

Domestic Hot Water (DHW) sizing and energy demand

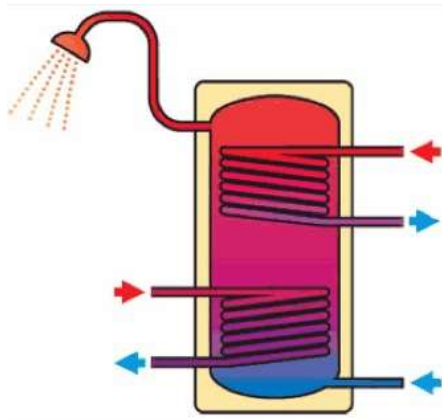
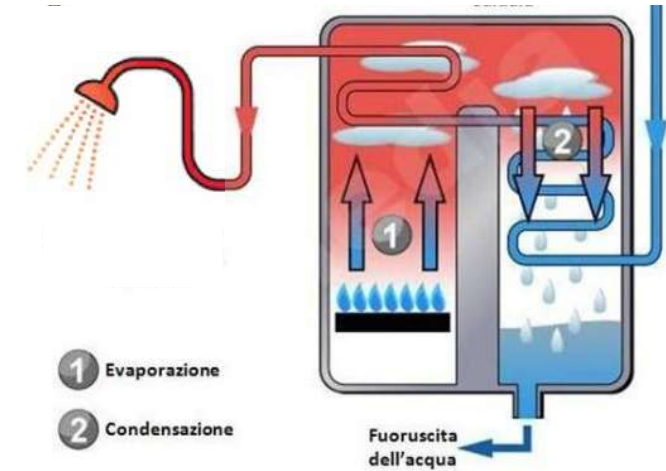
SYSTEMS FOR DHW PRODUCTION

- *Instantaneous water heater*
- *Stored heat:*
 - *Direct system*
 - *Indirect system with internal heat exchanger*
 - *Indirect system and instantaneous water heater*

SYSTEMS FOR DHW PRODUCTION

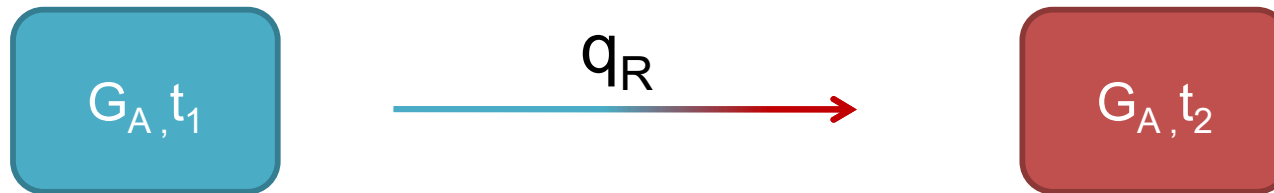
DHW can be heated in an instantaneous way or through a storage tank.

Instantaneous heating: the heat heats up instantaneously the required water flow rate by means of combustion products or through an electric resistance (gas boiler or electric boiler)



Stored Heat: the hot water is heated via a fluid (direct water or indirect fluid) which has been previously heated in tanks

Heating up a mass flow rate for DHW



Given a water mass flow rate G_A from an initial temperature t_1 to a final temperature t_2 requires a heat power q_R equal to:

$$q_R = G_A \cdot c_A \cdot (t_2 - t_1) \quad [\text{kW}]$$

where

G_A water flow rate [kg/s]

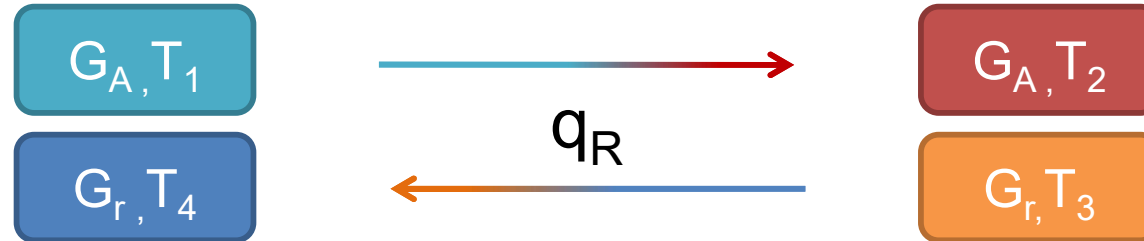
c_A specific heat capacity 4.186 [kJ/(kg K)]

t_1 water from aqueduct or from another reservoir
(conventionally fixed at about 10 °C)

t_2 is the water temperature after the heating process

Heat exchange between two fluids

Given two fluid flow rates G_A e G_r exchanging heat:



With an indirect heating system the warmer fluid with a mass flow rate G_r and specific heat c_r will cool down from an initial temperature of t_3 to a final temperature t_4 :

$$q_R = G_A \cdot c_A \cdot (T_1 - T_2) \quad [\text{kW}]$$

$$q_R = G_r \cdot c_r \cdot (T_3 - T_4) \quad [\text{kW}]$$

This is done through a heat exchanger whose heat exchange surface has to be sized

$$q_R = K \cdot S \cdot \Delta T_{ml} \quad [\text{kW}]$$

where:

K is the overall heat exchange coefficient [kW/(m² K)]

S surface of the heat exchanger [m²]

ΔT_{ml} mean logarithmic temperature [K]

Assuming K and ΔT_{ml} ,

the required surface for the heat exchange S is:

$$S = q_R / (K \cdot \Delta T_{ml})$$

REMARK:

in the instantaneous heating of the DHW (gas boiler) the sizing is not performed by the designer, but it is provided by the constructor: depending on the sizes of the systems different q_R will be available. Among the potential models the designer will choose the most suitable system.

INSTANTANEOUS HEATING

Instantaneous heating consists in a system with a heat exchanger where water flows and heats up **without storage**.

The instantaneous heating requires **relevant peak power** due to the increase of water temperature from **10°C** to **40°C**.

The problem is related to the limit of the power installed, especially with electric heaters. Hence in these cases, once fixed the maximum power, the flow rate is therefore defined.

These systems are limited to single users

shower

Flow rate di 8 l/min >> 0.133 l/s

$$P = m \text{ cp } (40 - 10)$$

$$P = 16.74 \text{ kW}$$

SYSTEMS FOR DHW PRODUCTION

Instantaneous heating systems

combustion of natural gas

q_R [kW]	G_{Amax} [l/min]	G_{Amin} [l/min]	Δt_{min} [°C]	Δt_{max} [°C]	Portata gas [m ³ /h]
8.72	5	2.5	25	50	1.06
17.44	10	5	25	50	2.41

electric heaters

Electric power [kW]	Portata d'acqua [l/s] > [l/min]	Δt [°C]
1	0.012 > 0.72	20
1.5	0.018 > 1.08	20
2	0.024 > 1.44	20
2.5	0.030 > 1.8	20

REMARK: with such reduced flow rates and small temperature differences it is recommended to limit the use to handbasins

SYSTEMS FOR DHW PRODUCTION

Thermal storage

Instantaneous systems need relevant peak powers for limited time frames.

In terms of energy the same result can be obtained by using a lower peak power for a wider time frame, supplying the required heat to water inside a tank

In this case the DHW is produced via a storage system

- It requires a certain time to heat up the water of the tank before using the water at the required temperature
- It requires a certain volume
- + it allows to sensibly reduce the peak power installed (it is possible to use also heat pumps)

STORED HEAT

Stored heat is based on a tank with a certain volume (sized as a function of the needs of the users).

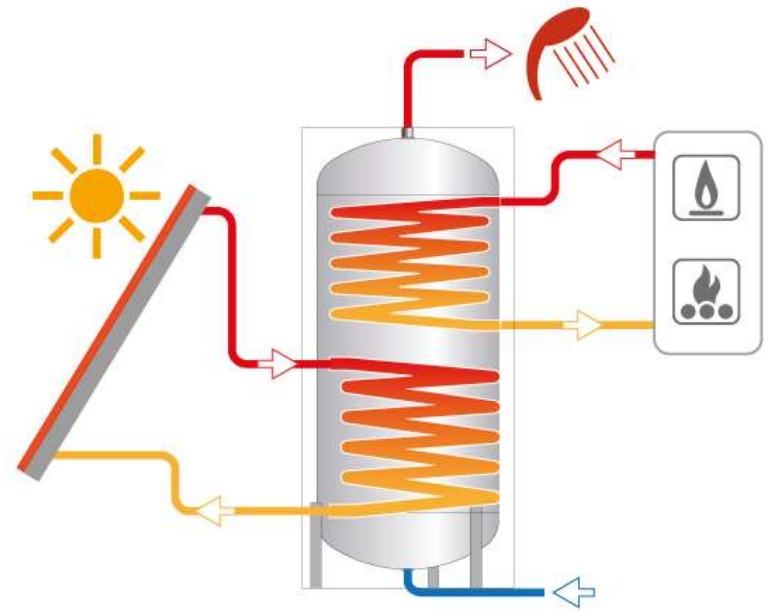
The water tank is heated by means of a limited thermal power for variable time frames.

The following systems are present in the market today:

- 1. direct systems**
- 2. indirect systems with internal heat exchangers**
- 3. indirect systems with external heat exchangers**

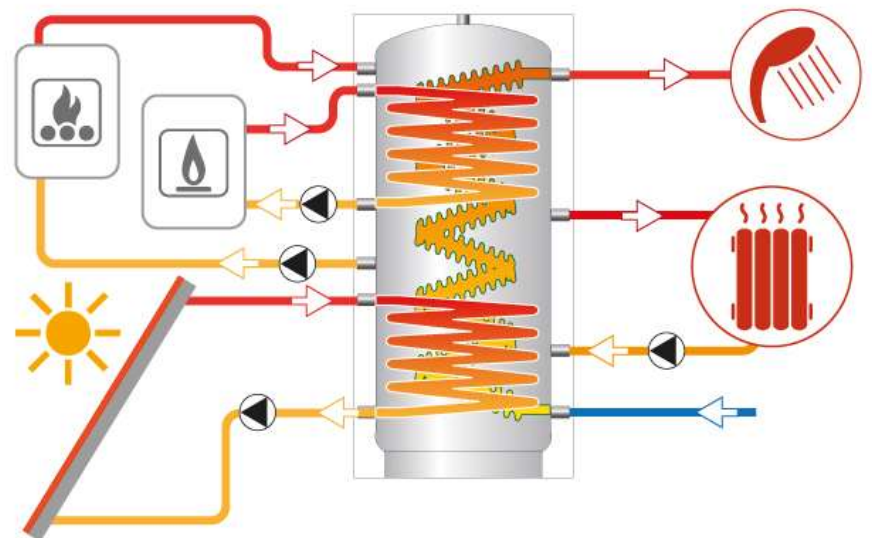
Direct systems

Cold water from the aqueduct is directly supplied in the water tank and mixed with the already present warm water



Indirect systems with internal heat exchanger

Cold water can flow inside a heat exchanger installed inside the water tank. The water tank could be the same as the one for the heating system circuit or separated from the heating system circuit

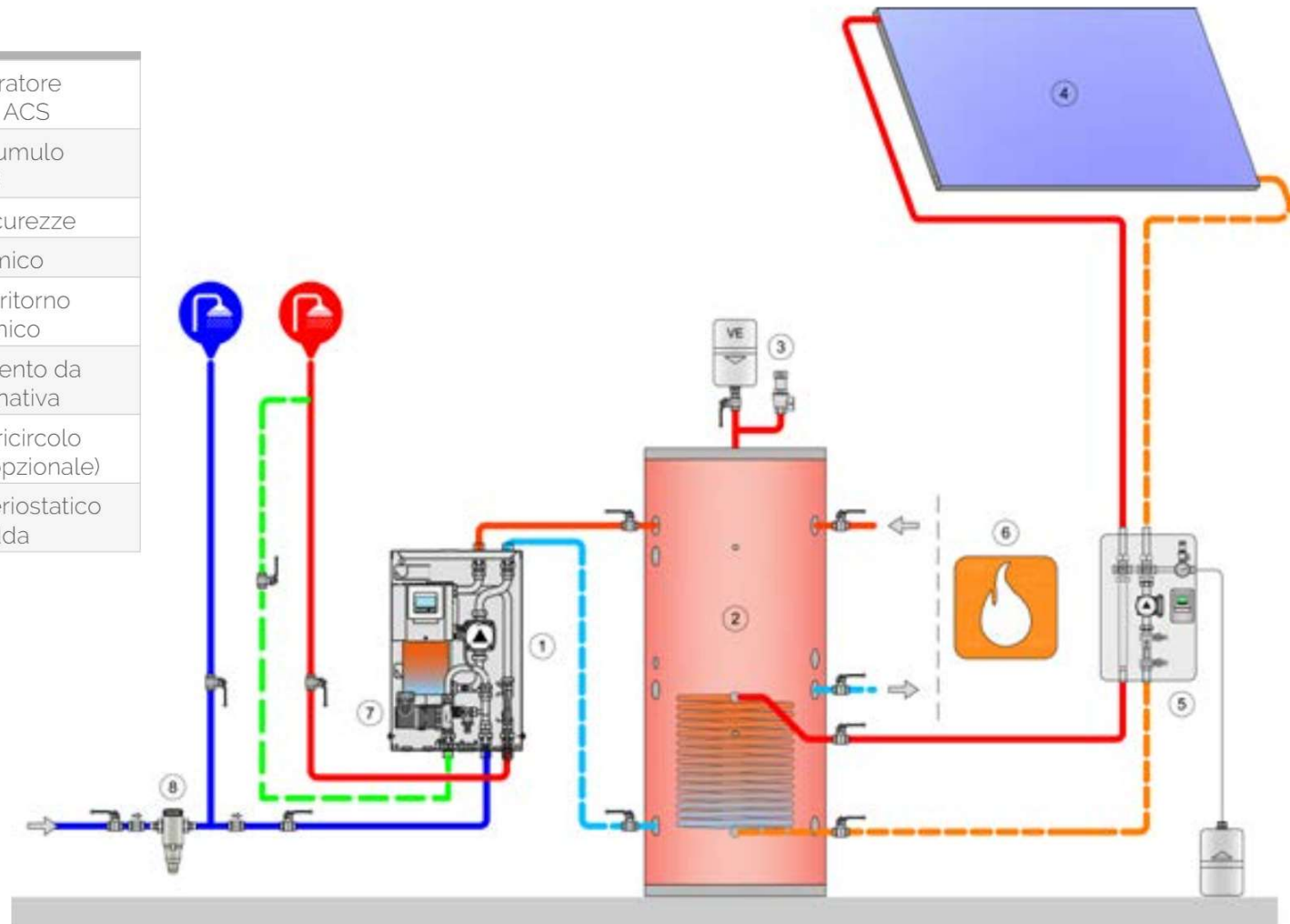


Indirect systems with external heat exchanger

Cold water from the aqueduct is heated inside a separated heat exchanger where hot water comes from the water tank

Legenda

1	SET preparatore istantaneo ACS
2	Termoaccumulo Fiorini PFB
3	Gruppo sicurezze
4	Solare termico
5	Gruppo di ritorno solare termico
6	Riscaldamento da fonte alternativa
7	Pompa di ricircolo sanitario (opzionale)
8	Filtro batteriostatico acqua fredda



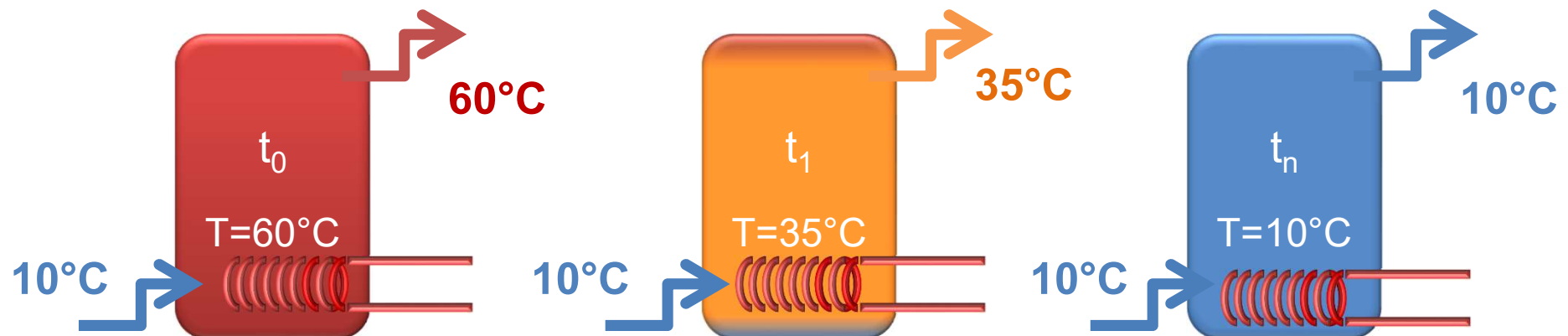
HEAT STORED SYSTEMS

All technologies need a heat up period necessary in order to achieve the maximum temperature (dependent on the volume in the tank, on the peak power installed).

When supplying the energy to the cold water, the two systems differ in the operation.

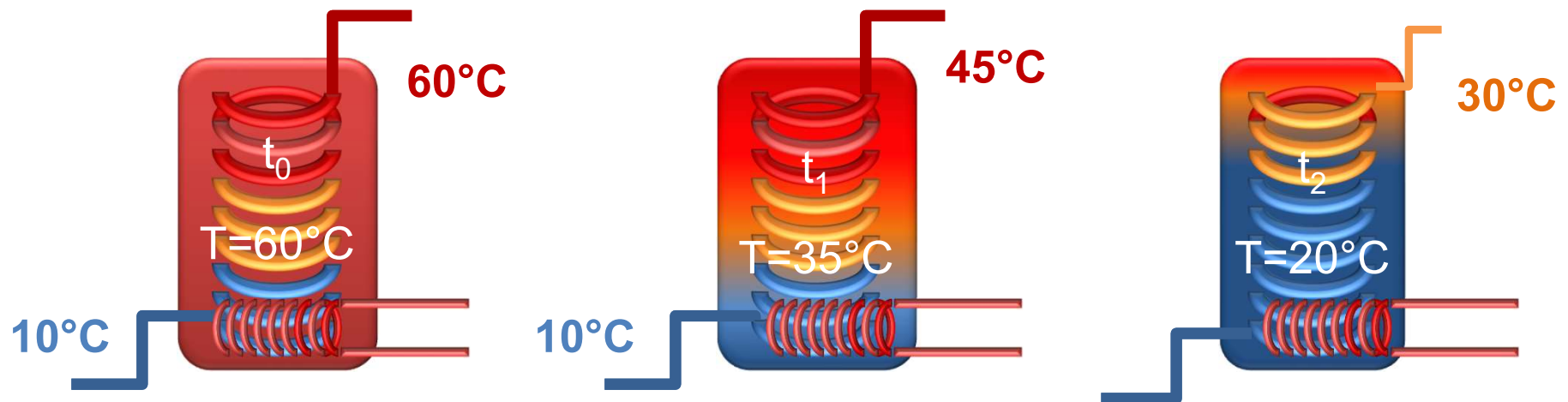
Direct heat stored

The cold water mixing with the hot water reduces gradually the water temperature inside the storage down to a lower limit. Once reached this limit it is not possible to reach the expected temperature for the DHW.



Indirect heat stored with internal heat exchanger

The cold water flows inside the internal heat exchanger (the coil in this case) and heats up while the water inside of the tank diminishes over the time. Compared to the direct system, thanks to the stratification of temperature within the storage, the outlet temperature will be higher until the heat capacity of the system finishes (the fluid, usually water, will be subjected to natural movement).



HEAT STORED SYSTEMS

Sizing of the heat stored system

The sizing method for the heat stored is based on the choice of two parameters: the thermal peak power q_R and the capacity C of the storage, once defined the following parameters:

T_e supply time

T_p preheating time

m_e amount of hot water supplied

t_e temperature of hot water supplied

t_A temperature of the available fresh cold water

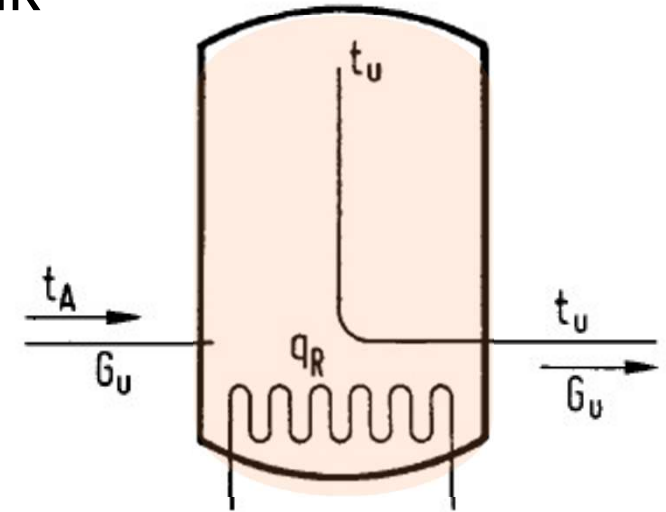
t_{\max} temperature of the water after the pre-heating period (set-point)

REMARK: The thermal peak power q_R is considered constant

This is true only for electrical resistance. If hot water in the heat exchanger is used to heat up the storage, only the flow rate of the water G_S and the entering temperature T_{es} are constant, while the temperature of the heat storage increases and hence the delivered power q_R will not be constant.

The mass flow rate G_u flows within the water tank increasing the temperature from the inlet temperature t_A to the outlet temperature t_u

Assuming that the whole volume C is at a uniform temperature t_u (hence neglecting any effect of stratification within the tank) the thermal behaviour of the system can be written by the following equation:



$$C \cdot c_A (dt_u / dt) = q_R - G_u \cdot c_A \cdot t_u + G_u \cdot c_A \cdot t_A - K_i \cdot S_i (t_u - t_a)$$

Internal energy of the system variation

Heat released by the heating fluid

Heat exchange due to the heat up of the water flow rate

Heat losses through the envelope*

The second hand side of the equation represents the heat exchanges in the water tank

* Heat transfer coefficient K_i and surface of the tank S_i , ambient temperature t_a

During the hot water supply a certain mass flow rate G_e is required (equal to m_e/τ_e) at a constant temperature t_e .

For this purpose there is a 3-ways valve before the tank which will allow to derive part of water (with a flow rate equal to G_r) at the aqueduct temperature t_A .

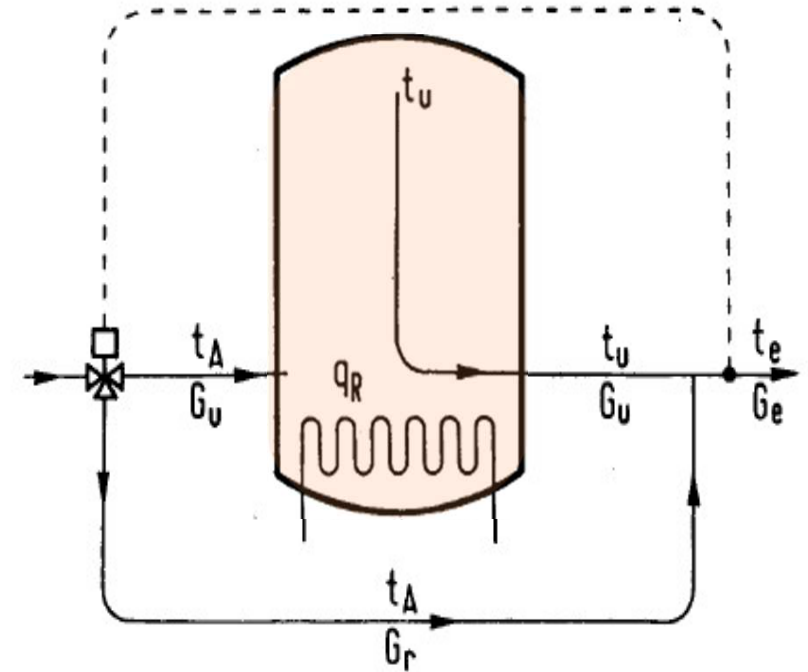
The cold water flow rate G_r mixes with the hot water flow rate G_u at high temperature t_u . This is necessary to provide the mass flow rate G_e at t_e , intermediate temperature between t_A and t_u . (in other words we need to store thermal energy at $t_u > t_e$).

The flow rates G_r and G_u will change because the temperature of t_u will decrease

over the time when fresh water at temperature t_A enters in the tank. The supply will stop in this case when t_u will reach t_e .

Once reached the temperature t_e in the tank the temperature of the tank will be supplied at decreasing temperature.

The dot line represents the control variable (t_e) acting on the 3-ways valve.



SIZING A DIRECT HEAT STORED SYSTEM

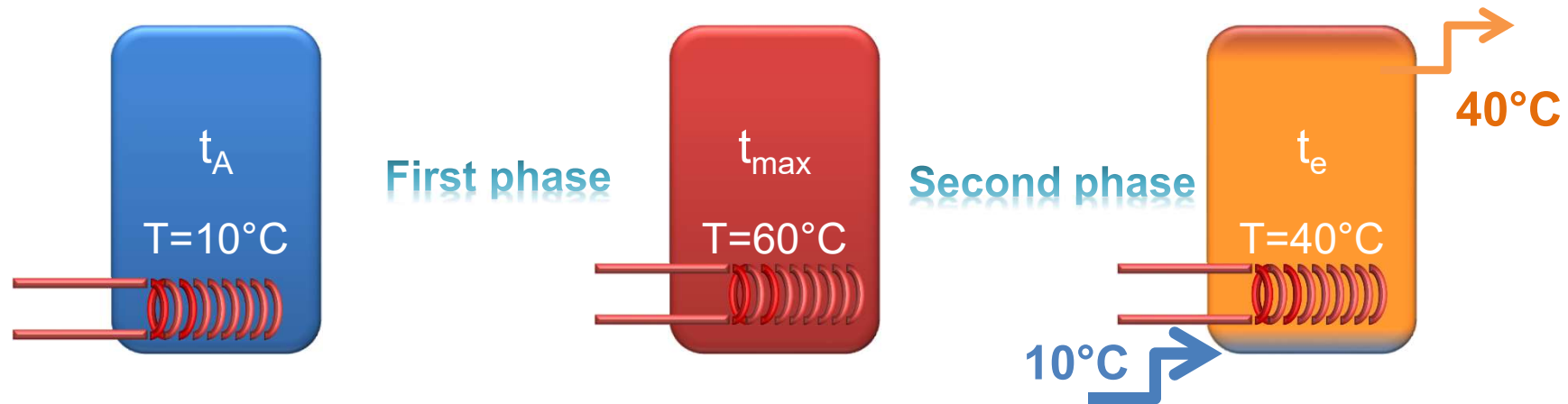
The main parameters which influence the required design variables q_R and C are:

- The required flow rate of DHW to be supplied to the user
- The temperature required to store the heat
- The ambient temperature where the water tank is installed

It is assumed that the water in the tank has an initial temperature equal to t_A .

During the pre-heating period the required time to increase the temperature from t_A to t_{max} (first phase).

After the hot water supply period (second phase) the temperature of the water tank lowers from t_{max} down to t_e



$$C \cdot c_A \left(\frac{dt_u}{dT} \right) = q_R - G_u \cdot c_A \cdot t_u + G_u \cdot c_A \cdot t_A - K_i \cdot S_i (t_u - t_a)$$

Integrating the general thermal balance equation in the tank in the whole period of preheating and supply, the required energy q_R in the time $\tau_p + \tau_e$ will allow:

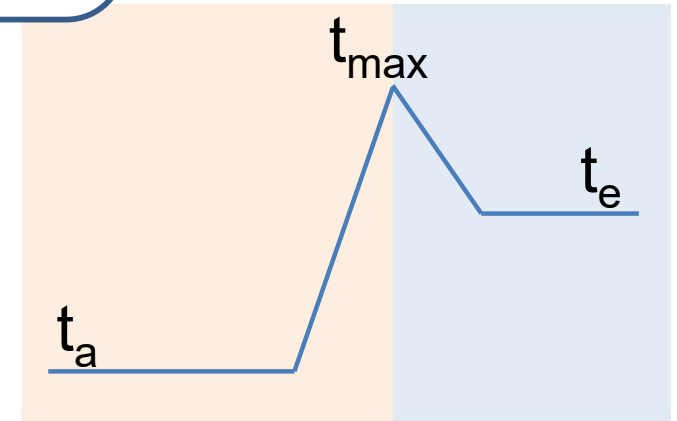
- to supply the **required amount of water m_e at t_e**
- to compensate the heat **losses through the envelope** of the tank
- To provide the **internal energy variation** in the tank

$$q_R (\tau_p + \tau_e) = m_e \cdot c_A (t_e - t_A) + q_{dp} \cdot \tau_p + q_{de} \cdot \tau_e + C \cdot c_A \cdot (t_e - t_A)$$

Heat losses during pre-heating phase (phase 1)

Heat losses during the supply phase (phase 2)

$$q_{dp} \cdot \tau_p + q_{de} \cdot \tau_e$$



Pre-heating

supply

q_{dp} and q_{de} are the heat losses of the tank:

$$q_{dp} = K_i S_i (t_{mp} - t_a)$$

$$q_{de} = K_i S_i (t_{me} - t_a)$$

$$t_{mp} = (t_A + t_{max}) / 2$$

$$t_{me} = (t_{max} + t_e) / 2$$

where: t_{mp} , t_{me} are the average temperatures during the pre-heating phase (phase 1) and the hot water supply phase (phase 2)

To calculate the losses through the tank's envelope it is necessary to know the heat exchange surface S_i .

This value is linked to the thermal capacity of the storage C together with the heat power supply q_R .



Hence an iterative procedure should be necessary.

In a first size for simplicity the losses can be neglected or can be fixed the S_i based on experience.

One heat balance can be written for the heat up period:

$$q_R \cdot \tau_p = C \cdot c_A \cdot (t_{\max} - t_A) + q_{dp} \cdot \tau_p$$

Heat supplied
during the pre-
heating phase

Internal energy
variation during the
pre-heating phase

Losses through the
envelope in the pre-
heating phase

These two equations can be solved together in order to achieve q_R and C , once defined the pre-heating time τ_p and the supply time τ_e :

$$q_R (\tau_p + \tau_e) = m_e \cdot c_A (t_e - t_A) + q_{dp} \cdot \tau_p + q_{de} \cdot \tau_e + C \cdot c_A \cdot (t_e - t_A)$$

$$q_R \cdot \tau_p = C \cdot c_A \cdot (t_{\max} - t_A) + q_{dp} \cdot \tau_p$$

Example:

Calculate q_R and C necessary for: $m_e = 100$ kg/h, at $t_e = 40^\circ\text{C}$, in a time $\tau_e = 1$ h, with $\tau_p = 5$ h.

The following conditions are also fixed: $t_{\max} = 60^\circ\text{C}$, $t_A = 10^\circ\text{C}$, $t_a = 20^\circ\text{C}$, $K_i = 0.93$ W/(m² K) and $S_i = 1.3$ m².

Solution:

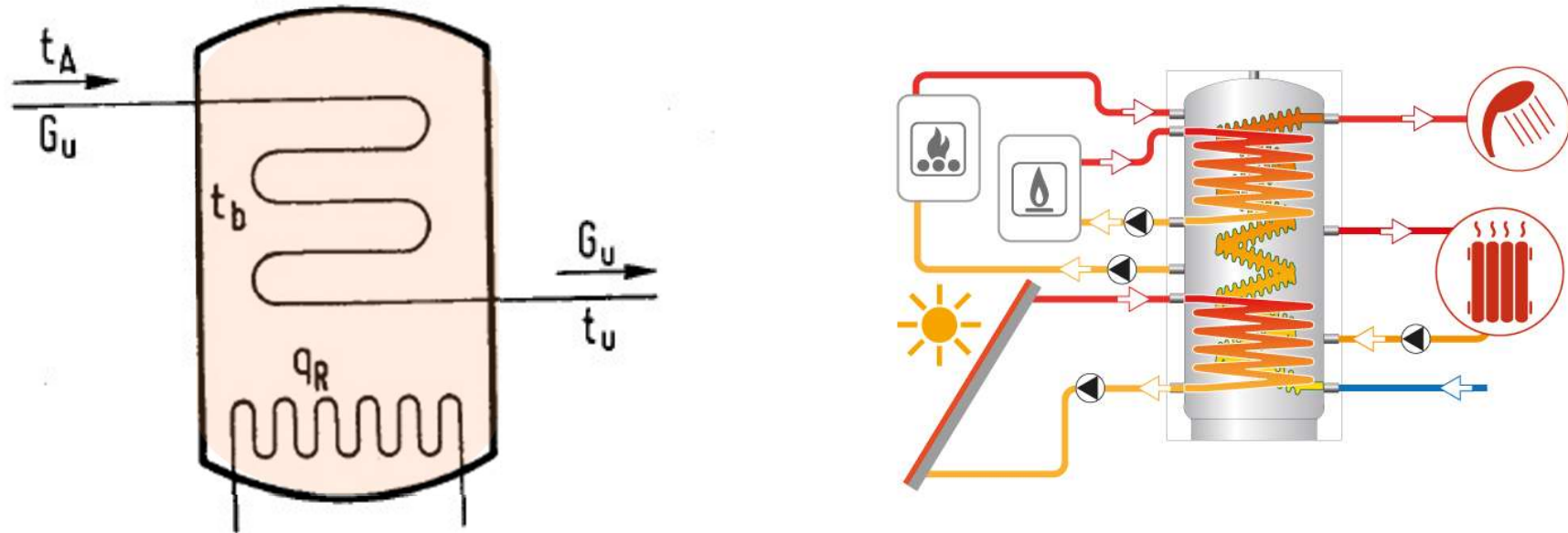
$$q_R = 1187 \text{ W} \quad \text{and} \quad C = 101 \text{ kg}$$

Considering negligible the losses:

$$q_R = 1163 \text{ W} \quad \text{and} \quad C = 100 \text{ kg}$$

SIZING AN INDIRECT HEAT STORED SYSTEM WITH INTERNAL HEAT EXCHANGER

The hot water is heated from t_A to t_u within the internal heat exchanger separating the hot water to be used in the building from the water heated by the generator and contained in the tank.



As a first hypothesis we can neglect stratification and hence we can assume a uniform temperature in the tank $t_b > t_u$.

t_b : temperature of the water inside the tank

The thermal balance in the tank provides the change in the internal energy for the volume C of water:

$$C \cdot c_A (dt_b / d\tau) = q_R - q_s - q_d$$

where:

- q_R is the heat supplied by the water heated by generator
- q_s is the heat exchange to generate the hot water
- q_d is the heat loss through the envelope

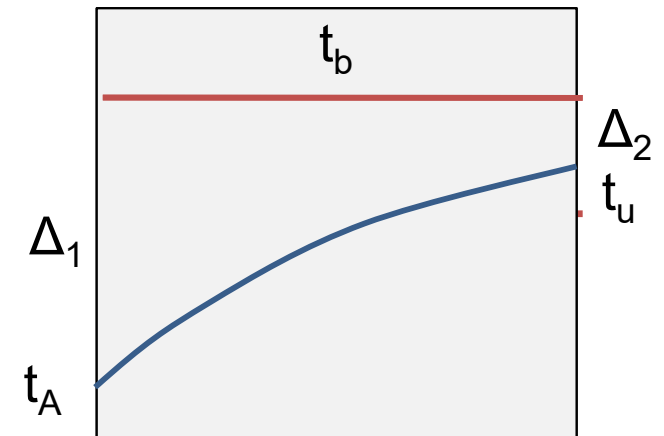
$$C \cdot c_A (dt_b / d\tau) = q_R - G_u \cdot c_A \cdot t_u + G_u \cdot c_A \cdot t_A - K_i \cdot S_i (t_b - t_A)$$

Assuming a uniform temperature t_b in the water tank, the heat exchange to generate the hot water q_s can be written as:

$$q_s = K_c \cdot S_c \cdot \Delta t_{ml}$$

where K_c is the global heat exchange coefficient and S_c is the surface of the internal heat exchanger which heats up the water from t_A to t_u .

$$\begin{aligned} q_s &= K_c \cdot S_c \cdot \frac{(t_b - t_A) - (t_b - t_u)}{\ln((t_b - t_A) / (t_b - t_u))} \\ &= K_c \cdot S_c \cdot \frac{(t_u - t_A)}{\ln((t_b - t_A) / (t_b - t_u))} \end{aligned}$$



The power q_s is the power to produce the hot water:

$$q_s = G_u \cdot c_A \cdot (t_u - t_A)$$

Merging the equations:
$$G_u \cdot c_A \cdot (t_u - t_A) = K_c \cdot S_c \cdot \frac{(t_u - t_A)}{\ln((t_b - t_A) / (t_b - t_u))}$$

$$\frac{(t_b - t_A)}{(t_b - t_u)} = e^{\frac{K_c \cdot S_c}{c_A \cdot G_u}} \Rightarrow t_u = t_b - (t_b - t_A) \cdot e^{-\frac{K_c \cdot S_c}{c_A \cdot G_u}}$$


Deriving:
$$dt_b = \frac{dt_u}{1 - e^{-\frac{K_c \cdot S_c}{c_A \cdot G_u}}}$$

Replacing dt_b in the thermal balance equation:

$$C \cdot c_A (dt_b / d\tau) = q_R - q_d - q_s$$

Replacing dt_b in the thermal balance equation:

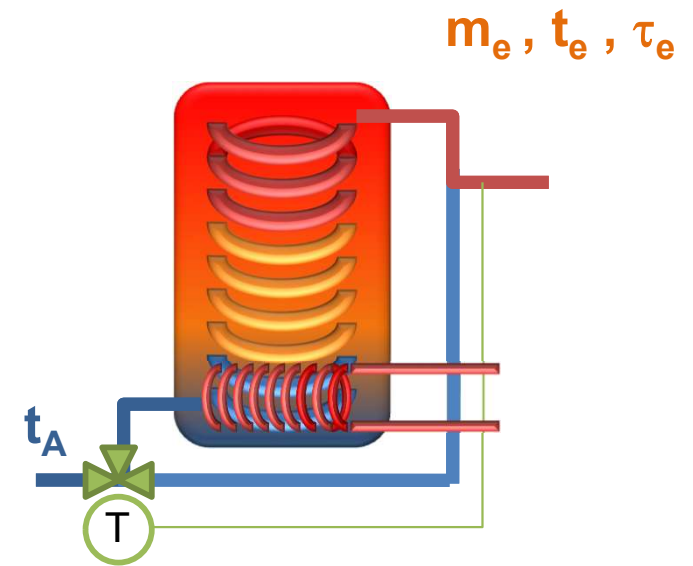
$$C \cdot c_A (dt_b / d\tau) = q_R - q_d - q_s$$


$$\frac{dt_u}{1 - e^{-\frac{K_c \cdot S_c}{c_A \cdot G_u}}} = \left(\frac{q_R - q_d}{C \cdot c_A} - \frac{G_u \cdot (t_u - t_A)}{C} \right) d\tau$$

This equation has to be integrated in a numerical or analytical way, thus allowing to get the trend of t_u at the outlet of the internal heat exchanger in different operating conditions.

For sizing the system, it is supposed to heat up a certain amount of water m_e at a certain temperature t_e in a certain time frame τ_e after the pre-heating period τ_p .

The temperature t_e is kept constant by mixing a suitable amount of cold water at aqueduct temperature t_A .



The first element to be sized is the internal heat exchanger through which the water to be heated up flows.

REMARK:

Respect to the direct systems the indirect system has an intermediate heat exchanger. This means that after the heat supply period the water in the tank needs a temperature $t_b > t_e$, so as to allow to heat up the cold water from t_A to the minimum temperature t_e .

In this case the hot water supplied has a flow rate $G_e = G_u$.

Choice of t_{\min} (minimum allowed temperature in the tank) is chosen by means of the characteristics of the heat exchanger ($K_c \cdot S_c$):

$$K_c \cdot S_c = \frac{G_e \cdot c_A \cdot (t_e - t_A)}{\Delta t_{ml}}$$

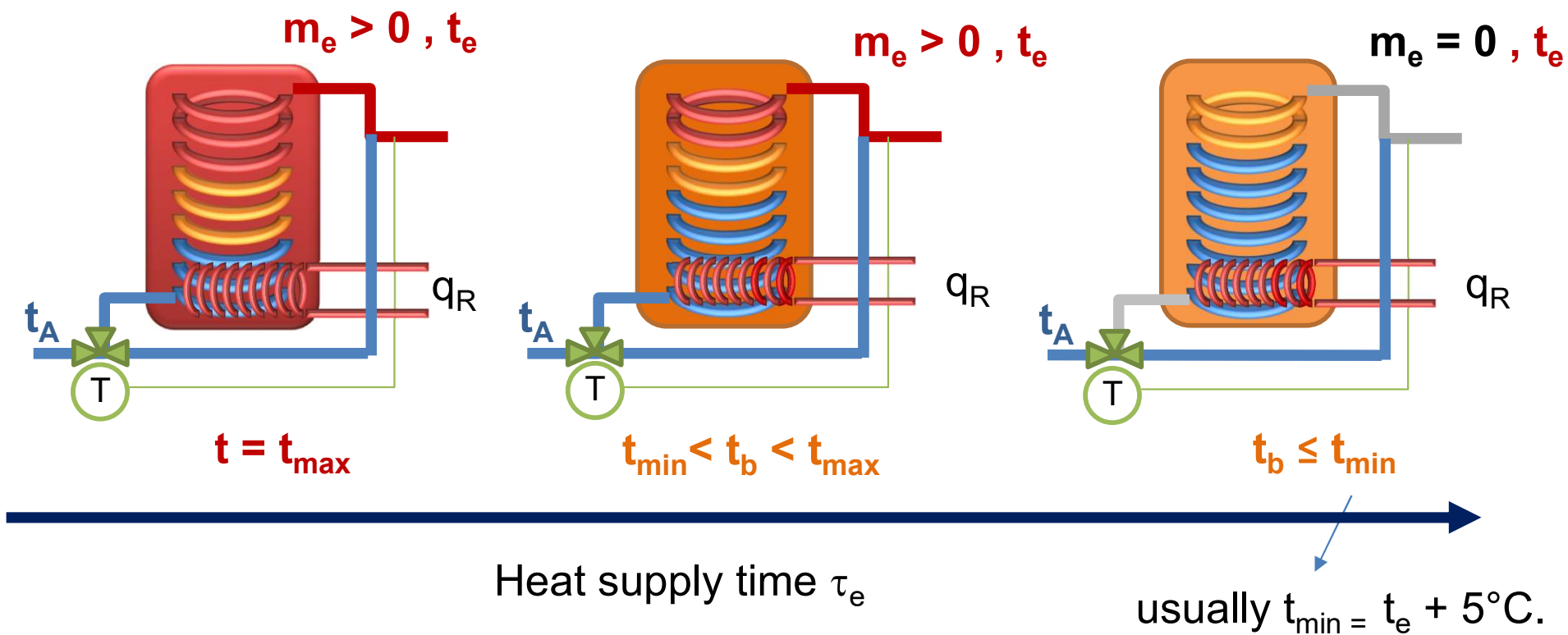
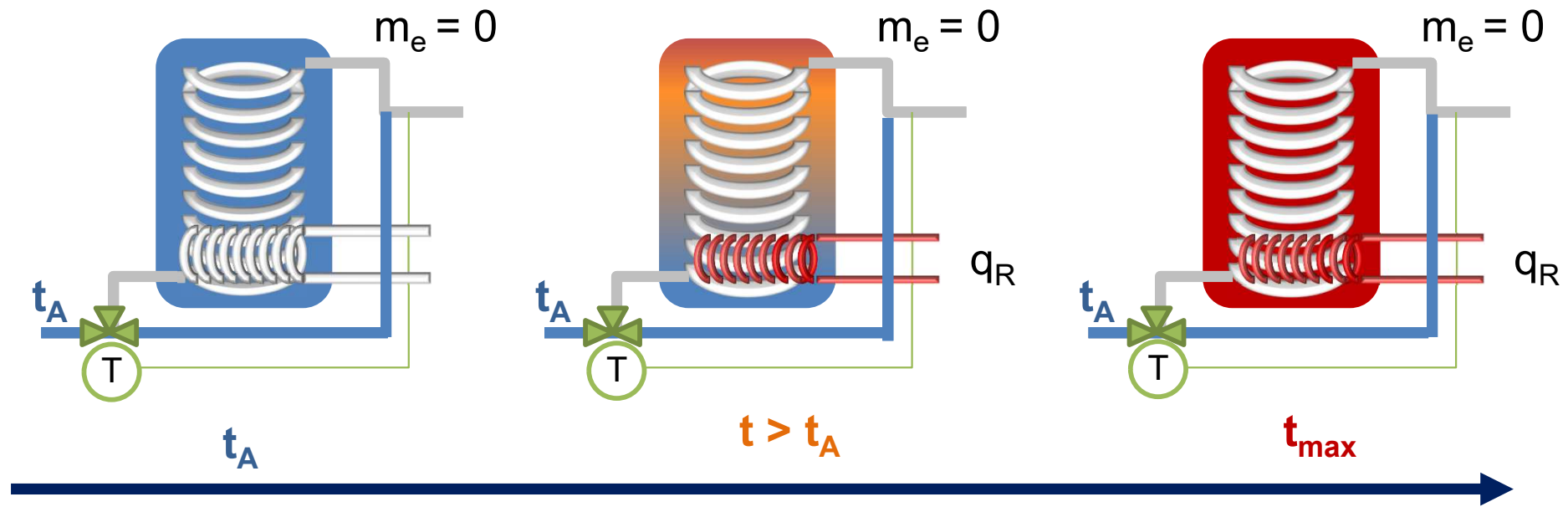
where Δt_{ml} is calculated in the most critical conditions for the heat exchange, i.e. at the end of the heat supply period:

$$\Delta t_{ml} = \frac{(t_{b=\min} - t_A) - (t_{b=\min} - t_{u=e})}{\ln((t_{b=\min} - t_A) / (t_{b=\min} - t_{u=e}))}$$

For avoiding to oversize the heat exchanger usually it is assumed to fix $t_{\min} = t_e + 5^\circ\text{C}$

To size the heat exchanger the heat balance equation has to be integrated in the pre-heating period and in the supply heat period:

$$C \cdot c_A (dt_b / dT) = q_R - q_d - q_s$$



Heat balance equation: $C \cdot c_A (dt_b / d\tau) = q_R - q_s - q_d$

Integrated over the whole time (pre-heating + supply) it is possible to obtain two equations which allow the two variables:

$$(q_R - q_{dp}) \cdot \tau_p = C \cdot c_A \cdot (t_{\max} - t_A)$$

$$(q_R - q_{de}) \cdot \tau_e + C \cdot c_A \cdot (t_{\max} - t_{\min}) = m_e \cdot c_A \cdot (t_e - t_A)$$

Where t_{\max} is the temperature of the water within the tank after the pre-heating period and t_{\min} is the temperature at the end of the heat supply period

The heat losses q_{dp} and q_{de} are calculated as:

$$q_{dp} = K_i S_i (t_{mp} - t_a)$$

$$q_{de} = K_i S_i (t_{me} - t_a)$$

$$t_{mp} = (t_A + t_{\max}) / 2$$

$$t_{me} = (t_{\max} + t_e) / 2$$

Example:

Calculate q_R and C necessary for: $m_e = 100$ kg, at $t_e = 40^\circ\text{C}$, in a time $\tau_e = 1$ h, with $\tau_p = 5$ h.

The following conditions are also fixed: $t_{\max} = 60^\circ\text{C}$, $t_A = 10^\circ\text{C}$.

The losses can be considered negligible.

Solution:

Let's fix t_{\min} : $t_{\min} = t_e + 5^\circ\text{C} = 45^\circ\text{C}$

Hence:
$$\Delta t_{ml} = \frac{(t_{\min} - t_A) - (t_{\min} - t_e)}{\ln \left(\frac{t_{\min} - t_A}{t_{\min} - t_e} \right)} = \frac{(35) - (5)}{\ln (35/5)} = 15.4^\circ\text{C}$$

Then: $G_e = m_e / \tau_e = 100/1 = 100$ kg/h

Thus:
$$K_C \cdot S_C = \frac{G_e \cdot c_A \cdot (t_e - t_A)}{\Delta t_{ml}}$$
$$= \frac{100}{3600} \cdot 4186 \cdot \frac{(40 - 10)}{15.4} = 226.5 \quad \text{W/K}$$

Solving the equations of balance:

$$q_R = 1421 \text{ W} \qquad C = 120 \text{ kg}$$

COMMENTS:

The heat stored system with an internal heat exchanger compared to a similar direct hot water system require a greater thermal storage and a greater peak heat load. This is due to the intermediate internal heat exchanger.

This system has also a great advantage: **Legionella** is the bacterium that causes **Legionnaires' disease** which can be caused by the presence of still water (as in the case of the direct systems).

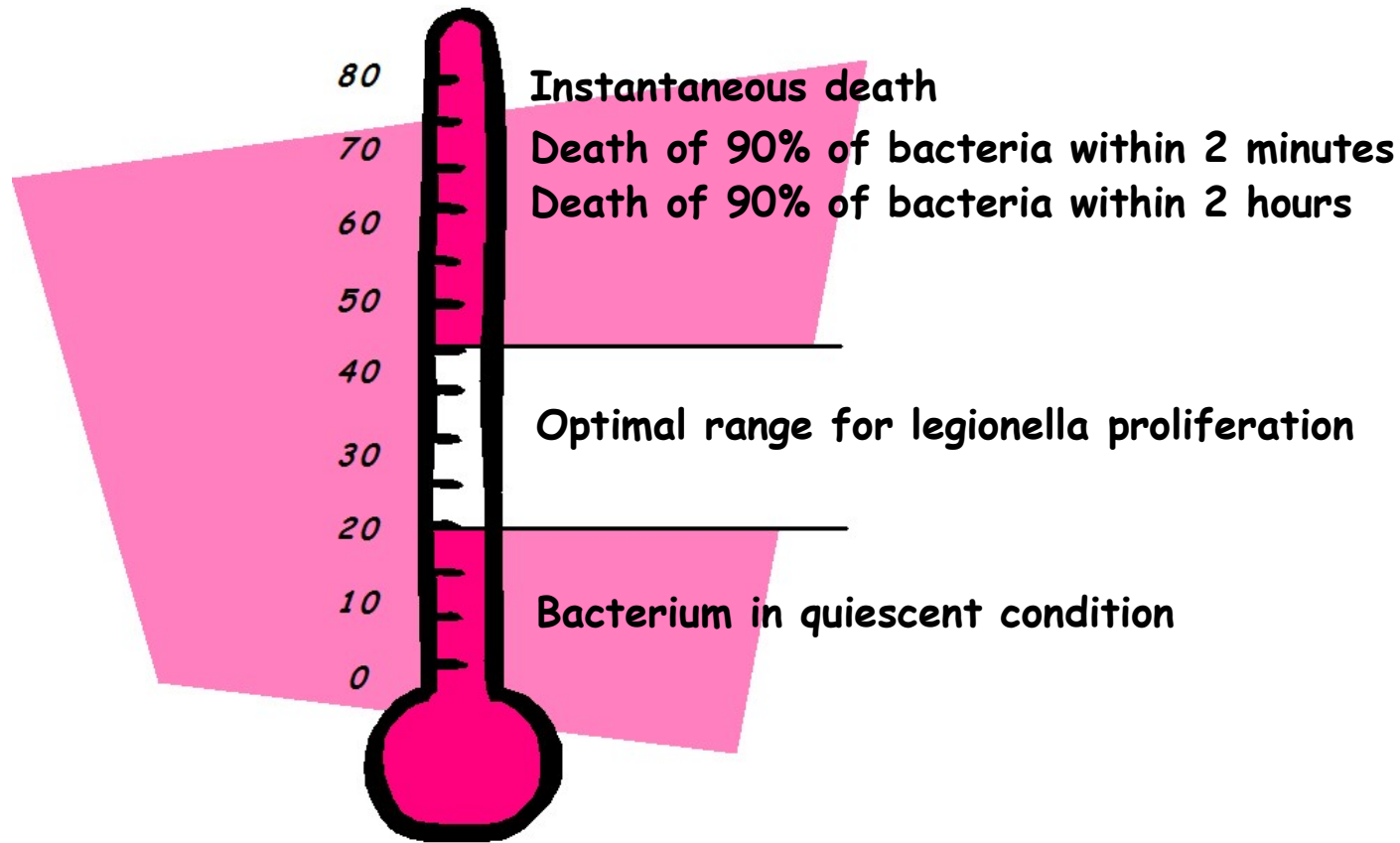
People can get Legionnaires' disease if they breathe in water droplets containing Legionella. Certain groups of people are at increased risk for getting Legionnaires' disease, including those 50 years or older, current or former smokers, and people with chronic disease or weakened immune systems.



<https://www.cdc.gov/legionella/wmp/overview/growth-and-spread.html>

Good rules to minimize the risks:

- Prevent Stagnation
- Operate within the correct temperature range



Indirect systems limit the water stagnation.

Direct systems: usually there is the need of thermal cycles (above 60°C) to prevent the problem (usually one night per week)

SIZING AN INDIRECT HEAT STORED SYSTEM WITH EXTERNAL HEAT EXCHANGER

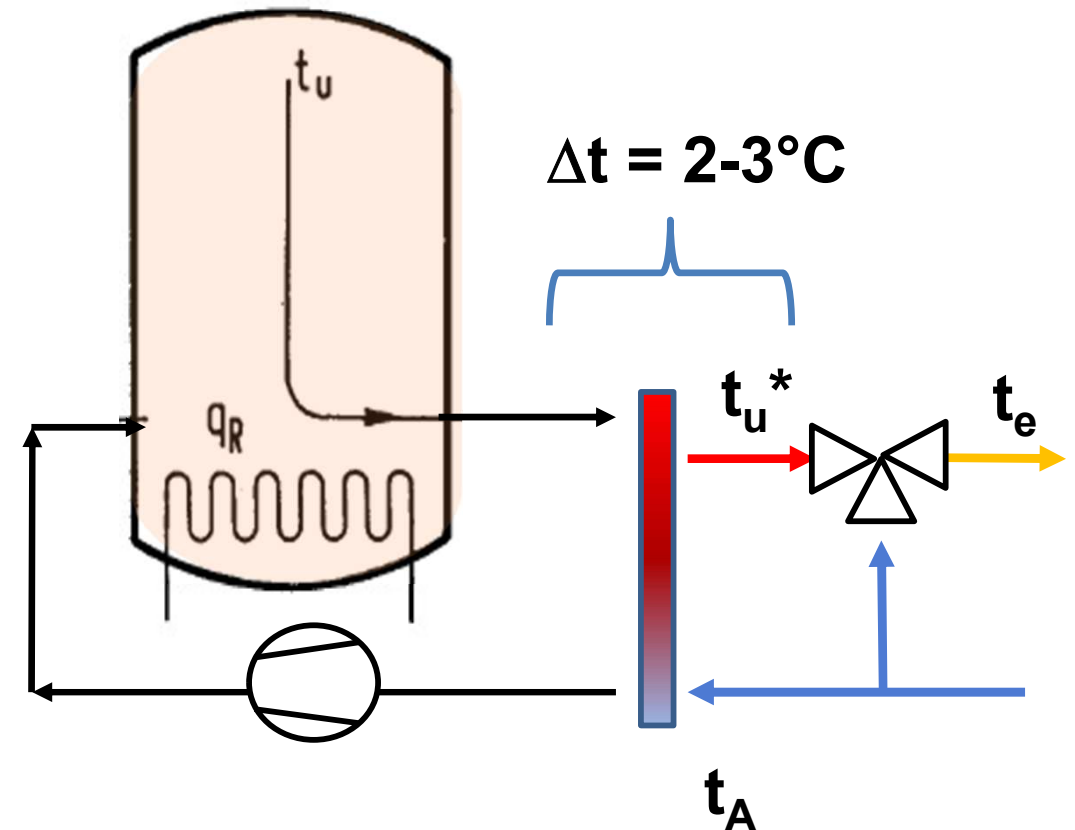
In this case the water of the heat storage is separated from the hot water used in the building. The hot water of the tank heats up the fresh water through an external heat exchanger. For this purpose a pump is needed to recirculate the water of the tank.

To guarantee a suitable supply temperature t_s there is the need to provide a $t_u > t_s$.

Depending on the heat exchanger, the temperature difference can be around 2-3 °C.

The system can be hence considered an equivalent direct heat stored system with a supply temperature:

$$t_e^* = t_e + \Delta t = 42-43^\circ\text{C}$$



Example:

Calculate q_R and C necessary for: $m_e = 100$ kg/h, at $t_e^* = 42^\circ\text{C}$, in a time $\tau_e = 1$ h, with $\tau_p = 5$ h.

The following conditions are also fixed: $t_{\max} = 60^\circ\text{C}$, $t_A = 10^\circ\text{C}$, $t_a = 20^\circ\text{C}$, neglecting losses.

Solution:

$$q_R = 1329 \text{ W} \quad \text{and} \quad C = 114 \text{ kg}$$

HOW CAN WE SIZE THE PEAK LOAD FOR THE HOT WATER?

Depending on the type of user, the daily demand of hot water can be evaluated (depending on the amount of occupants or the number of bathrooms, lavatories, etc.).

The peak power duration has to be defined (τ_e).

If there are more users a contemporary factor can be considered to take into account that different users can use the hot water in different moments of the day.

For residential buildings also the social status play a role in the amount of hot water used.

HOW CAN WE EVALUATE THE ENERGY DEMAND FOR THE HOT WATER?

There are different methods to calculate the energy demand for hot water. The different approaches lead to very similar results.

This is the method used in the Italian standard:

$$Q_w = \rho_w \times c_w \times \sum [V_{w,i} \times (\theta_e - \theta_A)] \times D$$

Q_w : energy demand for the hot water [kWh]

ρ_w : density of the water 1000 kg/ m³

c_w : 1.162 x 10⁻³ kWh/(kg K)

$V_{w,i}$: daily volume for the generic i-th user [m³/day]

θ_e : supply temperature of the i-th user [°C]

θ_A : aqueduct temperature [°C]

D: amount of days [day]

NET ENERGY DEMAND FOR A RESIDENTIAL BUILDING

In the Italian standard the volume of water has to be expressed in terms of liters per day [l/day].

$$V_w = a \times S_u + b \quad [\text{l/day}]$$

a: parameter in [l/(m² day)] reported in the following table

b: parameter in [l/(day)] reported in the following table

S_u: useful surface area of the dwelling [m²]

Useful floor area [m ²]	S _u < 35	35 ≤ S _u < 50	50 ≤ S _u < 200	S _u ≥ 200
Parameter a [l/(m ² day)]	0	2.667	1.067	0
Parameter b [l/(day)]	50	- 43.33	36.67	250

NET ENERGY DEMAND FOR NON RESIDENTIAL BUILDINGS

In the Italian standard the daily volume of water is expressed as:

$$V_w = a \times N_u \quad [\text{l/day}]$$

a: parameter in $[\text{l}/(\text{day} \times N_u)]$

N_u : parameter depending on the user

User/activity	a	N_u
Residences and B&B	40	Per bed
Hotels *, **, ***	60	Per bed
Hotels **** & *****	80	Per bed
Hospitals (night)	80	Per bed
Day hospital	15	Per bed
Sporthall	50	Per shower
School	0.2	Per child
Kindergarden	8	Per child
Offices	0.2	Net floor area

SUMMARY

As all other energy uses, also the hot water has to be properly evaluated.

For this purpose two different calculations are necessary:

- Peak load calculation
- Energy demand

Peak power calculation must consider also the peak load calculation for heating in winter. If the generator has to face the heating and the hot water, the size of the generator has to take into account the two values of peak load.

Usually the hot water need has the priority on the heating. In case of a boiler or a heat pump, when there is the need of hot water there is a switch from heating to hot water production.

Energy demand for Hot Water

