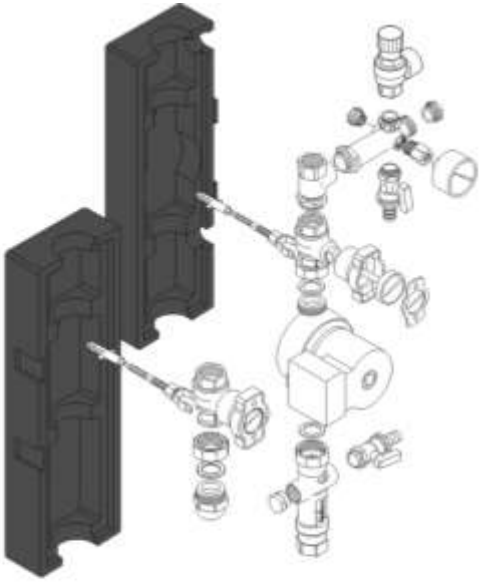
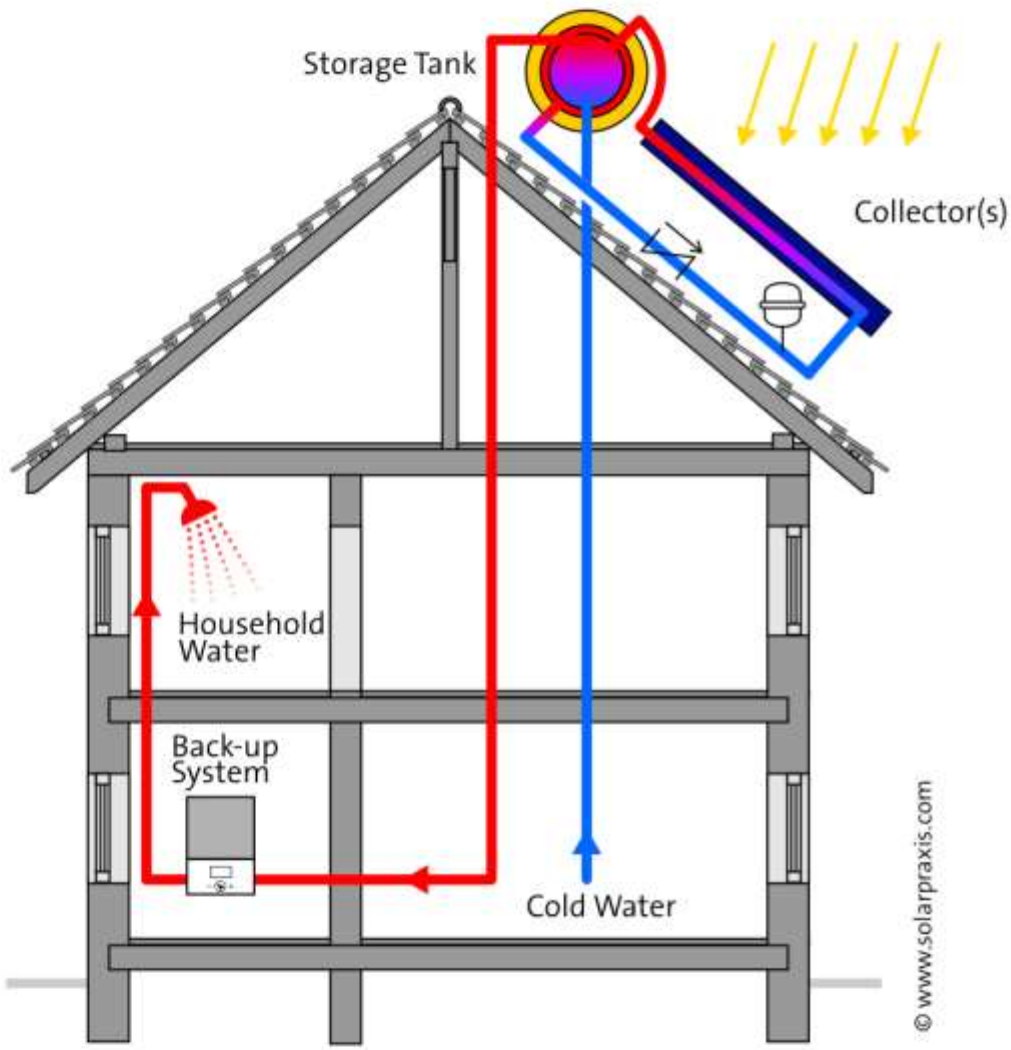
Components of solar systems

- storage
- heat exchangers
- safety and protection devices
- air vents, check valve
- control & measurement



Thermosiphon circulation system

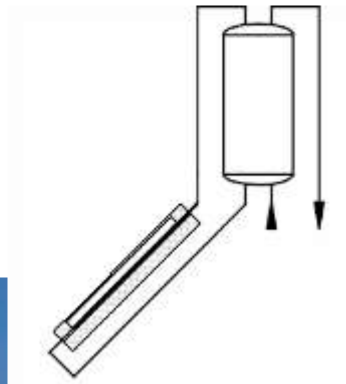


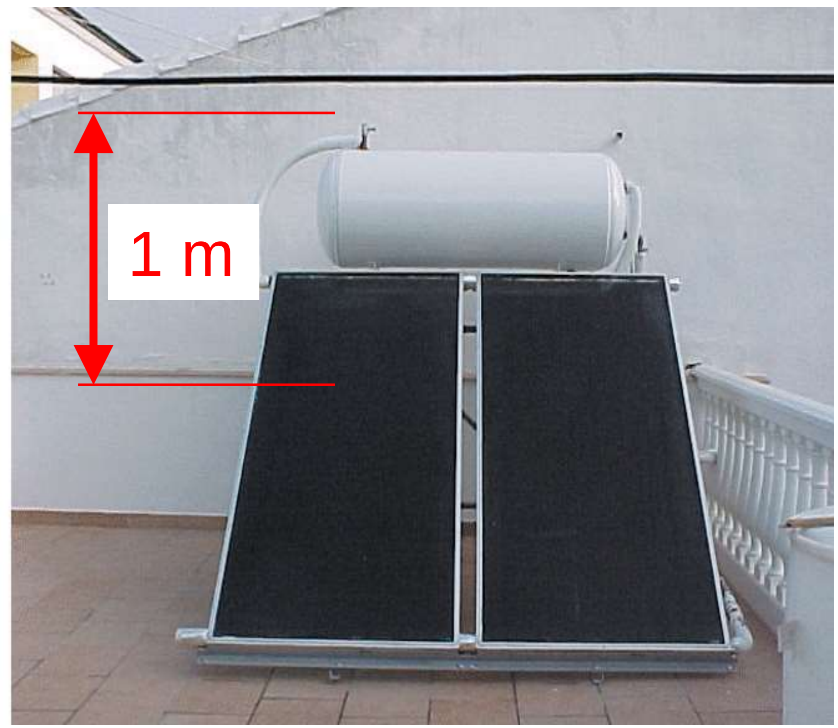
- **circulation induced by buoyancy effect**
  - difference in densities (temperatures) of fluid

water density: 20 °C is 998 kg/m3
80 °C only 972 kg/m3…. Dif ..26kg

- **self-controlled system**
  - higher temperature in collector – higher circulation (flowrate)

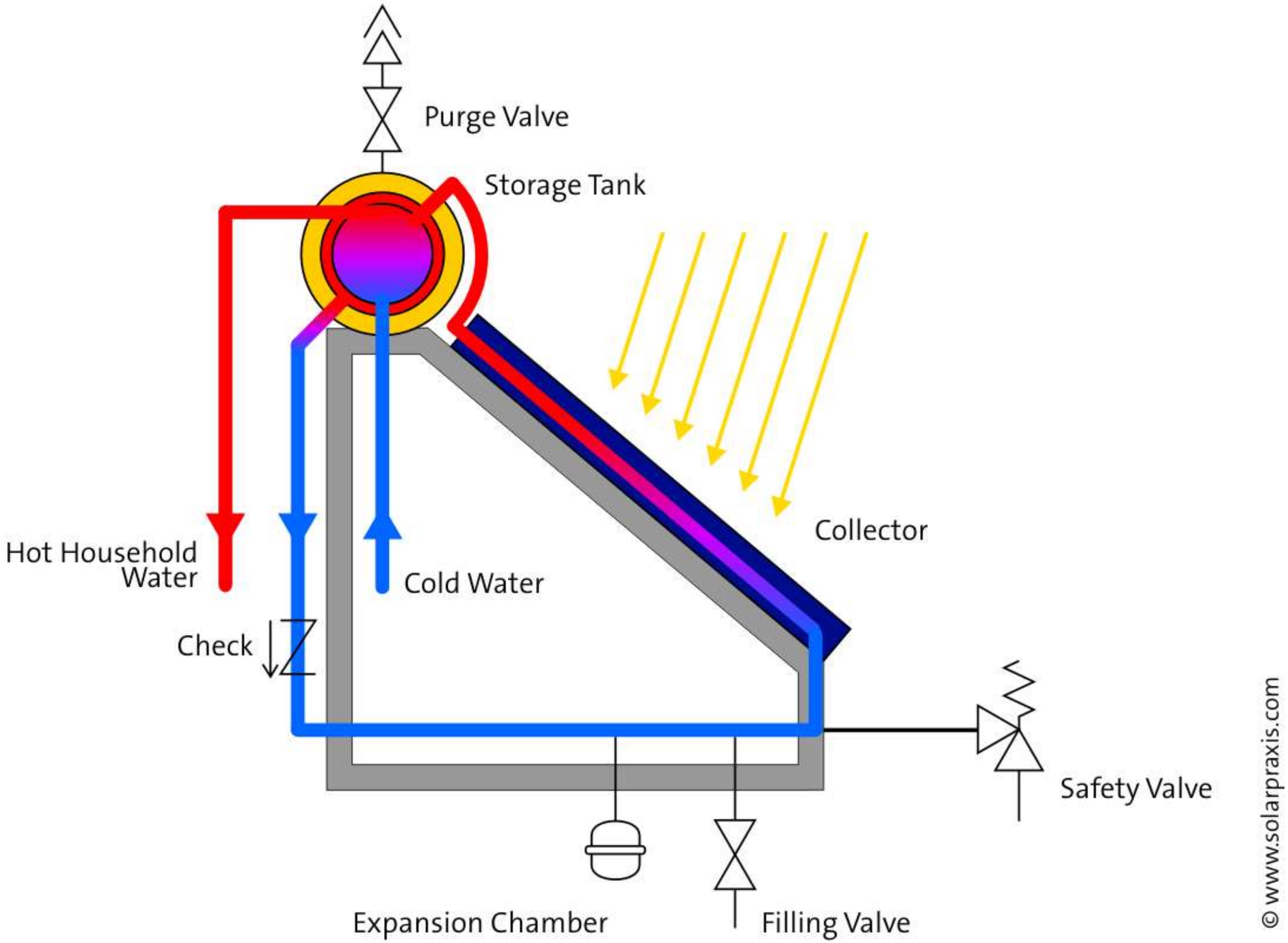
Thermosiphon circulation system



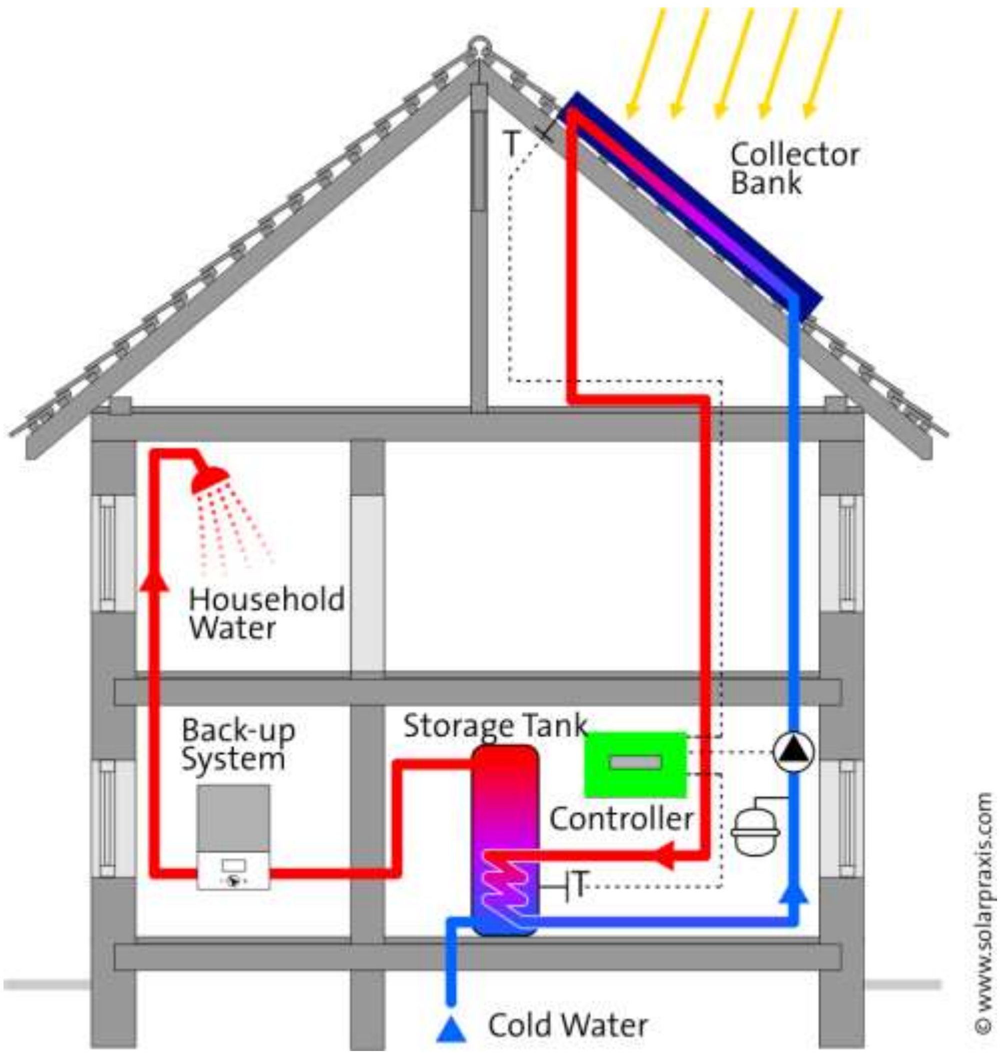


at least 1 m vertical elevation of storage above solar collector

Components of solar system

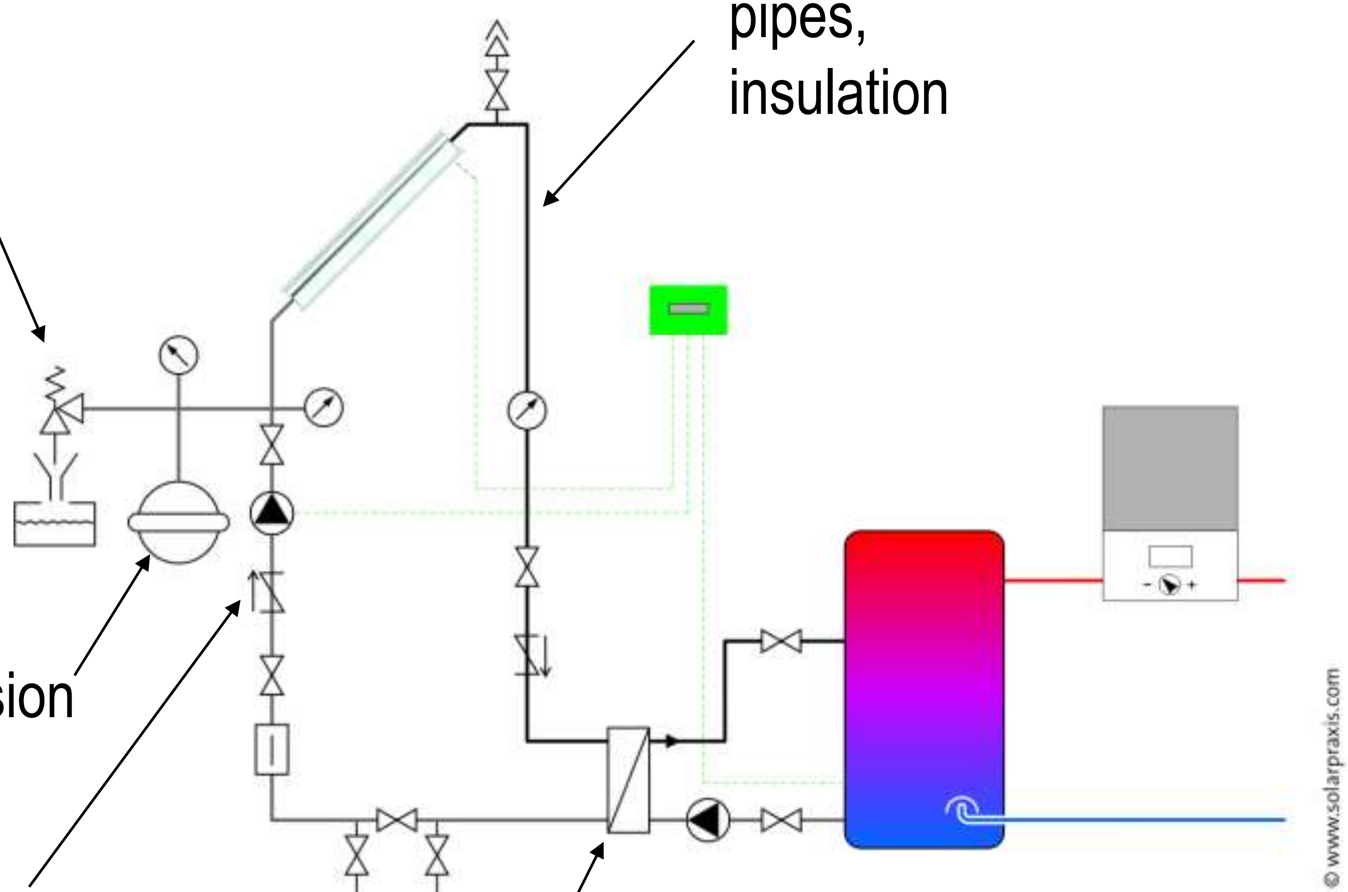


Forced circulation system



- **circulation induced by pump**
  - collector above storage
  - no limits
- **electronic controller**
  - measurement of temperature difference between collector and storage – signal for switching the pump on/off

Components of solar system



safety valve

expansion vessel

check valve

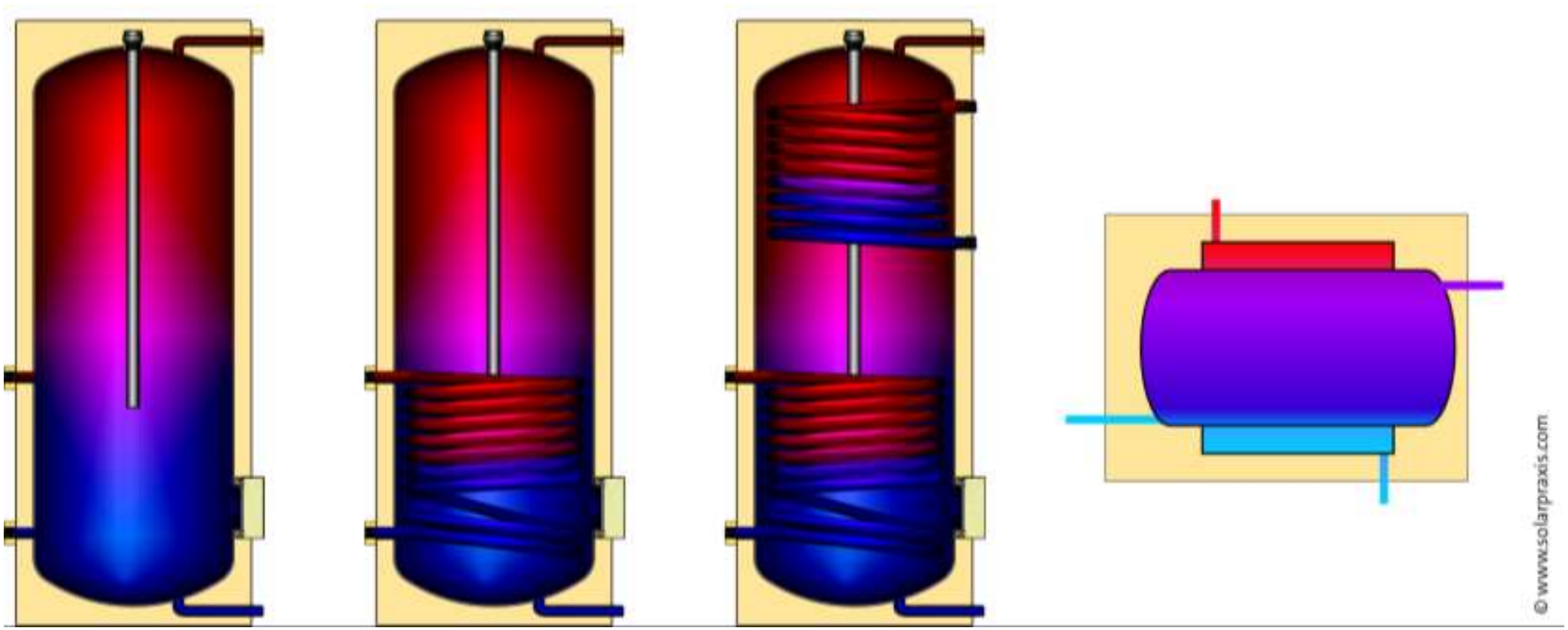
pipes, insulation

heat exchanger

storage tank

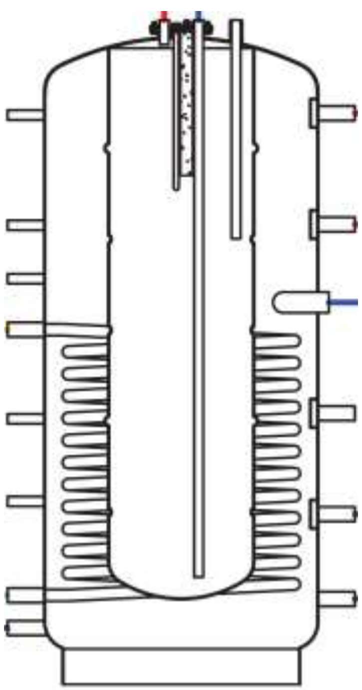
Storage tanks – hot water

- no heat exchanger (storage vessel)
- one heat exchanger (monovalent storage tank)
- two heat exchangers (bivalent storage tank)

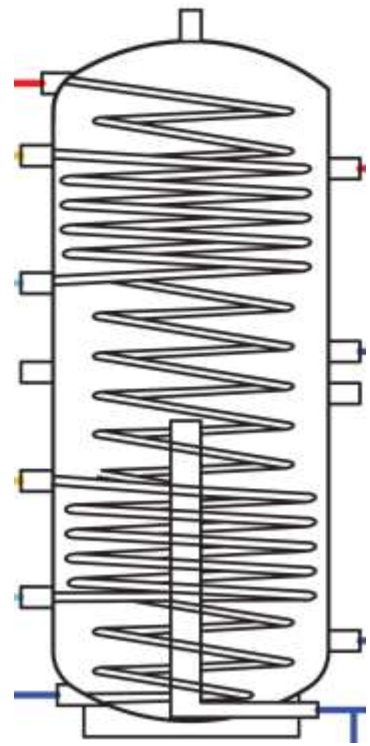


Storage tanks – combined with SH

- tank in tank (DHW tank in SH tank)
- with tube heat exchanger (DHW heat exchanger in SH tank)



small heat
transfer area
small loads
1 – 2 persons



double small heat
transfer surface
higher loads
3 – 4 persons

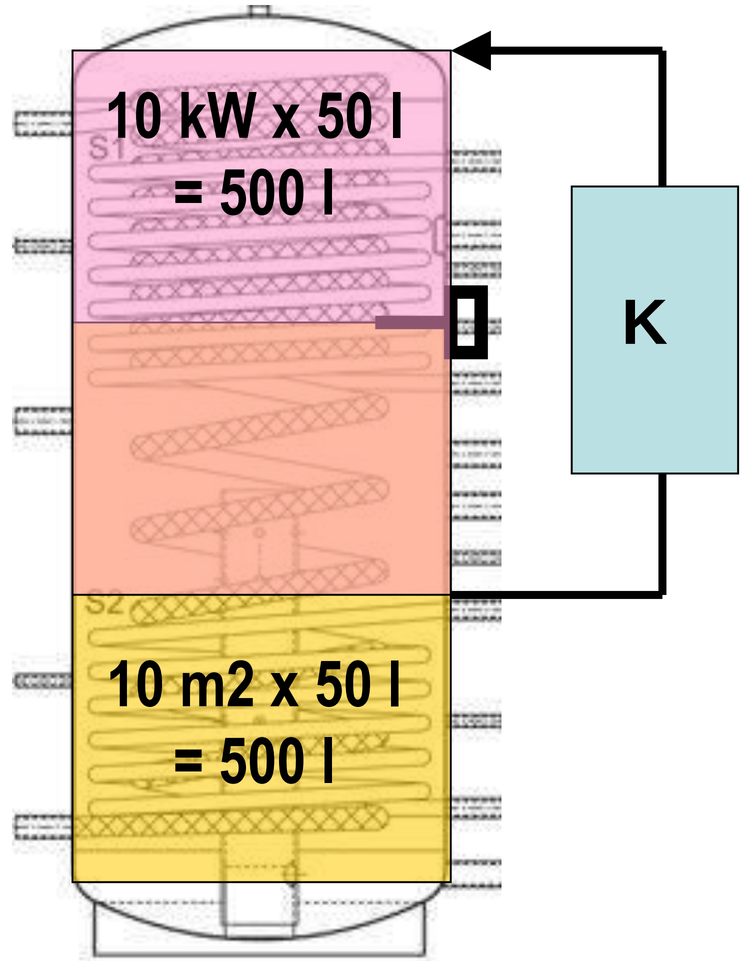
What size ?

- **domestic hot water**
  - **50 l/m^2** collector aperture area

- **combined with heating**
  - **50 to 70 l/m^2** collector aperture area
  - larger if backup heater supply heat into store
    - biomass boiler (logs) 50 l/kW
    - automatic biomass boiler (pellets) 25 l/kW
    - heat pump 15 to 30 l/kW
    - gas boilers 25 l/kW

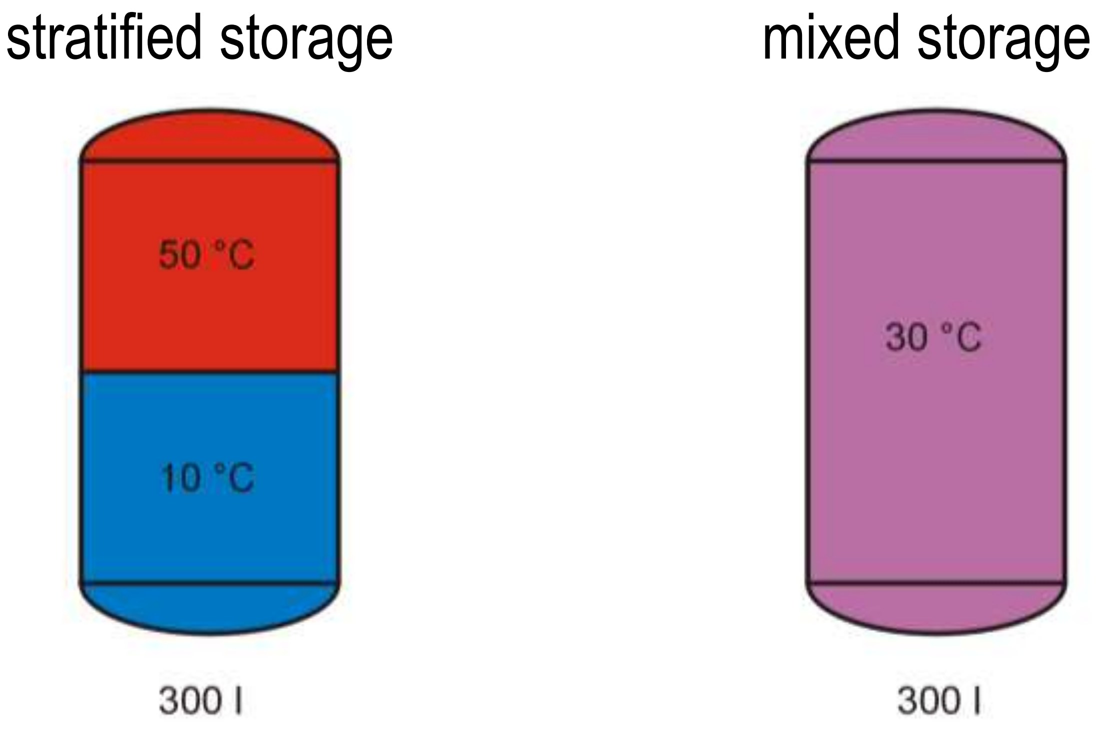
What size ?

- **solar combitank**
  - one for solar system and back-up
  - one for DHW and SH
- **example**
  - solar system 10 m^2
  - biomass boiler 10 kW
  - **2/3 volume = cca 500 l**
  - **storage size 750 l**



Exergy

usability of stored heat ~ usable temperature

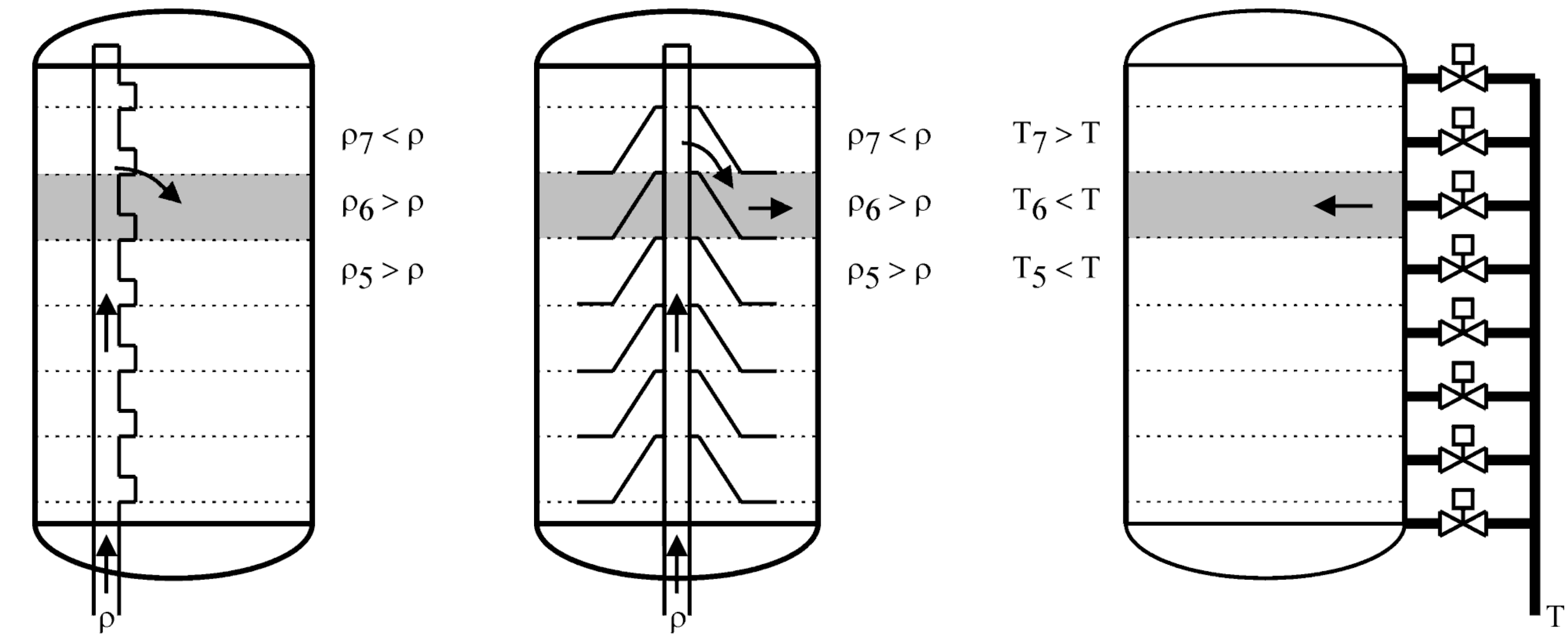


thermal stratification = higher efficiency, higher solar fraction

Factors influencing stratification

- aspect ratio of tank: Height / Diameter
- heat input (stratified, fixed)
- cold water input (bottom, prevented mixing)
- return flow from heating system input (stratified)
- heat loss of storage, thermal bridges
- stratification devices (for development of stratified volume)

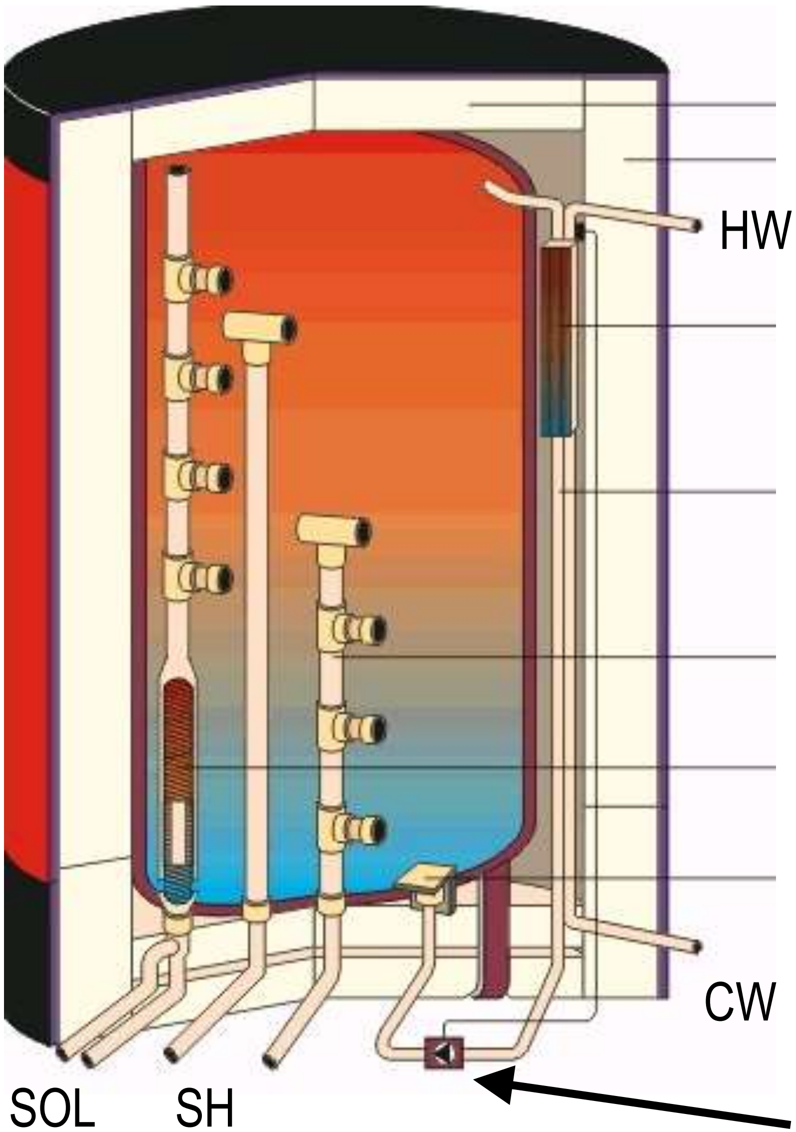
Controlled stratification



input of hot water into layer with similar temperature thanks to similar density (passive device)

complex control (active device)

Stratification devices in combined tank



insulation

external DHW heat exchanger

piping

stratified SH return flow

stratification device with integrated HX

input of cooled water from DHW heat exchanger

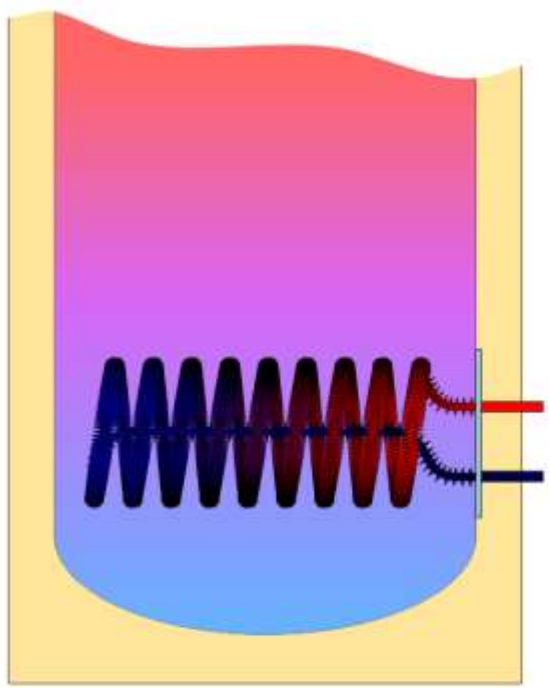
adaptable flowrate (controlled)

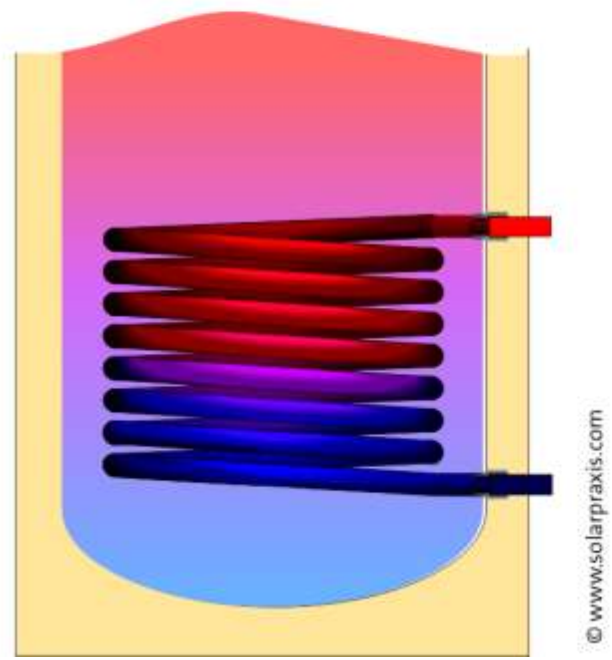
Heat exchangers (internal)

- **tube heat exchanger** immersed in the tank
  U-values = 120 to 300 W/m^2K

for small systems < 20 m^2

- (laminar flow, natural convection)
- , 0.4 m2 ribbed tubes / m2 col.area, 0.2 m2 bare exchange tubes / m2 col.area





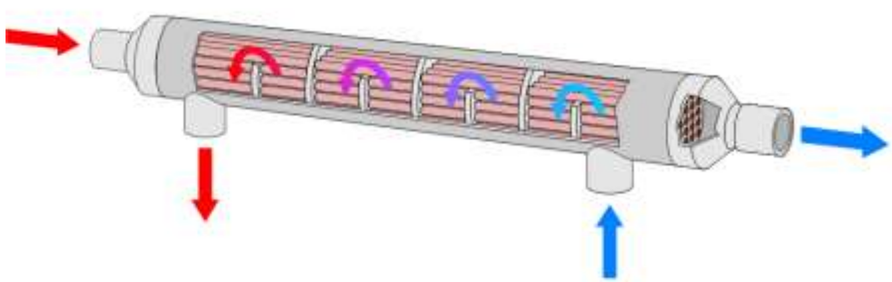
Heat exchangers (external)

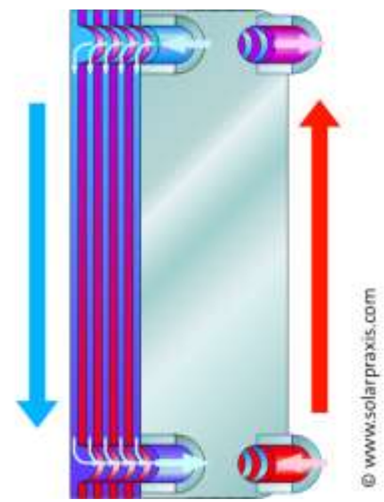
- **plate heat exchanger** out of the tank
  U-values = 1500 to 3500 W/m²K
  (turbulent flow, forced convection)

for larger systems > 20 m²

- **tube and shell heat exchangers** (swimming pools)
  U = 500 až 1000 W/m²K
  (laminar / turbulent flow)

0.05 to 0.08 m2 exchange area / m2 col.area





Heat exchangers - Heat power

- compared to nominal conditions: lower temperatures in SOLAR, lower flowrates, higher viscosity (antifreeze mixtures), laminar flow

→ **lower heat transfer rate (*U*-value)**

$$\dot{Q} = U \cdot A \cdot \Delta t_m$$

change of heat power for given heat exchanger

nominal conditions (80/60 °C – 20°C, 1,5 m^3/h) = **150 kW**

solar system conditions (55/45 °C – 20°C, 0,4 m^3/h) = **5 kW**

selection of heat exchangers with high heat transfer surface ***A***

Plate heat exchangers

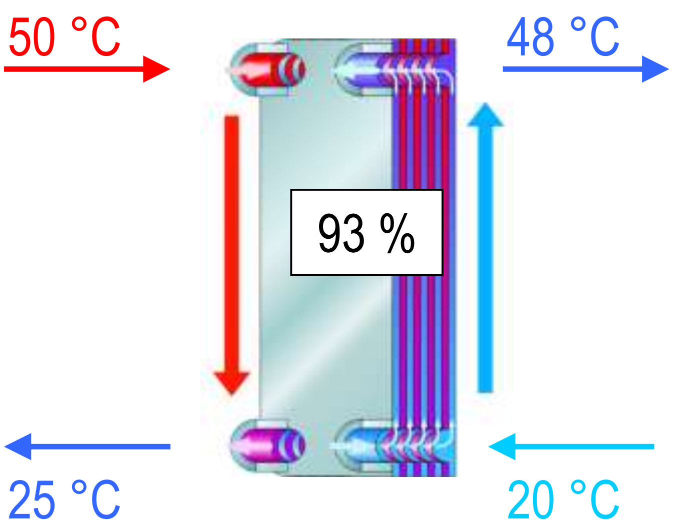
Q = 26 kW

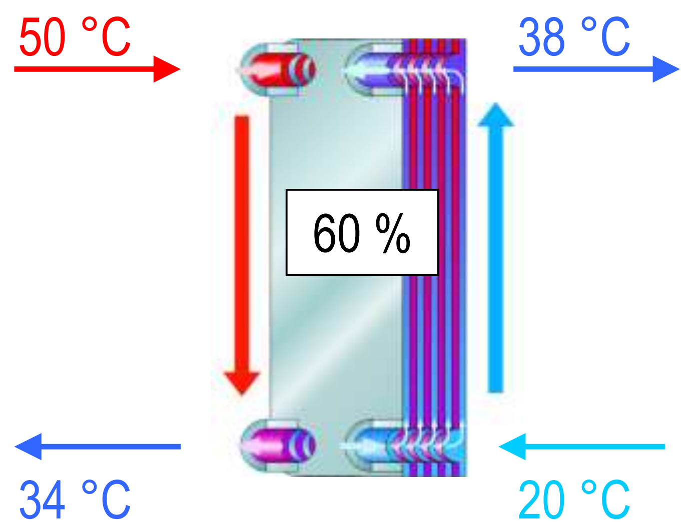
Δt_m = 3.3 K

Δt_m Arithmetic Mean Temperature Difference
$= (t_{pi} + t_{po}) / 2 - (t_{si} + t_{so}) / 2$

Q = 17 kW

Δt_m = 13 K





1000 l/h   900 l/h

1000 l/h   900 l/h

U = 2000 W/m²K

A = 4 m²

U = 1000 W/m²K

A = 1.3 m²

Stagnation

- **state without a heat removal from collectors at incident solar radiation**
- **causation:**
  - storage temperature achieves the limit value, controller stops the circulation pump
  - blackout
  - incompetent intervention (closure of collector loop)
- **consequence**
  - increase of temperature in solar collector
  - balance state: energy input = heat loss
  - collector achieves maximum temperature at given conditions
  - boiling of fluid, steam production

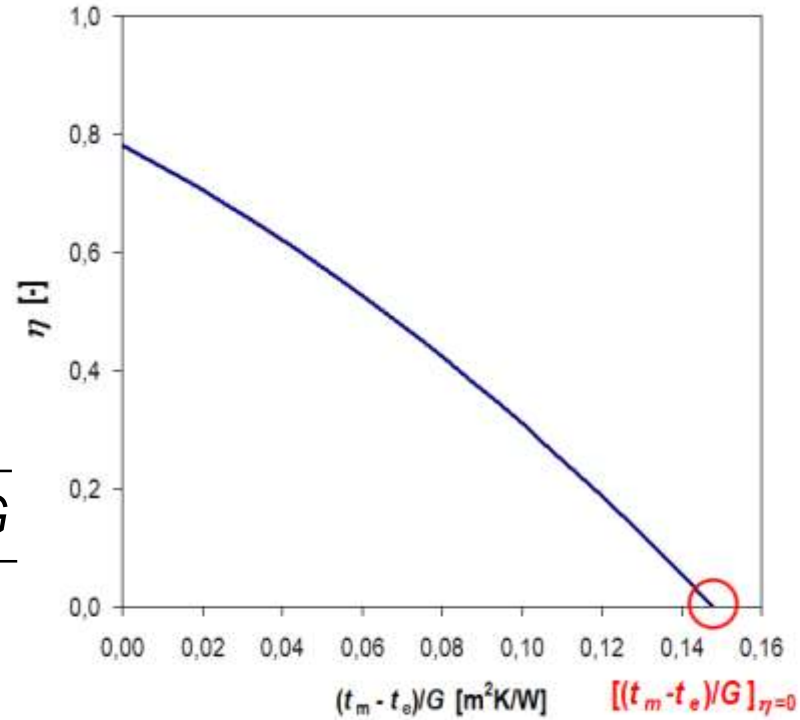
Stagnation temperature

- **depends on conditions**
  - extreme (nominal) conditions: G = 1000 W/m², t_e = 30 °C
  - calculation from intersection of efficiency characteristic with horizontal axis

$$t_{stg} = 30 + 1000 \cdot \left(\frac{t_m - t_e}{G} \right)_{\eta=0}$$

  - positive root of parabola

$$\left(\frac{t_m - t_e}{G} \right)_{\eta=0} = \frac{a_1 - \sqrt{a_1^2 + 4 \cdot \eta_0 \cdot a_2 \cdot G}}{-2 \cdot a_2 \cdot G}$$



Stagnation temperature

collector type	t_{stg} [°C]
unglazed collector	50 - 65
glazed non-selective collector	90 – 110
glazed selective collector	150 – 180
vacuum tube collector	250 - 300

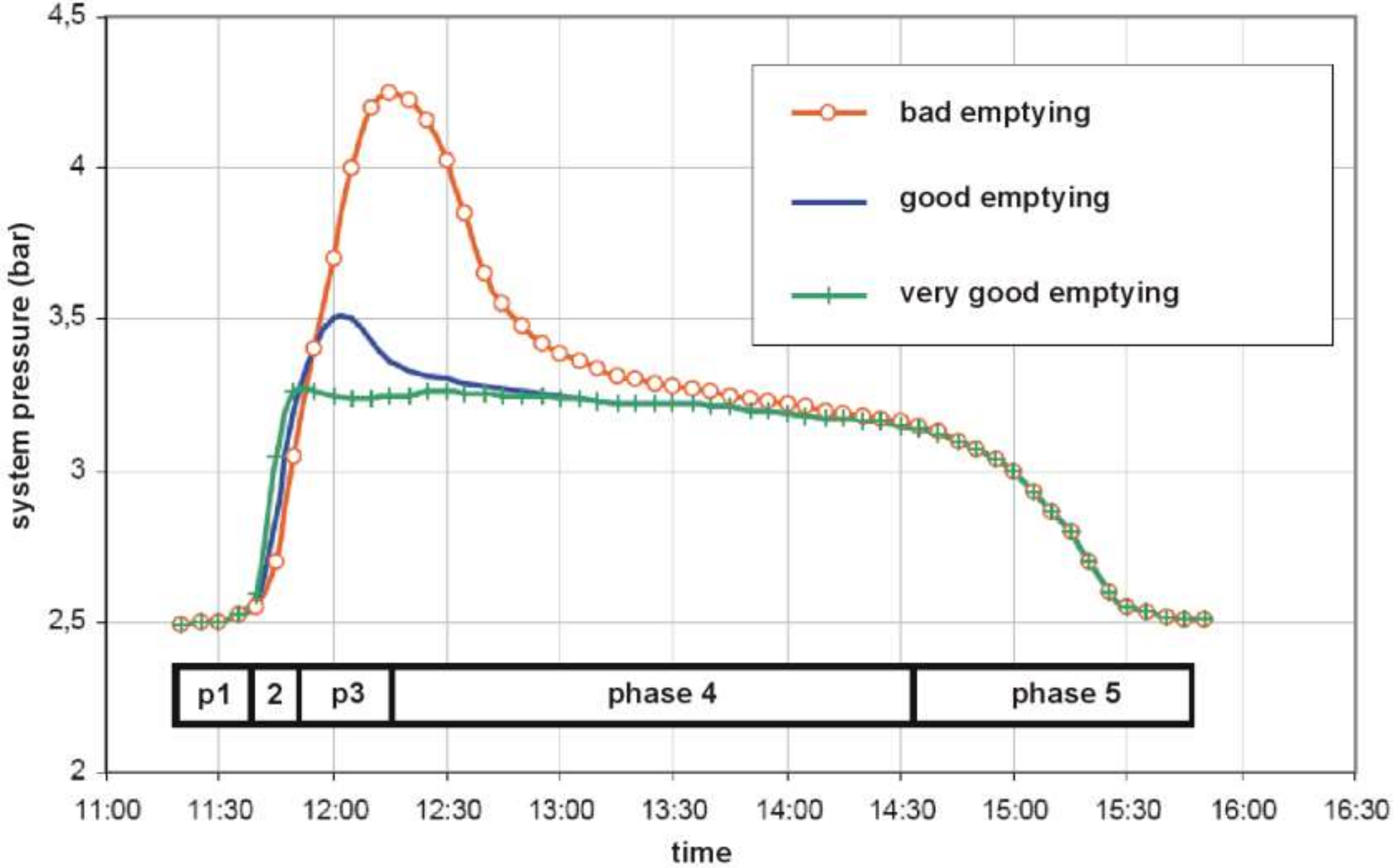
solar collector has to withstand it

temperatures could be lower dependent on real climate conditions

Stagnation behaviour

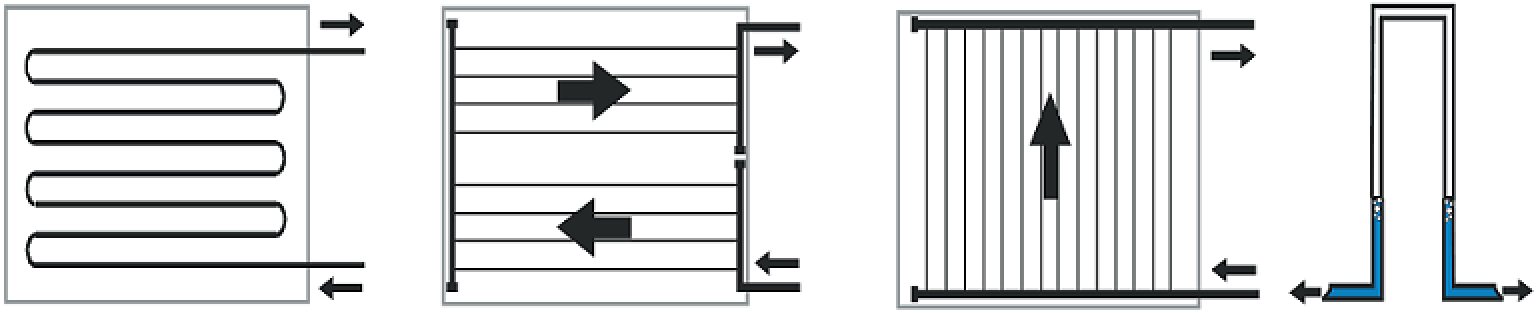
1. **liquid is expanding**
2. **achieves boiling point (at given pressure), boiling starts**
   - first bubbles appear, saturated steam, liquid is expelled from collector
3. **rest of liquid is transformed in steam**
   - volume of collector is filled by steam, high heat removal
4. **superheating of steam in collector**
   - emptying of collector, stable state, collector full of steam phase
5. **decrease of radiation, decrease of temperature**
   - condensation, liquid phase fills up the collector back

Stagnation behaviour

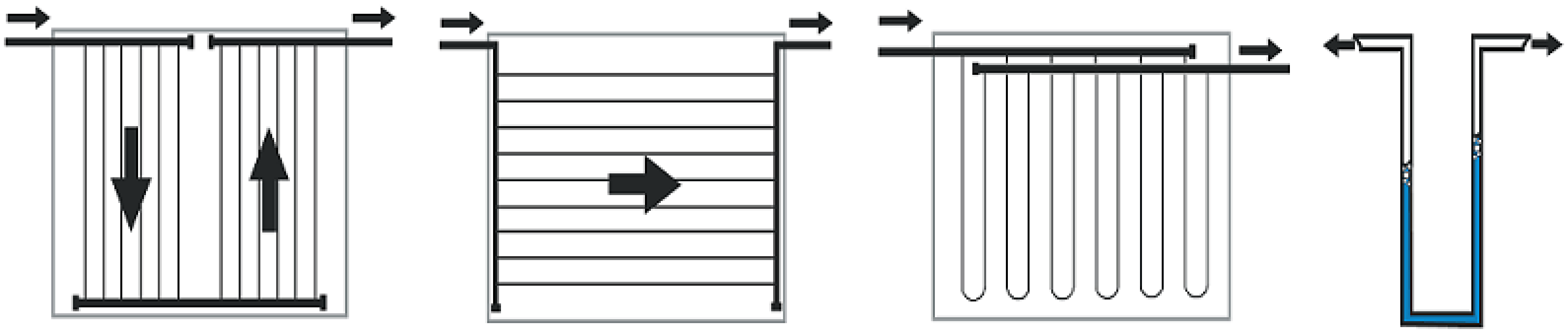


Emptying of solar collectors

good



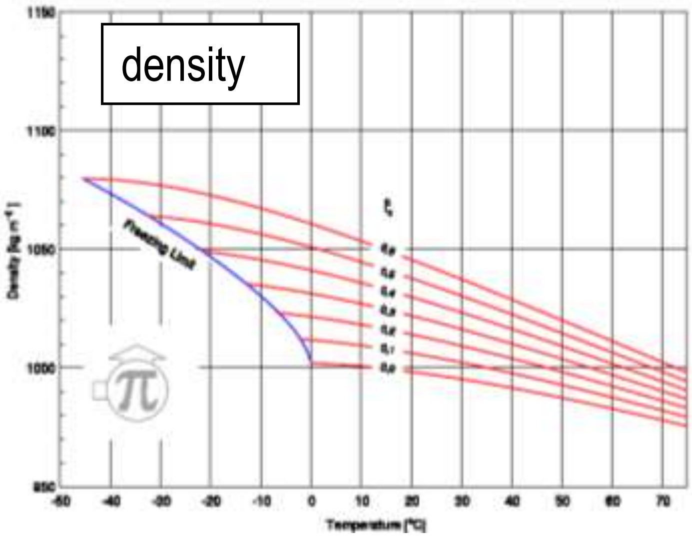
bad

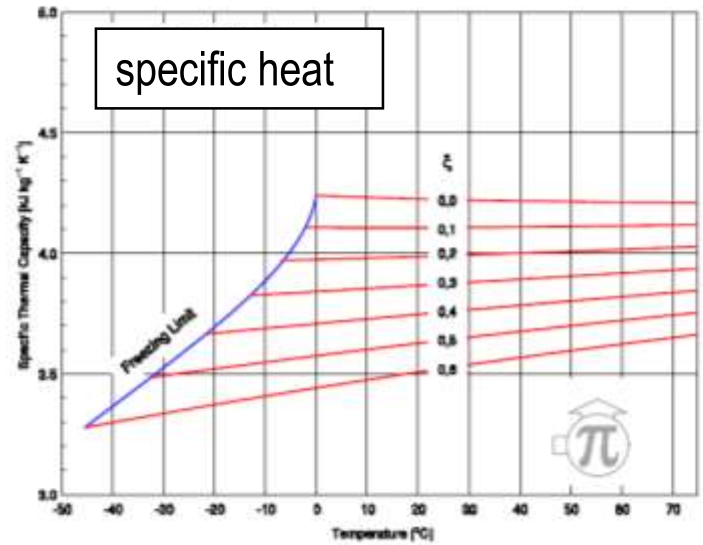


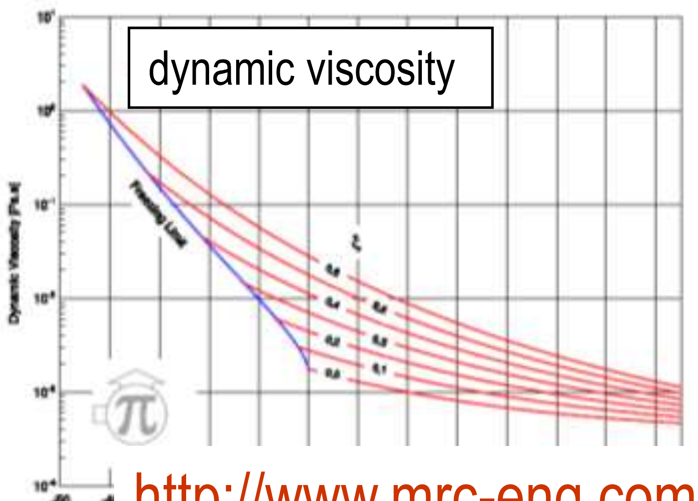
Types of solar liquids

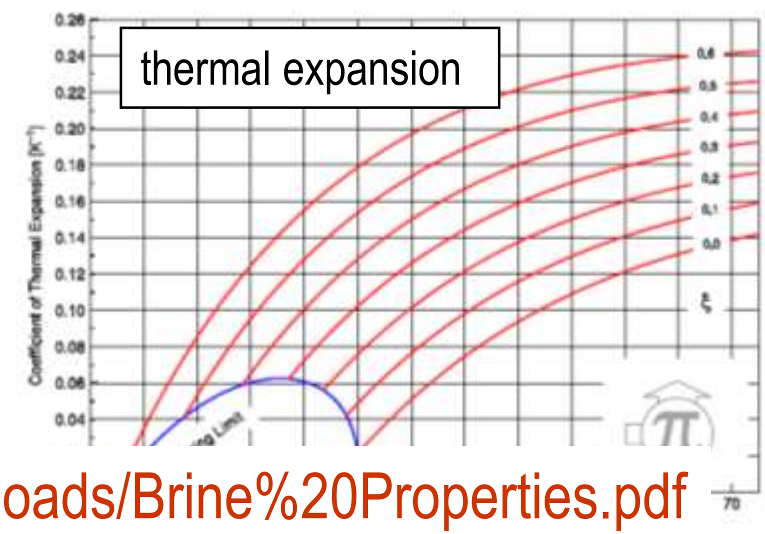
- **water**
  - nontoxic, nonflammable, cheap, high thermal capacity, low viscosity
  - limited usable temperature range (seasonal systems),
- **ethylenglycol**
  - antifreeze mixture with water, toxic, low viscosity
- **propylenglycol**
  - antifreeze mixture with water, high viscosity dependent on temperature, low thermal capacity (lower by 20 % than water), corrosion inhibitors, stabilisers and other additives

Properties of propylenglycol-water



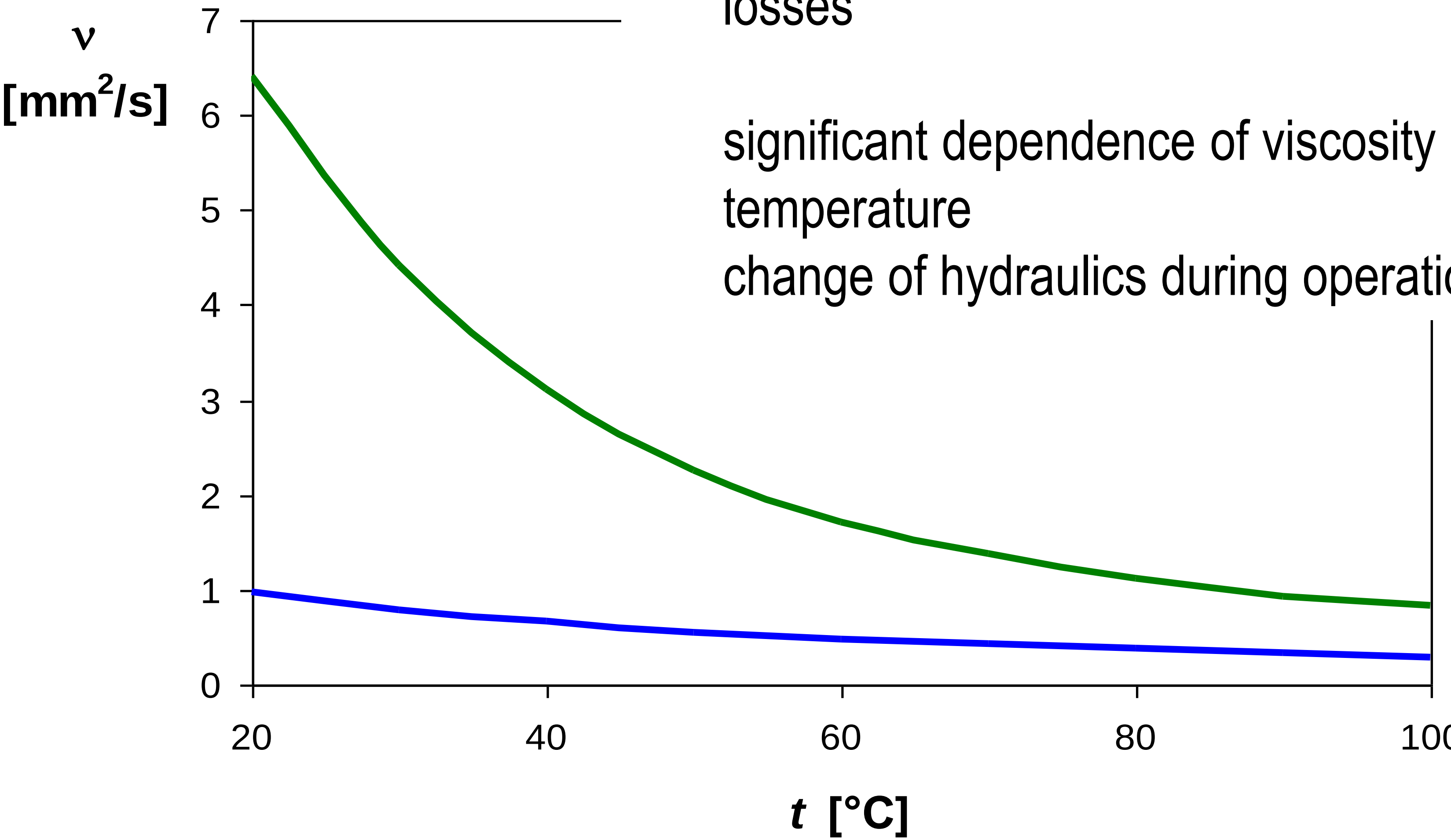






http://www.mrc-eng.com/Downloads/Brine%20Properties.pdf

Kinematic viscosity



higher viscosity, laminar flow, friction losses

significant dependence of viscosity on temperature

change of hydraulics during operation

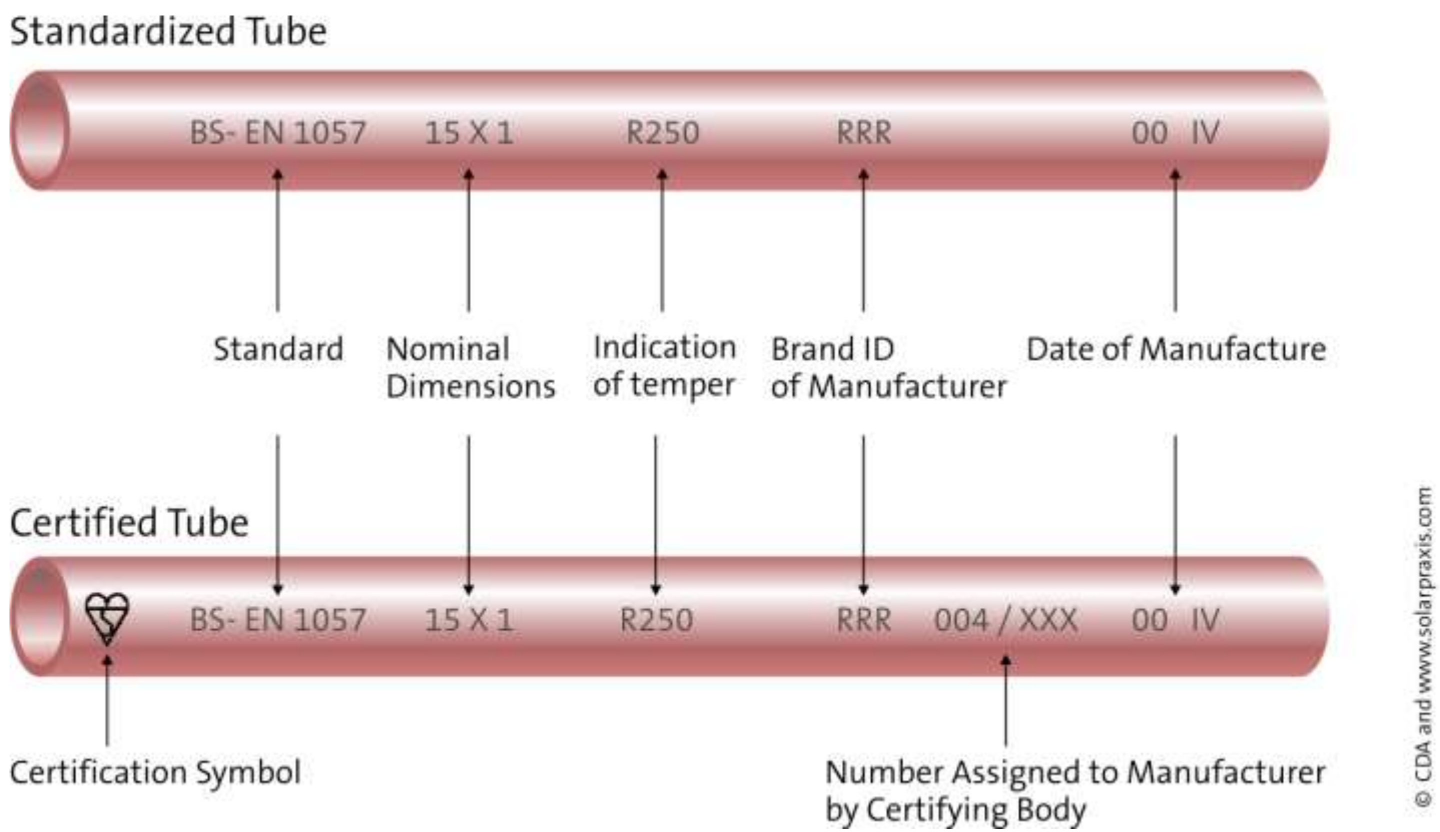
Piping and thermal insulation

- **durability**
  - resistant to pressures and temperatures
  - ageing, atmospheric conditions
- **energy performance**
  - piping – low pressure loss, consumption of electricity for pumps
  - thermal insulation – low heat loss, efficiency and gains of solar system, use of back-up heating

Materials for pipes

- **plastic pipes**
  - EPDM, UV protection, only swimming pools
- **copper pipes**
  - easy connections, soldering, pressing, same material as collectors, zero electro/chemical potential (corrosion)
- **steel pipes**
  - welding, complicated assembly, low price!
- **stainless steel (corrugated)**
  - easy assembly, formable, also for heat exchangers

Copper pipes



Copper pipes

soldering

pressing

Steel pipes

Pipe dimension

- **required flowrate in collector loop**

  - **low-flow** systems: 10 to 20 l/h.m^2
    high ΔT at collector 25 to 40 K

  - **high-flow** systems: 50 to 100 l/h.m^2
    low ΔT at collectors 5 to 10 K

  - recommended velocity in pipes w = 0,5 m/s

$$d = \sqrt{\frac{4 \cdot \dot{M}}{\pi \cdot w \cdot \rho}}$$

Thermal insulation - requirements

- **resistance to high temperatures**
  - at collector: stagnation temperatures min. 170 °C
  - distant places: min. 120 °C

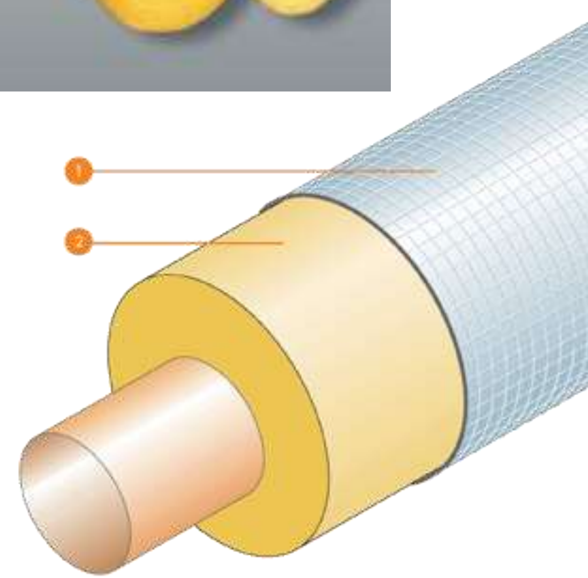
- **resistance to ambient environment**
  - humidity – increase of loss, degradation **closed cells**
  - UV radiation – carbon aditives
  - birds – „tasty“ material

Materials for thermal insulation

- **EPDM foams, syntetic rubber**
  - (+) low thermal conductivity
  - (+) closed structure
  - (0) UV protection
  - (–) birds
  - resistance:
    170 °C short-term
    130 °C long-term

Materials for thermal insulation

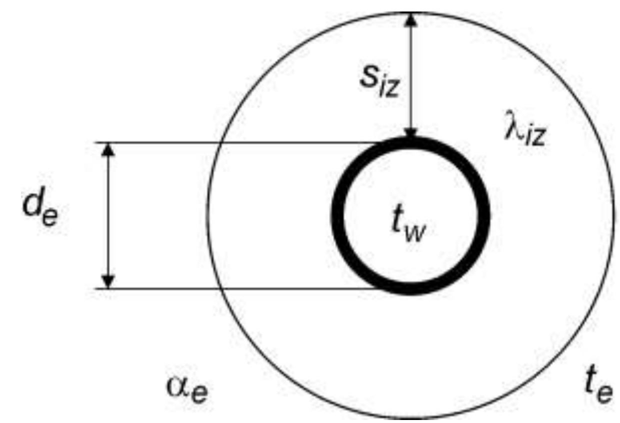
- **mineral wool (glass, stone)**
  - (+) UV radiation
  - (–) open structure
    need for sheeting (aluminium)
  - (+) long-term resistance to
    280 °C



Pipe heat loss

$$U = \frac{\pi}{\frac{1}{2\lambda_{iz}} \ln\left(\frac{d_e + 2 \cdot s_{iz}}{d_e}\right) + \frac{1}{\alpha_e} \cdot \frac{1}{(d_e + 2 \cdot s_{iz})}} \quad \text{[W/m.K]}$$

$$\dot{Q} = U \cdot L \cdot (t_w - t_e)$$



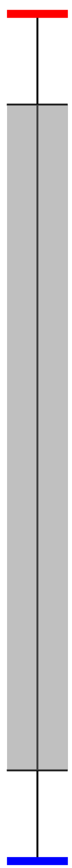
- **typical values**
  - insulation thickness s_{iz} = dimension d_e

Insulated piping

Safety and protection devices

- **safety valve**
  - protects the collector loop against non-permissible pressure
- **expansion vessel**
  - allows the changes of fluid volume (due to thermal expansion) without extreme increase of pressure above non-perimissible limit
  - **safety valve will not react during standard operation**
  - **even in case of stagnation**

Pressures in solar system



opening pressure of safety valve p_{SV}

maximum operation pressure p_e

$$p_e = p_{SV} - 20\,\text{kPa} \quad \text{for} \quad p_{SV} \leq 300\,\text{kPa}$$

$$p_e = 0{,}9 \cdot p_{SV} \quad \text{for} \quad p_{SV} > 300\,\text{kPa}$$

operation pressure range influences the sizing of expansion vessel

$$p_0 = h_s \cdot \rho \cdot g + p_d$$

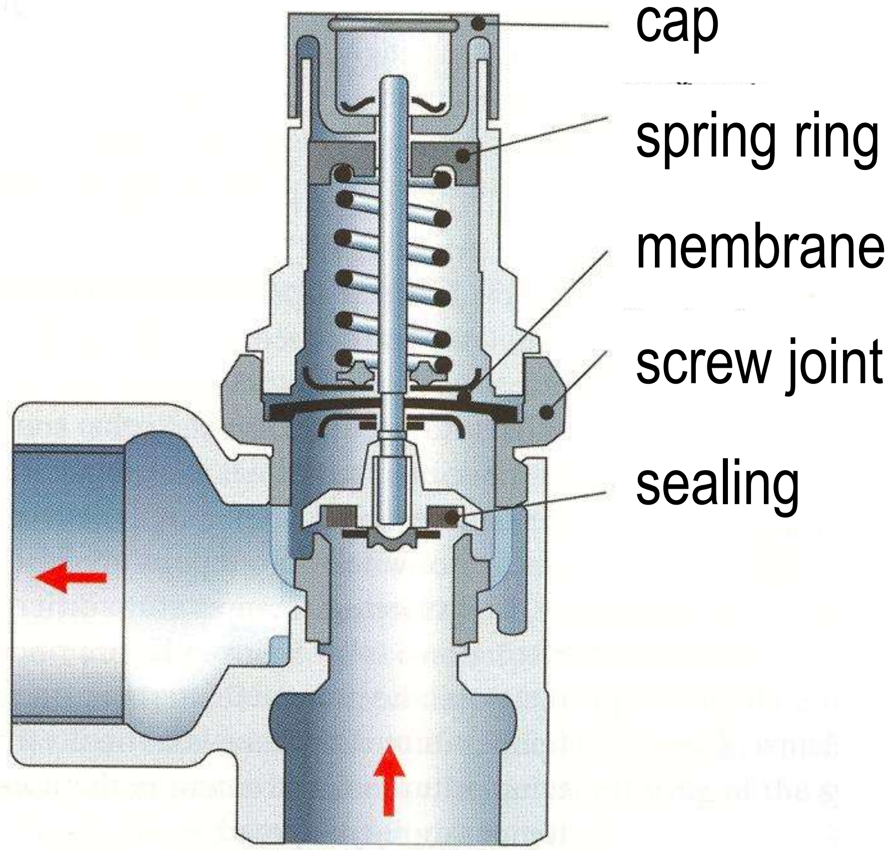
minimum operation pressure in highest point p_d = 20 kPa to ... kPa

filling pressure p_0

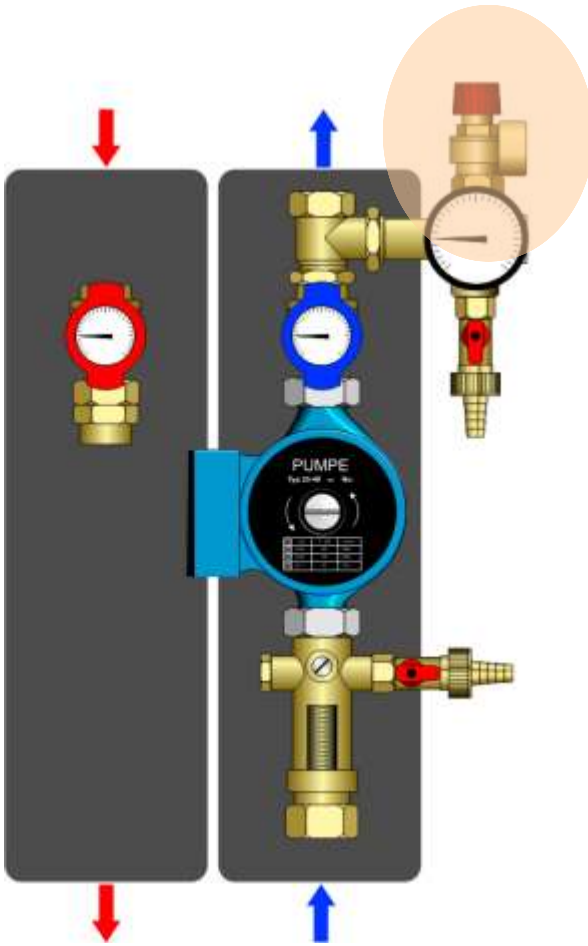
hydrostatic pressure p_h

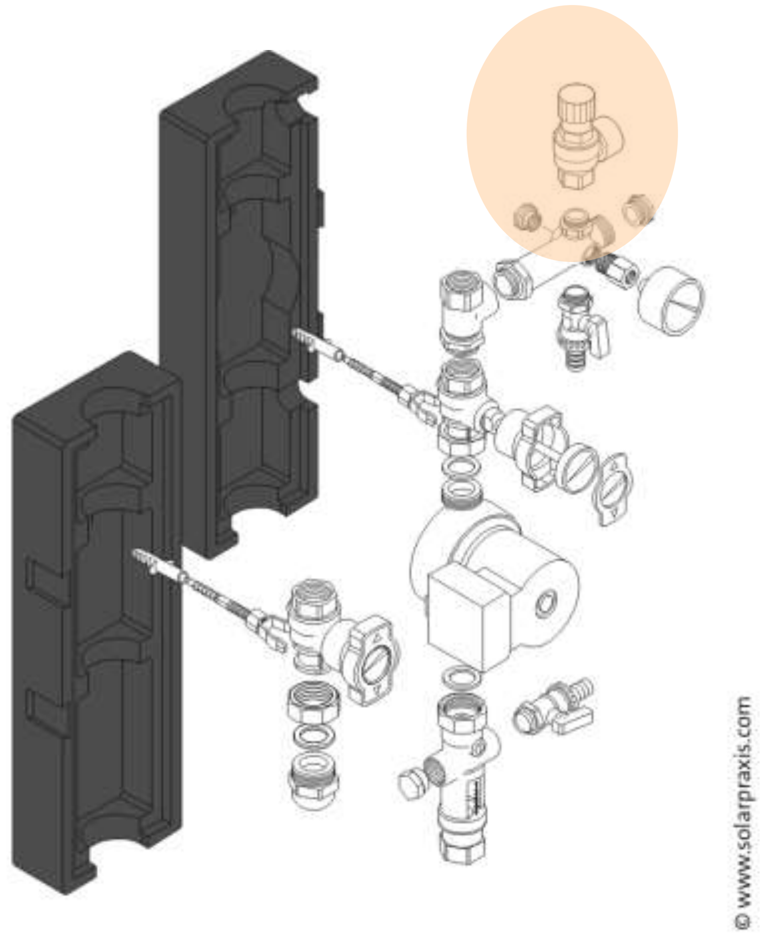
Safety (relief) valve

- **relief pressure**
  - respects pressure endurance of system components
  - influences size of expansion vessel



Safety (relief) valve



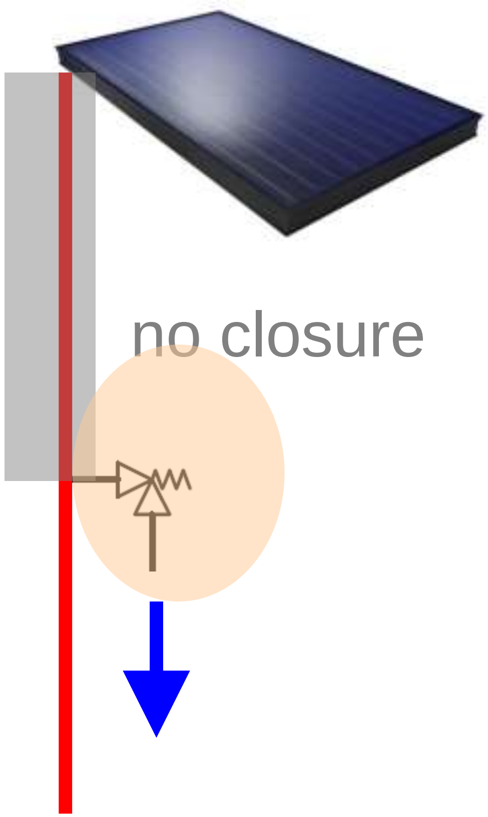


Location of safety valve

- between safety valve and collector must not be any valve
- pressure loss at vapour mass flowrate < 3 % of relief pressure

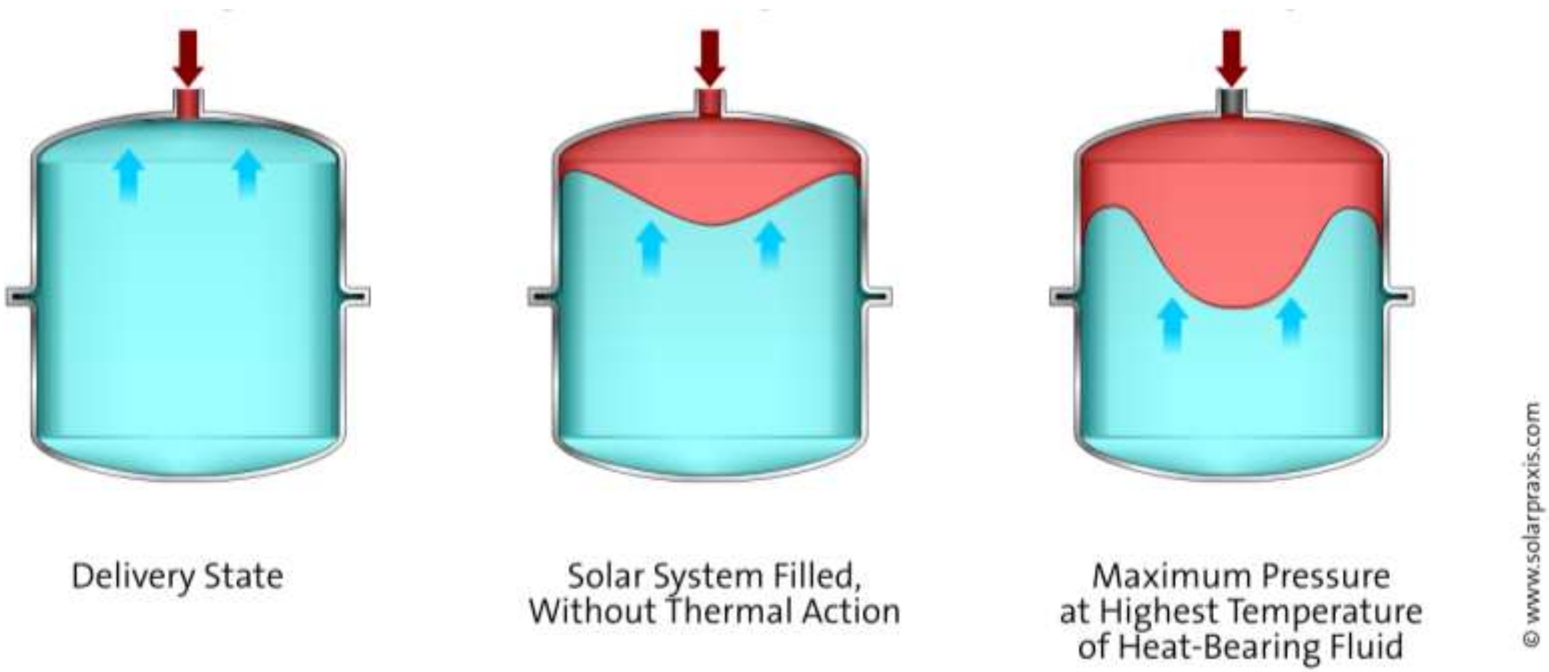
$$\dot{m}_p = \frac{\dot{Q}_p}{r_p} = \frac{\dot{Q}_p\ [\text{kW}]}{0.58\ \text{kWh/kg}} \quad [\text{kg/h}]$$

- free outflow has to be assured from relief
- regular checks provided



Expansion vessel

- **closed solar systems**
  - pressure expansion vessel with a membrane



Size of expansion vessel

$$V_{EN} = \left(V_s + V \cdot \beta + V_k\right) \cdot \frac{p_e + p_b}{p_e - p_o}$$

V_s ... initial volume in exp.ves., V_s = 1-10 % V, min 2 liters

V ... total fluid volume in collector loop [l]

β ... coefficienct of thermal expansion for $\Delta t = t_{max} - t_0$ = 120 K

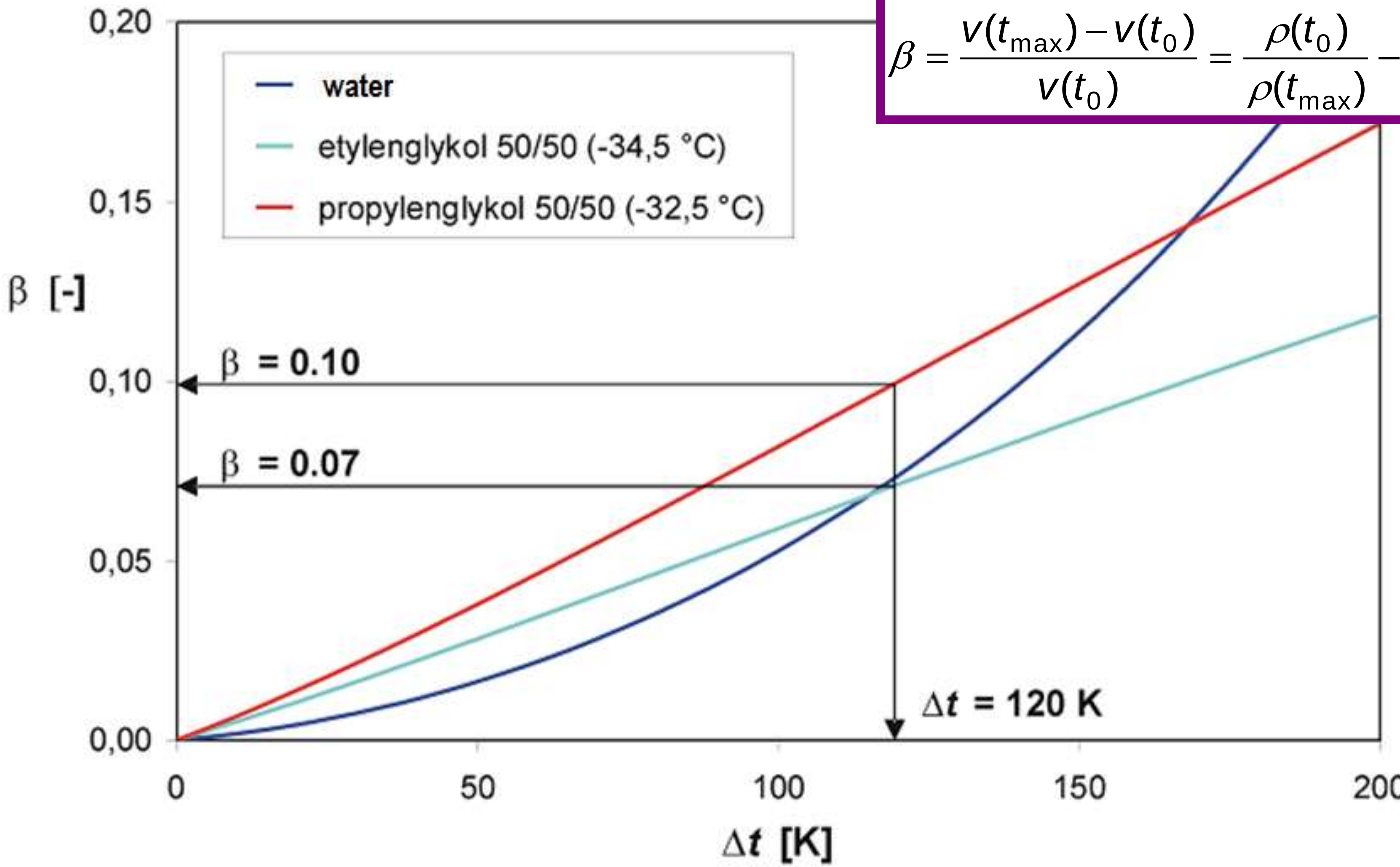
V_k ... volume of solar collectors (evaporated in stagnation) [l]

p_e ... maximum operation pressure [kPa]

p_o ... minimum operation pressure (filling pressure) [kPa]

Coefficient of thermal expansion

$$\beta = \frac{v(t_{max}) - v(t_0)}{v(t_0)} = \frac{\rho(t_0)}{\rho(t_{max})} - 1$$

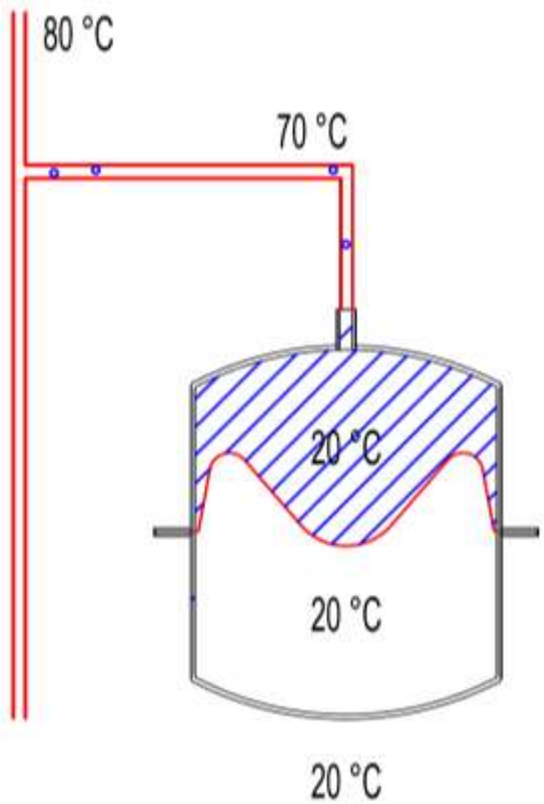


Expansion vessel

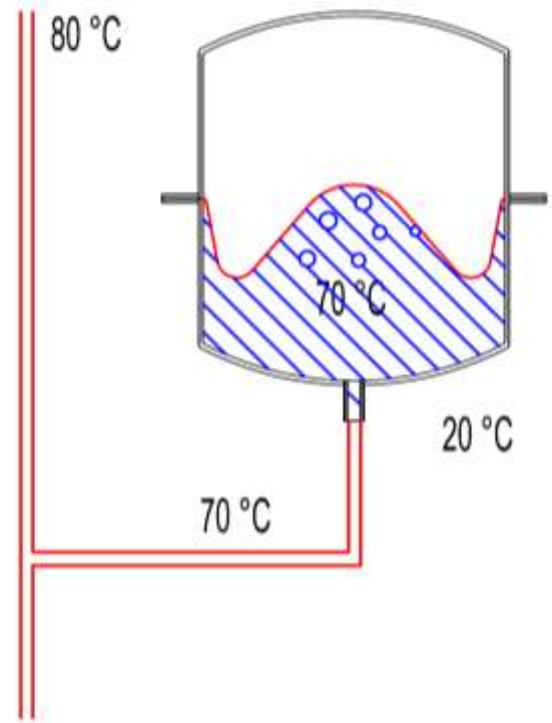
- selection of expansion vessel from a manufacturer predefined sizes

Expansion vessel - location

right

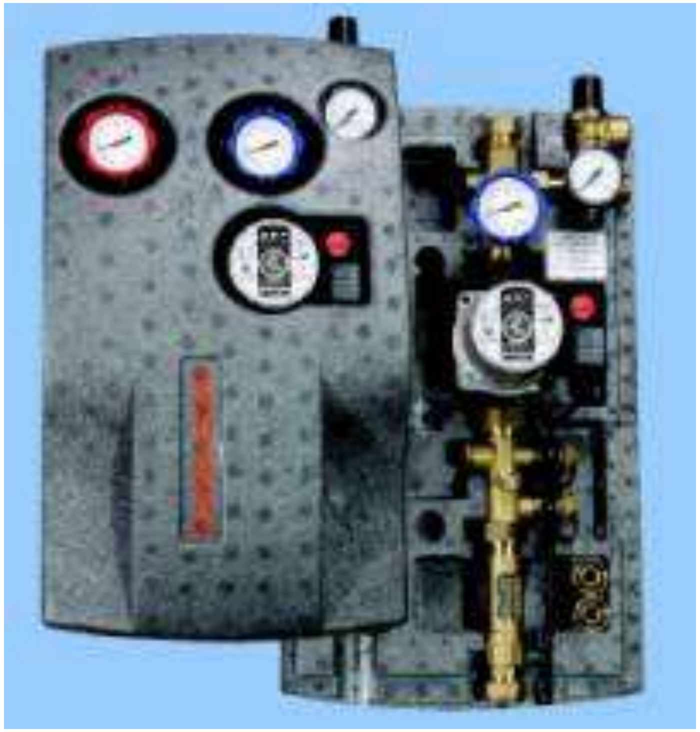


wrong

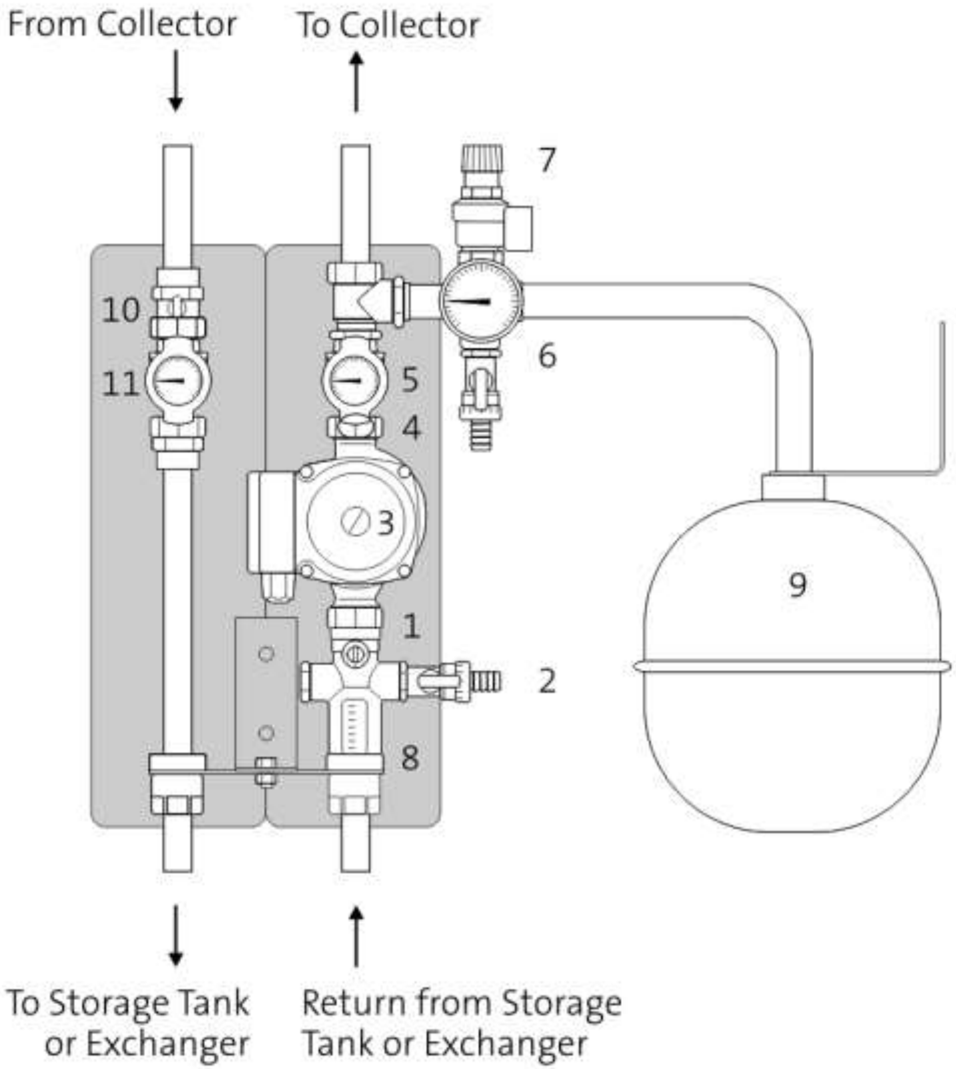


Hydraulic stations – integration

- ciruclation pump
- closing valves
- check valve
- connection of expansion vessel
- safety valve
- thermometers



Hydraulic stations – integration



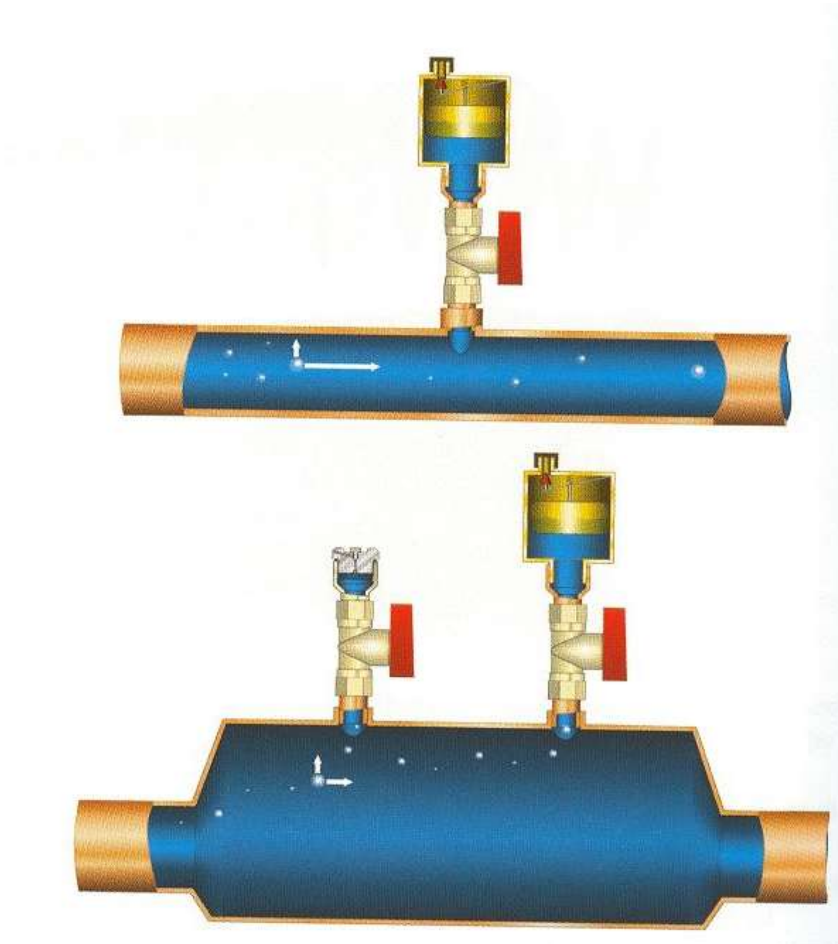
Return Circuit (cold)

1 Closing Valve
2 Filling Valve
3 Pump
4 Check Valve
5 Thermometer
6 Manometer
7 Safety Valve
8 Flow Gauge
9 Expansion Chamber

Hot Circuit (hot)

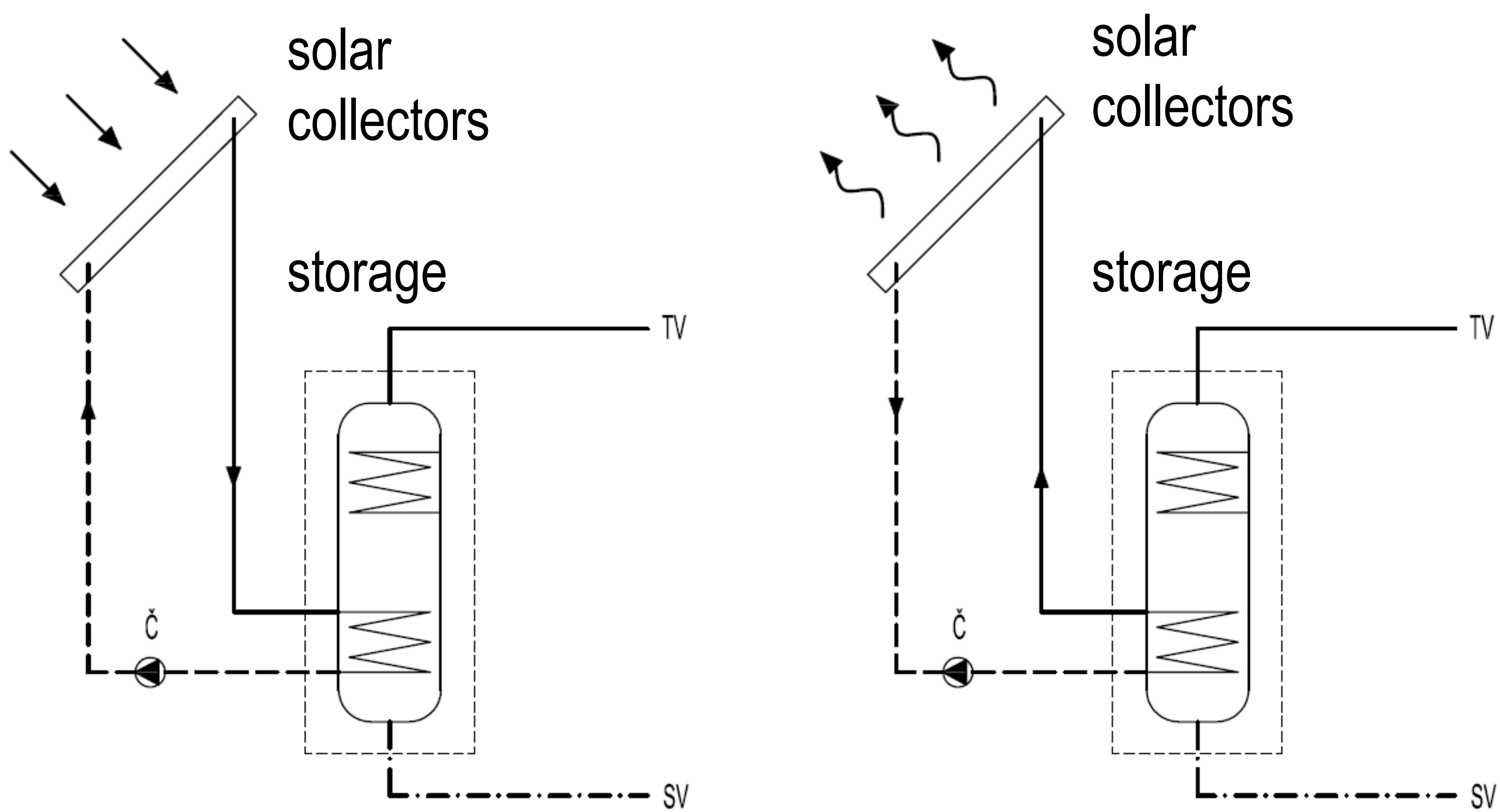
10 Closing Valve
11 Thermometer

Air venting

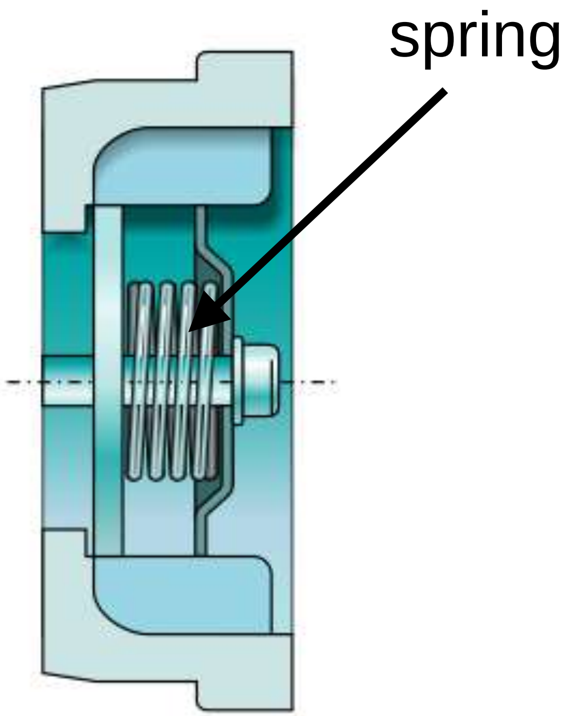


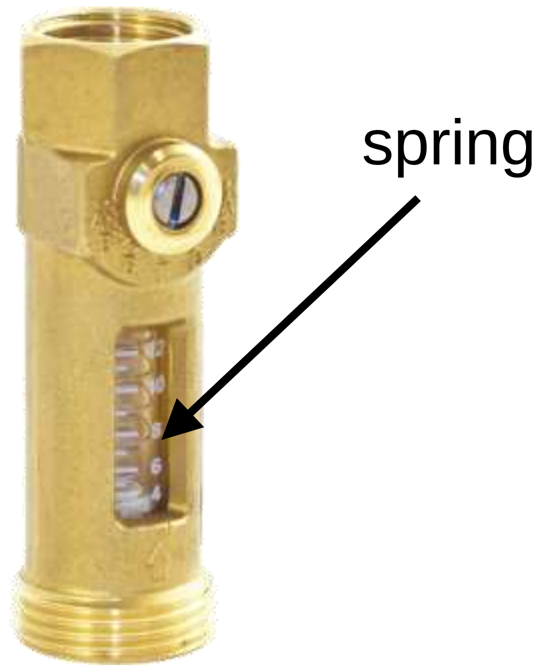
Check valve

- eliminates spontaneous circulation in collector loop



Check valve





Controller

- **differential control** – temperature difference between collector and load (storage tank, swimming pool)

  ΔT > set „switch on“ value (8 K) - circulation pump ON

  ΔT < set „switch off“ value (3 K) – circulation pump OFF

- one-loop
- multi-loop

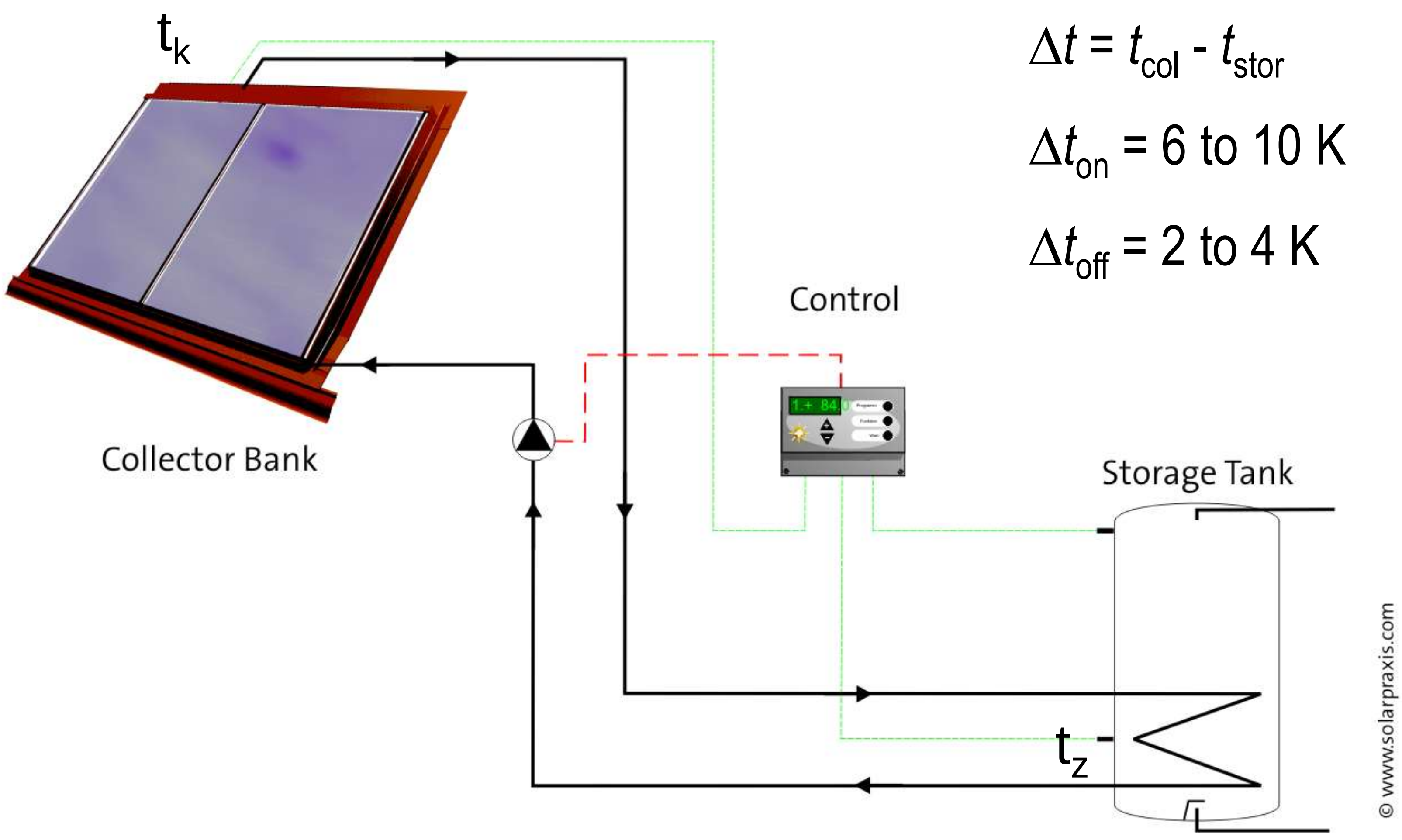
- **safety functions**

  storage temperatures > 85 °C – circulation OFF

  collector temperatures > 130 °C – circulation OFF

Controllers

Function

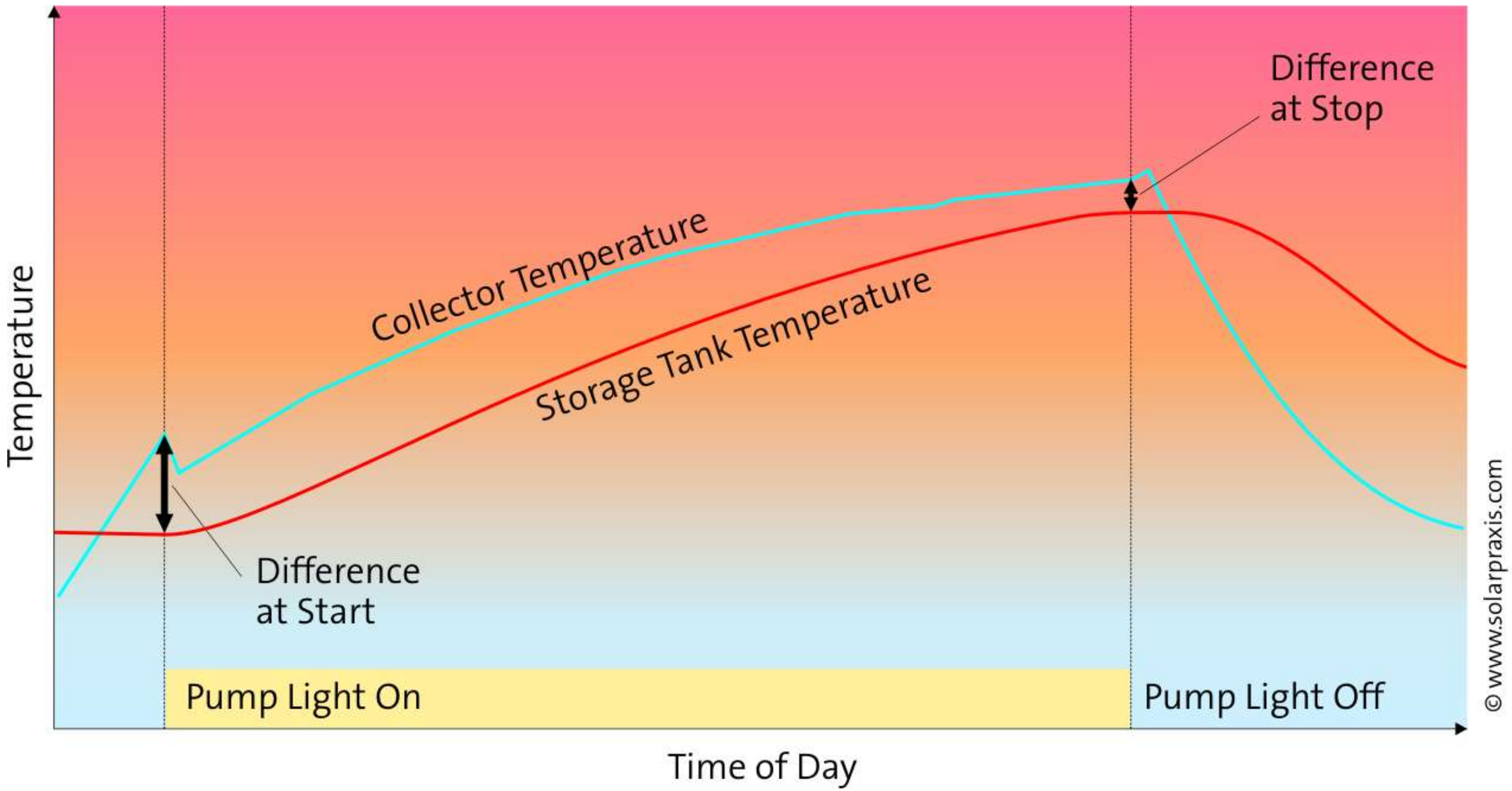


$\Delta t = t_{col} - t_{stor}$

Δt_{on} = 6 to 10 K

Δt_{off} = 2 to 4 K

Control during a day



Evaluation of solar system – heat gains

$$Q = \dot{V}\rho c\left(t_2 - t_1\right)\cdot \Delta\tau$$

volume flowrate

thermophysical properties of fluid

input / output temperature

time period