat generators is defined by the part on caloric energy content of the fuel that is converted into the useful heat. Rest of the caloric energy of the fuel is lost thought flue gases and heat losses of the boiler. Efficiency depends on temperature of heated fluid and temperature of flue gases.

High temperature boilers; made from steel; water was heated continuously to 80° to 90°C to avoid condensation of water vapor from flue gases; high flue gas temperature > 180°C; efficiency up to 80%; temperature in heating system is regulated by 3-way valve.

Low temperature boilers; made from corrosion resistant cast steal; lower water temperature 45° to 65°C; flue gasses temperature 140° to 160°C; efficiency up to 95%.
**Condensing boiler**: flue gasses are cooled below dew point of water vapor and additional latent heat can be utilized; condensate must be collected and redraw into the water sink; heating water temperature is between 30° to 55°C, temperature of flue gasses ~ 40°C; fan is needed to exhaust cold flue gases; efficiency up to 103% for oil boilers, up to 109% for gas boilers.

Low temperature heating system must be used to ensure low temperature of return water. Because latent heat of water vapour is biggest when gaseous fuels is used, condensation technology is obligatory in this case in many countries.
Gas boiler with integrated flow-through heat exchanger for DHW

Gas condensation boiler with integrated heat storage (86 lit). Tap water is heated in plate heat exchanger with water from heat storage.

Gas condensation boiler with integrated heat storage (130 lit) and tube heat exchanger.

Source: www.viessmann.de
BAT heat generators: compact condensing gas boilers

Source: www.viessmann.de
Biomass boilers – log wood

1. Fill area: Large fill door, spacious fill area, long burning time
2. High-temperature circulation combustion chamber: Perfect burnout, low emission, efficient fly-ash separation
3. Air ducting: Separate adjustable primary and secondary air shutters
4. Heat exchanger: Upright tube heat exchanger with special turbulators
5. Induced draft fan: Speed-controlled, modulating capacity adjustment
6. Lambda control system: Permanent flue gas analysis, stable combustion, low emissions
7. Operating and control system KWB Comfort 3: Innovative, easy-to-operate, automatic, and unique
Use of wood-chips and especially pellets enable adjustment of thermal power to current thermal load. This can be done by precise adjustment of delivered amount of pellets and primary combustion air. In case of log-wood boilers, fuel is fed manually and only combustion air can be adjusted. This leads to lower efficiency and higher emissions.

This can be improved if buffer heat storage is connected to the boiler. Now boiler can operate at full thermal power in seldom time intervals. Volume of the HS should be 50 to 80 lit per 1 kW of boiler thermal power.

Source: www.kwb.at

KWB Easyfire pellet burner reduce the emissions of PM to 5 mg/Nm³ which is 95% less compared to old solid fuel boilers.
Boilers for biomass fuels - wood chips

KWB Multifire 15, 25, 30, 40, 50, 60, 80 and 100 kW
1. Heat exchanger: Upright, automatic dedusting heat exchanger with special turbulators
2. Combustion system: Underfeed gasifier, ring nozzle burner, high-temperature bounce dome, turbulent burnout zone
3. Fire shutter: Gas-tight, burnback-proof, tested
4. Ash removal system: Automatic ash removal, ash compaction and fill level monitoring
5. Fuel extractor: Reliable conveyor technology for rigorous individual requirements
6. Operating and control system KWB Comfort 3: Innovative, easy-to-operate, automatic, and unique
7. Stoker screw: Stainless steel spirals with carbide coating

Source: www.kwb.at
1. **Wideband lambda probe** for precise oxygen measurement, long service life through reference measuring cell and precise probe temperature regulation system

2. **Operating and control system KWB Comfort 3**: Easy-to-operate, modulating capacity adjustment (infinitely adjustable), negative pressure control system, speed monitoring of stoker motor, suction air and combustion air fans

3. **Integrated return flow temperature increase** with variable volume flow

4. **Heat exchanger with automatic cleaning** consisting of cleaning springs and high-efficiency turbulators

5. **Dust separator with cyclone effect**

6. **Combustion system**: Cast under-feed burner with stainless steel burner plate and KWB EasyFlex – reliable with different fuel qualities

7. **Fire protection device**: Cellular sluice wheel with seven transport chambers; metering screw for controlled pellet feed

8. **Automatic ash removal** into an ash container – the comfort version is movable with an extendable handle
“LowEx” systems can be defined as systems, which enabled the use of low-quality energy as energy source; this means low temperature source for heating and high temperature source for cooling. Heat contained in surrounding air or in the ground is an example of such an energy source.

Heat pumps, ground heat exchangers and systems enable evaporative cooling are one of the so-called “low-ex” technologies used for heating and/or cooling of the buildings.

Indoor comfort in the buildings can be achieved with low exergy energy sources like solar or geothermal energy, environmental heat; these energy sources are more environmentally friendly and on the long run cheaper, than high exergy sources like fossil fuels or electricity.
Buildings become much more energy efficient in last decades. As consequences the heating load for space heating as well as heat demand in such buildings is much lower.

In this case heat generators could be smaller and even more important - temperature for heating fluid could be lower. This is reason why heat generators called heat pump (HP) become very popular recently.
HP operation is based on two thermodynamic facts:

- heat transferred to heat transfer fluid is much intense if fluid change physical state (eg. liquid to vapour or vapour to liquid)

- the boiling temperature of fluid is dependent on it’s pressure. For example water boils at lower temperature that 100°C on the top of high mountain, because the air pressure at the free water surface is lower that at see level. In HP fluid can boil and change to vapour at the temperature below the 0°C if it’s pressure is sufficient low and can condensate at 50°C if pressure raise.

Much more energy is needed (received if process is reverted) if 1 kg of water is transferred to vapour comparing to heating the water from freezing point to boiling point.

This looks like temperature of ambient air in winter and temperature of heating water in heating system – aren’t they?
Therefore HP transfer heat from lower temperature source (environment) to warm sink (space in buildings).

From basic knowledge of heat transfer we know that heat flows in reverse direction! What’s wrong here?

Nothing! HP need additional energy in most cases in form of external work for that process!

The efficiency (called coefficient of operation) of HP as heat generator is measured by ratio between useful heat and external work needed for operation:

\[
\text{COP}_h = \frac{Q_{\text{out}}}{W} \quad [1]
\]
Heat pump efficiency

Maximal = theoretical value of COP or Carnot COP can be defined by **absolute temperature** of heat source $T_C$ (environment) and heat sink $T_H$ (building):

$$\text{COP}_{th,h} = \frac{T_H}{T_H - T_C} \quad [1]$$

EXAMPLE: what is theoretical COP$_{th,h}$ of the same HP if heat source has temperature $10^\circ C$ (eg. underground water) and building is well thermal insulated (sufficient temperature of heating fluid is $35^\circ C$) comparing to the case when heat source has temperature $5^\circ C$ (eg. ambient air) and temperature of heating fluid must be $55^\circ C$ because poor thermal insulation of the buildings?

$$\text{COP}_{th,h,a} = \frac{273 + 35}{(273 + 35) - (273 + 10)} = 12.3$$

$$\text{COP}_{th,h,b} = \frac{273 + 55}{(273 + 55) - (273 + 5)} = 6.56$$
Real COPs of HP are 50% to 70% lower than theoretical ones, nevertheless COP is higher if available source temperature is higher and required sink temperature is lower!

EXAMPLE: COP of commercial HP. Real COP ($= \frac{Q_{out}}{W}$) is a) 4.03 and b) 2.25. The difference is smaller, but still significant!
What the COP of 4,03 means? It means that HP will deliver 4,03 kWh of heat to the heating system meanwhile will consume 1 kWh of electricity!

The price of heat produced by HP depends upon ration between price of electricity and alternative heat source (e.g. fossil fuel) and the overall emissions of greenhouses' gasses emitted because HP is operating depends upon electricity-mix. Bought parameters must be calculated regarding to the local conditions, but in general, will point out benefits using HP.

There are some other advantage, using the HP in buildings. For example, HP can be used for space cooling, because it consists exactly the same elements as cooling engines!

Heat pump efficiency

- 1 kWh from electrical grid
- 3,03 kWh extracted from environment
- Heat delivered for space heating
Technical solution of HP

Heat source
- here working fluid evaporates at low temperature

Compressor
- compress and heat working fluid; demand electricity for operation

Expansion valve
- here working fluid expands and cool down, no additional energy is needed

Condenser
- here working fluid condensate at higher temperature

Space heating system
Technical solution of HP - elements

**Heat source**: Here working fluid evaporates at low temperature.

**Evaporator**: Here working fluid expands and cool down.

**Expansion valve**: Here working fluid expands and cool down.

**Compressor**: Compress and heat working fluid.

**Condenser**: Here working fluid condensate at higher temperature.

**Space heating system**
About heat sources

- **Ambient air** is free and widely available, and it is the most common heat source for heat pumps. Air-source heat pumps, however, achieve on average 10-30% lower seasonal performance factor (SPF) than water-source heat pumps. This is mainly due to the rapid fall in capacity and performance with decreasing outdoor temperature, the relatively high temperature difference in the evaporator and the energy needed for defrosting the evaporator and to operate the fans.

In mild and humid climates, frost will accumulate on the evaporator surface in the temperature range 0-6°C, leading to reduced capacity and performance of the heat pump system. Coil defrosting is achieved by reversing the heat pump cycle or by other, less energy-efficient means.
About heat sources

- **Exhaust (ventilation) air** is a common heat source in commercial buildings. Continuous operation of the ventilation system is required during the heating season or throughout the year. For large buildings exhaust air heat pumps are often used in combination with air-to-air heat recovery units.

- **Ground water** is available with stable temperatures (4-10°C) in many regions. The ground water is pumped up, cooled and then reinjected in a separate well or returned to surface water. Systems should be carefully designed to avoid problems such as freezing, corrosion and fouling.

A major disadvantage of ground water heat pumps is the cost of installing the heat source. Additionally, local regulations may impose severe constraints regarding interference with the water table and the possibility of soil pollution.

Source: Termotehnika
About heat sources – most used

- **Ground-source** HP are used for residential and commercial applications, and have similar advantages as water-source HPs, because the ground deep enough has relatively high and constant annual temperatures.

Heat is extracted from pipes laid horizontally or vertically in the soil (horizontal/vertical ground heat exchangers/coils). In most cases brine solution (mixture of water and antifreeze fluid) is used because temperature out of the expansion valve could be below freezing point of the water.
About heat sources

- Beside that, direct expansion with the working fluid evaporating in underground heat exchanger pipes can be utilize. Due to the extra internal temperature difference, heat pump brine systems generally have a lower performance, but are easier to maintain.

Extracted quantity of heat from the soil varies with the moisture content and the climatic conditions. Due to the extraction of heat, the soil temperature will fall during the heating season. In cold regions most of the energy is extracted as latent heat when the soil freezes. However, in summer the sun will raise the ground temperature, and complete temperature recovery may be possible.
Sizing of HP – rule of thumb

- HP for DHW

Heat source: air

Heating power: 2kW to 15 kW

COP: 4

Duration: all year

Alternative systems: in combination with heating system, in combination with solar thermal system, in combination with ventilation system

Source: Termotehnika
HP for heating

Heat source: air

Heating power: 4 kW to 40 kW

Nominal air flow rate: 0.15 m³/h per 1 kW power

COP: 2.8 to 4.3

Alternative systems: in combination with electrical heater, in combination with heating system, in combination with solar thermal system

Defrosting of the evaporator is necessary

Easy installation without earth work

Source: Lebensräume, Konemmnn, Termotehnika
Sizing of HP – rule of thumb

- HP for heating – water to water/ water to air

Heat source: underground water, river water, waste water, temperature 8 to 12°C

Heating power: 4 kW to 100+ kW

Nominal ground water flow rate: 200-300 l/h per 1 kW power

COP: 5 to 6

Alternative systems: not necessary

Before installing pressure pumping test and chemical analyze of ground water is needed.

Source: Lebensräume, Konemmnn, Termotehnika
Sizing of HP – rule of thumb

- Nominal ground water flow rate: 0.2 m³/h per 1 kW power
- Hole deep: 3 to 60 m
- Minimal distance between production and reinjection hole: 15 m
- Cost of drilling: 50 - 100 €/m

Source: Lebensräume, Konemmnn, Termotehnika
Sizing of HP – rule of thumb

- HP for heating – ground to water/ground to air

Heat source: underground water, river water, waste water, temperature 0 to 10°C

Heating power: 4 kW to 100+ kW

Nominal size of horizontal heat exchanger: 20 to 35 W per m length, 10-30 W/m² of the soil

Size of the used ground: 2 to 3 times of heated area in building, no construction on this area (carport, pool)

Distance between tubes: 0.8 m to 1 m, PE, water-glycol dilution (brine) should be used

COP: 4 to 4.5

Alternative systems: not necessary

Source: Lebensräume, Konemmnn, Termotehnika
Sizing of HP – rule of thumb

- HP for heating – ground to water/ground to air

In case of direct evaporation the refrigerant circulating in the earth collector and withdraws the energy from the earth, which means that the collector is the evaporator.

Advantage: smaller amount of equipment, higher annual efficiency

Danger: leakages – exposure of the refrigerant to the environment

Source: Lebensräume, Konemmn, Termotechnik
Sizing of HP – rule of thumb

- HP for heating – ground to water/ground to air

  Heat source: underground water, river water, waste water, temperature 0 to 10°C

  Heating power: 4 kW to 100+ kW

  Nominal size of vertical heat exchanger: 50 – 55 W per m length

  Distance between tubes: 5 m to 7 m, PE, water-glycol dilution (brine) must be used

  Cost of drilling: 70 -100 €/m

  COP: 4 to 4,5

  Alternative systems: not necessary
Environmental issues of HP

- as working fluid “freons” with chlorine, fluorine or bromine, like CFC-11 or CFC-12, was used in the past. Such fluids are “ozone depletion chemicals” and have a high “ODP ozone depletion potential”. When escape from HP, freon travel through troposphere into stratosphere and decompose ozone molecules ozone \( \text{O}_3 \) at the upper layer of stratosphere. This is harmful process, because \( \text{O}_3 \) in stratosphere act as shield for the part of danger UV solar radiation. This process is known as enlarging of “ozone hole”

- since the year 2000 CFC’s, as result of several international agreement (Copenhagen’s, London’s) are not allowed and nowadays. However, by HP decomposition, working fluids must not be realise to atmosphere!

- hydrofluorocarbons (HFCs) like R134a, R407c and R410a are commonly used in heat pumps (electricity driven compressors) their ozone depletion potential is zero, however they have a high global warming potential (on 100 years base) between approx. 1300 and 1700 (R134a Tetrafluorethane C2H2F4, R407c a blend of R32/R125/R134a, R410a a blend of R32/R125).

- in the future natural refrigerants shall be used like propane (R290), propane (R1270), ammoniac (R717), carbon dioxide (R744) or water (R718) with zero ODP and zero or low GWP
Solar radiation is most important energy source for the planet Earth. Less that 0.05% of primary energy needed nowadays is provided using non-renewable energy sources.

Almost 50% of all final energy in EU is needed in form of heat, 80% of that at the temperature level below 250°C.

This heat could be entirely produced by thermal solar systems. This are systems that convert, store and delivery heat to the user when the heat is needed.

Thermal solar collectors as heat generators will be discussed in this lecture.

Most of the heat demand at temperature level below 250°C could be covered with utilization of solar energy.
Thermal solar collectors (SC) – types regarding to the heat transfer media

- Thermal solar collectors are devices that convert solar radiation into the heat and transfer heat to the heat transfer fluid.

- Transfer fluid could be water, mixture of water and antifreeze solution or high thermal resistant oil in case of liquid solar collectors (LSC) or air in case of air solar collectors (ASC).
Thermal solar collectors (SC) – open and close loop systems

- Thermal solar collectors can operate in close or open system. In close systems heat transfer fluid flows in pipes or channels into heat storage or into the building, cool down and return to SC.

- In open cycle systems heat transfer fluid is taken from surroundings and heat up in SC. Mainly ASC operates in such a way as preheated for ventilation air.

When operate in closed system, SC heat up transfer fluid circulating in pipes or channels. In open systems, heat transfer fluid entrance into SC directly from ambient. Such kind of operation is not common for LSC, but is widely used then ASC is used for preheating of ventilation air or for drying crops.

Source: James&James
Low temperature: air/unglazed
Mid-temperature: Flat plate/vacuum
High temperature concentrators

- Air preheating, space heating, drying, pool heating
- Domestic hot water heating, space heating, drying, solar cooling
- Solar cooling, process heat

Thermal solar collectors (SC) – operation temperature
Efficiency of thermal solar collectors

- Thermal solar collector consist of absorber with pipes or channels where heat transfer fluid flows, transparent cover, back and edge thermal insulation and casing.

- Heat flux balance in SSE

\[
G_{\text{glob}, \beta} \quad \text{on the cover reflected solar radiation} \\
G_{\text{abs}} \quad \text{on the absorber reflected solar radiation} \\
\dot{q}_{\text{loss, top}} \\
\dot{q}_{\text{loss, bottom}} \\
\dot{q}_{\text{useful}} \\
\]

- \( G_{\text{glob}, \beta} \): solar radiation on the SC cover
- \( G_{\text{abs}} \): absorbed solar radiation
- \( \dot{q}_{\text{loss, top}} \): heat flux from the absorber to environment through the cover
- \( \dot{q}_{\text{loss, bottom}} \): heat flux thought bottom and edge thermal insulation
- \( \dot{q}_{\text{useful}} \): heat flux transferred by heat transfer fluid out of the 1 m² of SC
Absorbed solar radiation per 1 m² SC is equal to:

$$G_{abs} = G_{glob, \beta} \cdot \tau_{cover} \cdot \alpha_{absorber}$$

- $G_{glob, \beta}$: solar radiation transmittance of the cover (W/m²)
- $\tau_{cover}$: solar radiation transmittance of the cover (-)
- $\alpha_{absorber}$: solar radiation absorption of the absorber (-)

Heat losses are equal to:

$$\dot{q}_{loss} = \dot{q}_{loss, bottom} + \dot{q}_{loss, top} - U_{SC} \cdot (T_{abs} - T_{amb})$$

- $U_{SC}$: overall thermal transmittance of the SC (W/m²K)
- $T_{abs}$: absorber temperature (°C, K)
- $T_{amb}$: ambient temperature (°C, K)
Specific useful heat flux produced by 1 m² of SC is equal to:

\[
\dot{q}_{\text{useful}} = G_{\text{abs}} - \dot{Q}_{\text{loss}}
\]

\[
\dot{q}_{\text{useful}} = G_{\text{glob}, \beta} \cdot \tau_{\text{cover}} \cdot \alpha_{\text{absorber}} - U_{\text{SC}} \cdot (T_{\text{abs}} - T_{\text{amb}})
\]

Two problems:

? How to calculate overall thermal transmittance \( U_{\text{SC}} \)

? How to calculate \( T_{\text{abs}} \) since it defers from point to point on the absorber

Thermal image of the unglazed SC: big difference between the temperatures of fins and pipes on absorber can be seen
Efficiency of thermal solar collectors

- For real products analytical models are too simple and efficiency of solar collectors is most cased deteminate by field measurements. The test procedure is standardized (EN ISO 9806 group standards).

- In this case calorimetric methods are used for determination of $Q_{\text{useful}}$ at different operating conditions. Heat flux (or SC thermal power) is calculated as average value in time interval between $t_1$ and $t_2$:

$$
\dot{Q}_{\text{useful}} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \dot{m} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}}) \, \text{dt} \quad [W]
$$

- Integral equation can be discrediteded in a form:

$$
\dot{Q}_{\text{useful}} = \frac{1}{N} \sum_{1}^{N} \dot{m} \cdot c_p \cdot (T_{\text{out},N} - T_{\text{in},N}) \quad [W]
$$

- $m$ - mass flow rate (kg/s)
- $c_p$ - heat capacity of heat transfer fluid (J/kgK)
- $T_{\text{out}}$ - outlet heat transfer fluid temperature (K)
- $T_{\text{in}}$ - inlet heat transfer fluid temperature (K)
- $t_1$ - start time (s)
- $t_2$ - end time (s)
- $N$ - number of discrete measurements
Efficiency of thermal solar collectors

- Efficiency of SC is then defined as:

\[
\eta_{SC} = \frac{\dot{Q}_{useful}}{A_{SC} \cdot G_{glob,\beta}} [1]
\]

- Linear fit to data *(see next page)* can be used presenting temperature and solar radiation flux dependant SC efficiency:

\[
\eta_{SC} = \eta_0 - a_1 \cdot T^* [1]
\]

\( T^* \) reduced temperature difference (Km²/W)
In theory values of $F'$ are between 0 and 1. It is obvious that $F'$ should be close to the 1 to. How this can be achieved?

With high fin efficiency – tubs in LSC are bonded to heat conductive fin. In this way cost of absorber is lower. If fin has reasonable short length $l_{\text{fin}} \sim 100$ to $120$ mm), good thermal conductivity ($\lambda_{\text{fin}} > 150$ W/mK) and thickness $d_{\text{fin}} \sim 0.5$ mm, the fin efficiency will be above 0.97.

Rubber made unglazed SC absorber for low temperature applications (pool heating) shown on the picture must have very short fins, since rubber has low thermal conductivity; that’s way rubber tubes are so close together.
In theory values of $F'$ are between 0 and 1. It is obvious that $F'$ should be close to the 1 to. How this can be achieved?

- by reducing bond conductance between absorber fin and tubes; several techniques can be used, like roll-bond, ultrasound or laser welding.

Efficiency of thermal solar collectors

absorber made by roll-bond technique, two Al and two Cu ribbons are press together to ensure best possible contact between Al fin and Cu pipe

2 to 3 mm thick visible line at the top of the absorber is characteristic for ultrasound welding

nearly invisible points at the top of the absorber indicate laser welding
In theory values of $F'$ are between 0 and 1. It is obvious that $F'$ should be close to the 1 to. How this can be achieved?

- Tubes in LSC could be in form of serpentine or parallel between two integrated collective tubes at the bottom and top of the SC.

- In case of vacuum SC heat transfer fluids flows either thought “U-shaped” pipe or heat pipe is used for transfer heat from SC to collective pipe at the top of SC.
Efficiency of thermal solar collectors

- Efficiency of SC can be determined by outdoor test or indoor test using solar simulator. In both cases, this is steady state efficiency – “instantaneous efficiency”. Term $\eta_0$ is “eta zero” or optical efficiency, constant $a_1$ is regression slope coefficient.

- Measured point – at least 16 points must be determinate by constant mass flow rate (0.02 kg/s m$^2$ SC), with solar radiation intensity greater than 800 W/m$^2$ and at different reduced temperature difference $T^\ast$. Typical measurement error is indicated for each point.

- Because area of SC ($A_{SC}$) is needed for calculation of efficiency, this can cause some obscurity; $A_{SC}$ can be measures as absorber area, aperture area or gross area of SC. The differences between them are extreme in case of vacuum (tube) SC.
Efficiency of thermal solar collectors – how can be improved?

- using low-iron glass transitivity of cover of solar radiation is enlarged

Ordinary window glass consist ferrous oxides. That’s why edge colour of such glass is slightly green. SC glass cover without ferrous oxides (so called low-iron glass) is more transparent for solar radiation. This improves efficiency at all operating temperatures.

- with selective absorber layer, using coating or sputtering procedure, highly solar radiation (short wave) layer can have very low emissivity for thermal radiation (long wave). This property is measured by selectivity $S$:

$$S = \frac{\alpha_{S,\text{absorber}}}{\varepsilon_{\text{IR,absorber}}} \quad [1]$$

$\alpha_{S,\text{absorber}} = 0.95 \quad \varepsilon_{\text{IR,absorber}} = 0.05$

Ordinary bloc paint has $S \approx 1$, meanwhile $S$ up to 20 is characteristic for contemporary SC
Selective layer reduce radiation heat losses between absorber and cover. Further improving of efficiency can be achieved if air is removed from interior of SC. If technical vacuum (absolute pressure is lower than 0.05 Pa) is reached, convection heat losses between absorber and cover are almost zero.

Because high pressure difference between environment and interior of SC, casing must be inform of tube.

Vacuum SC has little lower optical efficiency (zero eta) $\eta_o$ comparing to flat plate SC, because some spacing between tubes is necessary for avoiding shading effect.
### Efficiency of thermal solar collectors

<table>
<thead>
<tr>
<th>Type of SC</th>
<th>$\eta_0$ (-)</th>
<th>$a_1$ (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unglased</td>
<td>0.85</td>
<td>20</td>
</tr>
<tr>
<td>Flat, black painted absorber</td>
<td>0.80-0.82</td>
<td>7-9</td>
</tr>
<tr>
<td>Selective</td>
<td>0.75-0.80</td>
<td>4-5</td>
</tr>
<tr>
<td>Selective with low-iron glass</td>
<td>0.82-0.85</td>
<td>4-5</td>
</tr>
<tr>
<td>Vakuum</td>
<td>0.70-0.75</td>
<td>1.5-2.5</td>
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Share of different technologies of SC on Austrian market.
Integration into the buildings

- Quite often installing of SC is not appreciated by architects or urban planners. In heritage cities SC are not allowed to be installed on visible parts of the facades or roofs.

- Several solutions are available to overcome this problem:

  Integration into the roof construction; beside good looking, such installing improve efficiency of SC, because back heat losses decreasing. In some countries such mounting is obligatory (ex. In Slovenia)

Source: James&James
Most popular applications of thermal solar systems (TSS)

- Domestic tap water heating is most popular application of TSS. Beside SC, components like heat storage, piping, circulation pump, backup heating and regulation consist such systems. ! To 2 m² of SC per person and volume of heat storage 50 to 75 lit per 1 m² of SC is typical for this systems.

Heat storage with integrated tube heat exchangers. Bottom one is connected with SC, top one with backup heat generator.
Most popular applications of thermal solar systems (TSS)

- Space heating assisted TSS have larger solar collector area (up to 1/3 m² of SC per 1 m² heated area and larger heat storage - up to several m³ in family house. Heat storage has integrated smaller heat storage for tap water heating. Important is temperature stratification inside heat storage. Adequate computer tool is needed for planning.

Heat storage with integrated heat exchanger or heat storage for tap water heating. Wirth intakes on different highs, thermal stratification can be achieved. This improves exergy balance of the system.
Most popular applications of thermal solar systems (TSS)

- TSS for multifamily building become very popular in recent years. Four pipes (left) or two pipes systems (right) are common.

In case of four pipes TSS, tap water system is divided from space heating. Backup heating is needed. Special care to avoiding growth of microorganisms is needed – such thermal shock, then whole system is heated up to 60° to 70° for several hours once per week.

Two pipes TSS are more advanced. Each flat has own heating substation for space and tap water heating. Tap water is heated on demand through integrated plate heat exchanger. This prevent unhealthy tap water conditions. Return water has lower temperature. As consequence, SC operate with higher efficiency.
Heat production – calculation methods

Rule of thumb

- Yearly production of heat (heat indicated per 1 m² of aperture area of SC for place having yearly solar irradiation ~ 1200 kWh/m²) differ a lot upon technology:

  - Unglassed SC; 250 kWh/m²a
  - Flat, selective SC; 500 kWh/m²a
  - Vacuum SC; 650 kWh/m²a

- If SC are not orientated optimal (due to SE-S-SW direction, with tilt angle between 25° to 45°, the reduction factor, shown on the figure, must be taken into account. Tilt angle should be decrease for 10° for summer-only operating systems, and increased for 10° for solar heating assisted systems. (Attention: chart is valid for latitudes between 30° and 50°)
EXAMPLE:

Flat, selective SC will be installed at optimal orientation in the city having annual global solar irradiation 1000 kWh/m². SC will be used for domestic tap water heating in one family building. Useful area of building is 120 m². If 65% of tap water should be prepared by solar system, what will be required SC area?

Average heat demand for tap water heating is 12 kWh to 16 kWh per year per 1 m² of house useful area:

- \( Q_{\text{tap}} = 15 \text{ kWh/m}^2 \text{a} \times 120 \text{ m}^2 = 1800 \text{ kWh/}\text{a} \)
- \( \text{Asc} = 0.65 \times \frac{Q_{\text{tap}}}{500 \times 1000/1200} = 2.81 \rightarrow 3 \text{ m}^2 \)

Note: fraction 1000/1200 is correction factor of solar irradiation on the site
The future of thermal solar systems (TSS)

- Past market development and future plans for TSS in EU. For wider implementation of TSS, reduction of cost will be crucial, as well as improved confidence of investors. Methods, such as “Guaranteed solar results contract” can play important role.

- European Solar Thermal Technology Platform published ambition plans for the year 2030.

- EPBD 2 -> all new buildings after 2018 (2020) must be “Near Zero Energy Houses”. TSS will have an important role if this goal will be achieved.
Ground heat exchangers

- Ground heat exchanger (GHX) are made from tubes or channels buried horizontally 1 to 2 m below the surface. Ground heat exchangers can be dug in vertically into the ground, in this case depth between 50 to 100 m are common.

- Polypropylene tubes for small and concrete tubes for large systems, as well as concrete channels are usually used.

- Heat transfer fluid is most cases ambient air, but can be water as well.

- Ground heat exchangers can operate as open looped system, in this case air is used as heat transfer fluid, or as close loop system. In this case water is common heat transfer fluid.
Regarding to the temperature, ground can be divided in three layers: shallow sub-surface layer (up to 20 m below the surface), mid layer (20 to 50 m) and deep layer (below 100 m).

In sub-surface layer strong influence of solar radiation and ambient temperature is noticed; that’s why temperature in ground up to 20 m deep varies periodically with period of one year.

In mid layer, temperatures are constant (no gradient is present). Below this layer, temperatures are not time dependant and slightly rise with deepness. Gradient dT/dz depends on thermal properties of ground, under ground water presents and geological structure. Average values are between 30°C/km and 80°C/km.
Engineering solutions

- Technical characteristics and operation principles of multy-parallel tube open cycle air ground heat exchanger. If such system is used for pre-cooling, bypass for night-time summer cooling must be installed as it is shown on the picture.
Close loop water ground heat exchanger. In this case pump, expansion vessel and heat exchanger in ventilation system is needed. Main advantage of such systems is much lower electricity consumption for running pump in comparison to ventilator in open loop systems.

Two parallel polietilen tubes are installed for enlarging of heat transfer surface.

Additional pump and expansion vessel are needed (right) as well as additional heat exchanger which is installed in ventilation system (most right).
Concrete tube ground heat exchanger (U-tube type) with diameter of 800 mm and length 75 m for pre-heating of ventilation air in Shopping centre. Air flow rate 2800 $\text{m}^3/\text{h}$.

This is how the concrete tubes look likes. Two channel are connected in U-tube form.

Tubes are mounted under the small angle. This enables cleaning of inner surface and runaway of the (potential) water. Here difference in depth of channel can be notes at the beginning (left) and at the U-turn (right).
Ambient and soil temperature on the site

Heat / coldness transferred into the building

<table>
<thead>
<tr>
<th>Deepness of GHX</th>
<th>1,7 m</th>
<th>2,3 m</th>
<th>2,9 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat (kWh/a)</td>
<td>8286</td>
<td>9328</td>
<td>10239</td>
</tr>
<tr>
<td>Coldness (kWh/a)</td>
<td>(-)4551</td>
<td>(-)5311</td>
<td>(-)5943</td>
</tr>
</tbody>
</table>

Outlet and inlet air temperature difference

Heat / coldness transferred into the building
Ground heat exchanger of Office building. Six parallel polypropylene tubes with length of 35 m and diameter of 315 mm are connected with tube 500 mm in diameter. Special pipes with antibacterial inner layer (AWADUKT) produced by REHAU company are used for sanitary reasons. Configuration was optimized regarding to heat transfer surface area, heat transfer coefficient (air flow rate) and pressure drop (electricity demand for running the ventilator).

Six parallel tubes are connected with connection pipe (here intake side can be seen) and buried 1,5 m bellow finished surface.
Air is a mixture of gases and water vapour. Amount of water vapour is dependant on temperature of the air. If air is saturated, than content maximal amount of water vapour at this temperature. Partial pressure of water vapour in total air pressure is called saturation pressure ($p_{\text{sat}}$).

In indoor air is not saturated. Therefore the water vapour pressure is lower that saturated and equal to $p_i$. Relative humidity of air is defined by:

$$\varphi = \frac{p_i}{p_{\text{sat}}} \cdot 100 \%$$

Air humidity can be express as absolute humidity $x$. This is mass of water vapour in unit mass of dry air:

$$x = \left[ \frac{\text{kg}}{\text{kg}} \right]$$
Water vapour in the air could change phase to water or ice. Such processes are related to latent heat transfer. Therefore heat transfer to and from the air can’t be analyze just with it temperatures. New thermodynamic properties of moist air must be used – it’s called enthalpy.

Thermodynamic state of air can be shown on Mollier T-x or psychometric chart shown on the figure.

Evaporative cooling is thermodynamic process of adding water (in form of small droplets or fog) into the air, meanwhile enthalpy of the air remain constant (h = cont).
EXAMPLE:

- If 4 grams of water evaporates into the 1 kg of surrounding air near the fountain having temperature $t_1$ 29°C and relative humidity $\phi_1$ 30%, what will be the temperature of the air?

- Answer: $t_2$ 19°C
Beside using plants or water areas, air can be cooled by evaporation in mechanical devices. Two of such air misting appliances are shown.
EXAMPLE:

- How much water is needed per 1 kg of air with temperature $t_1$ 33°C and relative humidity $\varphi_1$ 38%, if humidifier efficiency $\eta_{\text{humid}}$ is 65%?

\[
\eta_{\text{humid}} = \frac{\Delta x}{\Delta x_{\text{max}}} \cdot 100 \quad [\%]
\]

From chart can be seen that $\Delta X_{\text{max}}$ is equal 5 g/kg ->

\[
\Delta x = \frac{\eta_{\text{humid}} \cdot \Delta x_{\text{max}}}{100} \quad [\%]
\]

- Answer: $\Delta x$ is 3.25 g/kg
Instead of humidifying of the fresh air, exhaust air living the building is humidified. Another type of humidifier is used in this case – plate heat exchanger. It is the same element that is used for heat recovery in winter time.

During the summer heat transfer in heat exchanger is enhance because simultaneous heat and mass transfer. Evaporation cooling is more intense because water flows in thin layers all over heat exchanger plates.

Because exhaust air is humidified instead of fresh, supply air, the presents of water droplets potentially caring microorganisms in supply air is eliminated as well.
Air handling unit with integrated evaporative cooling is shown on figure (Menerga).

Efficiency of evaporative cooling depends mostly on local climate (state of supply air), size of heat exchanger and humidifier efficiency. Special computer tool must be used for hour-to-hour analyzes.
Overall efficiency of evaporative cooling technique is presented on chart for location with mild summer. It can be concluded that evaporative cooling is most efficient when needed most – during hottest period of the year. This is perfect for “peak shaving” of electricity use. Therefore evaporative cooling should be used every time if climate conditions are suitable. This technique of energy conservation is already mandatory in some countries – in Slovenia for example.
Why efficiency of condensation boilers is more than 100%?

What you know about heat generators for combined heating and tap water heating?

Describe main elements of pellets boilers!

What is the COP of the heat pumps?

Explain how COP is dependent on heat source temperature!

Explain the thermodynamics behind the HP operation!

Describe commonly used HP heat sources! How these heat sources influence on COP of HP?

What you are know about environmental impacts of HP?

Describe the types of solar collectors regarding to the heat carriers and solar thermal systems regarding to the operation temperature?

How efficiency curve of the SC can be constructed?

What you know about the types of solar thermal systems?

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