SOLAR POWERED COOLING AND REFRIGERATION

COURSE TRANSCRIPT

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Background:

This course transcript has been developed within a project carried out by the Strathmore Energy Research Center and the University of Hohenheim Supported by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ).

The aim of the project, which took place between September 2019 and February 2022, was the establishment of a training course to facilitate capacity building for the design, production, assembling, installation and maintenance of small-scale Solar cooling systems in Kenya. The Energy Research Center (SERC) attached to the Strathmore University is a highly recognized and accredited institution for the training of technicians in the area of Solar Energy. The Institute of Agricultural Engineering of the University of Hohenheim has being developing since 2014 several solar powered cooling solutions, which are suitable for local production. Both institutions cooperated since 2018 for the creation of awareness on the use of Solar energy for refrigeration of agricultural products. Within the project, a technical training course was established with focus on:

- Agricultural value chains and promising business models
- Cooling requirements of food regarding storage temperature, humidity and ventilation needs
- Basis on refrigeration technologies, with focus on vapour compression heat pumps
- Calculation of cooling load for the most typical cooling systems (based on design tools)
- Design of PV panels and electrical/thermal storage
- Local production of solar cooling systems based on the use of cooling units
- Optimal insulation, ice-storage and PV yield based on climatic conditions
- Practical assembling work with example systems (Cold room, ice-makers and refrigerators)
- Energy efficiency indicators of cooling solutions
- Installation, maintenance and remote monitoring

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Table of Contents

Table of Contents

1 SOLAR COOLING UNIT

1.1 Overview

The mobile Solar Cooling (SC) unit for this course program is mounted on a moveable slotted angle iron-structure which can be moved outdoors for practical training purposes. The Solar part consists of a regular PV stand alone system with an adjustable 160Wp panel (A), a Solar charge controller (B) and a lead acid battery (C). It provides power for the cooling unit (D). Alternatively to the battery supply, the cooling unit can also be connected directly to the Solar panel (PV direct mode, see 11.7).

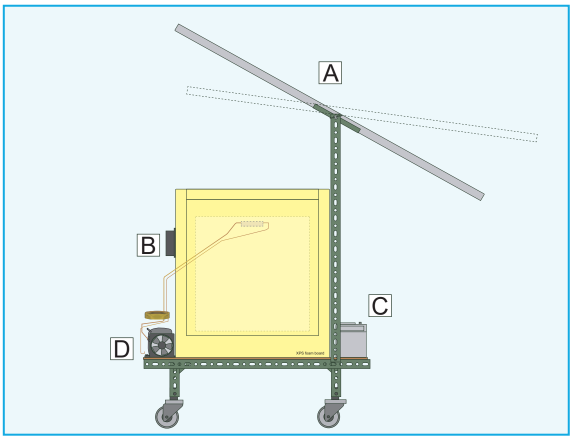


Fig. 1 Side view of the SC mobile unit

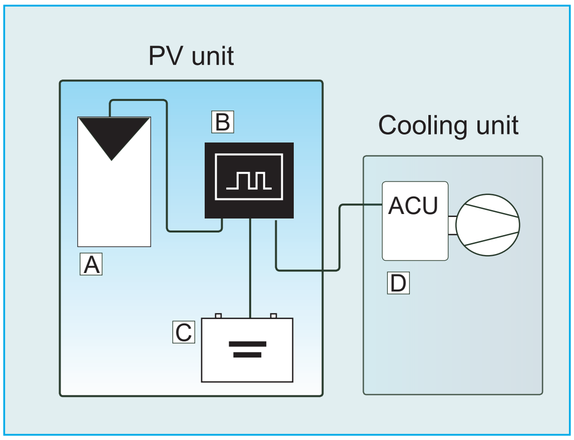


Fig. 2 Cooling unit with battery power supply

1.2 Cooling Unit

The (1) Adaptive control unit (ACU) measures the voltage level of the battery and the temperature of the three temperature sensors, T1 (cooling product), T2 (optional: ambient or thermo box) and T3 (evaporator plate). The ACU adjusts the power supply for the cooling compressor (2). Power is also supplied to the cooling fan of the condenser (3) and an additional axial ventilator that supports the cooling effect of the evaporator plate (4).

Before starting any initial testing arrangements with the SC unit, all the revelant specifications and manuals, especially the safety instructions, should be studied thoroughly and any open questions should be clarified in advance with the training instructors.

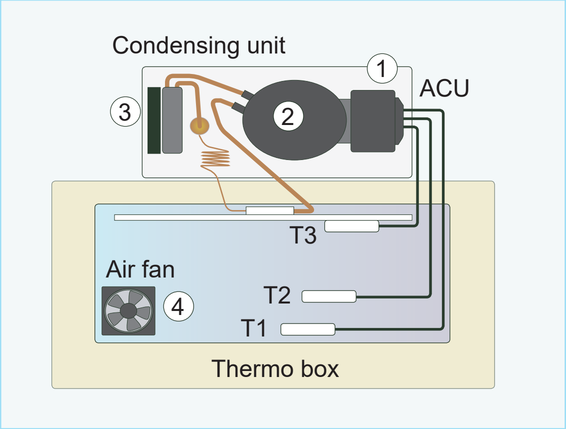


Fig. 3 Top view of the cooling unit

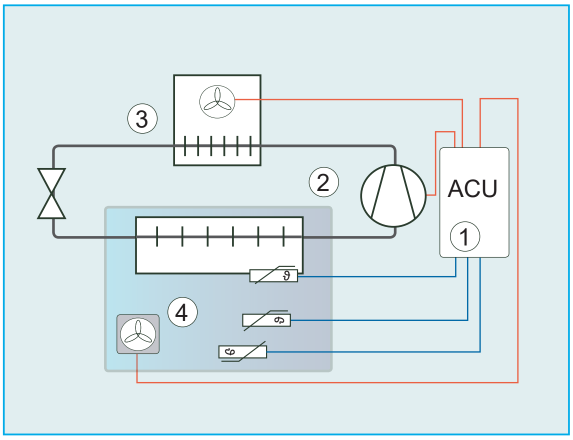


Fig. 4 Cooling circuit and electrical diagram

2 HEAT AND TEMPERATURE

In a first test arrangement it will be measured how long it takes for the cooling unit to chill the air inside the empty thermo box from ambient temperature (~25°C) down to a target temperature of 5°C. The first measurement will be conducted with no air ventilation, the second one will be done with air fan switched on. The initial temperature at the beginning of the test should be noted in the table, then in two minute increments until the air in the thermo box has chilled down to the final target temperature of 5°C.

The results show that ventilation leads to a much better distribution of cold air coming from the evaporator plate (compare T3 results). Non air fan supported cooling can lead to a layer buildup (stratification) of more dense, cold air at the bottom and warmer, less dense air in the upper parts of the thermo box.

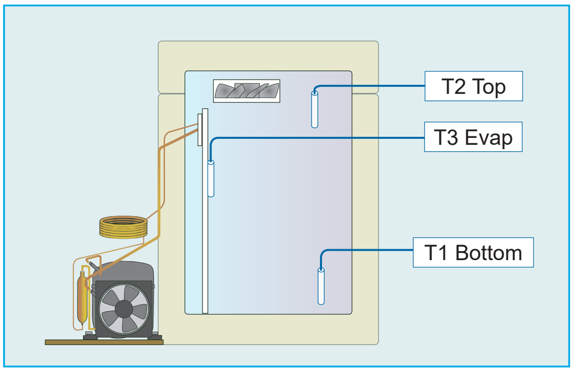
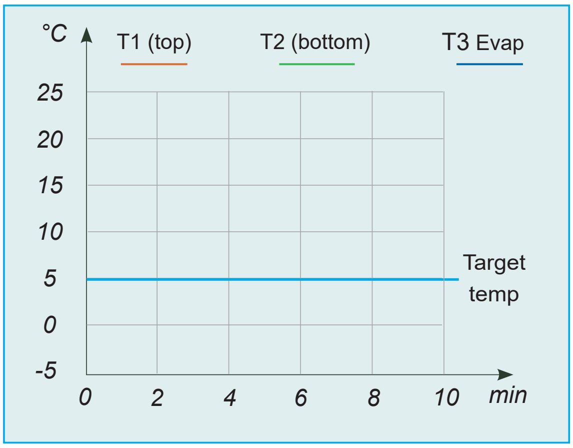


Fig. 5 Postition of temperature probes

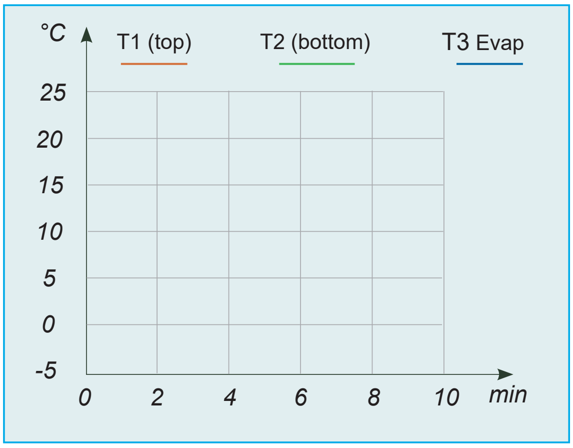
Tab.1 Non Convection Air Chilling

Voltage		RPM	
Amps		Target temp	5°C
t [min]	T1 (bottom)	T2 (top)	T3 (Evap)
0			
2			
4			
6			
8			



Tab.2 Forced Convection Air Chilling

Voltage		RPM	
Amps		Target temp	5°C
t [min]	T1 (bottom)	T2 (top)	T3 (Evap)
0			
2			
4			
6			
8			



2.1 Temperature Scales

In the 18th century heat was believed to be an invisible, massless fluid that could penetrate all objects and that determines their temperature (Caloric theory). The discoveries of modern science showed that all matter is made of atoms and molecules. The atomic particles of a substance are in constant movement and the total average movement of these particles is proportional to the temperature of the substance. An increase of these atomic movements also leads to an expansion of the substance. This phenomenon can be observed on the level of a mercury thermometer. The effect is amplified because the volumen of the bulb reservoir is larger than the increment tube. When temperature decreases, the kinetic energy of the substance decreases.

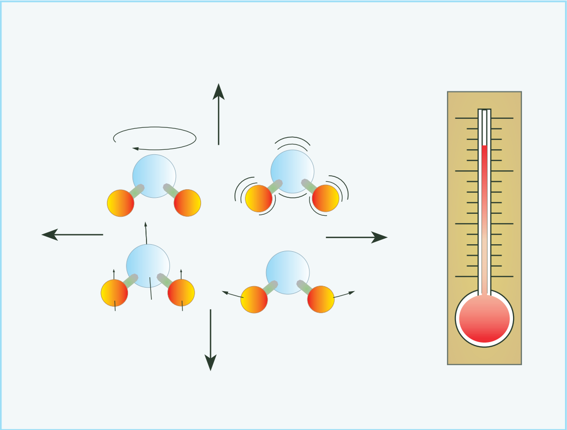


Fig. 6 Atomic movement leads to expansion

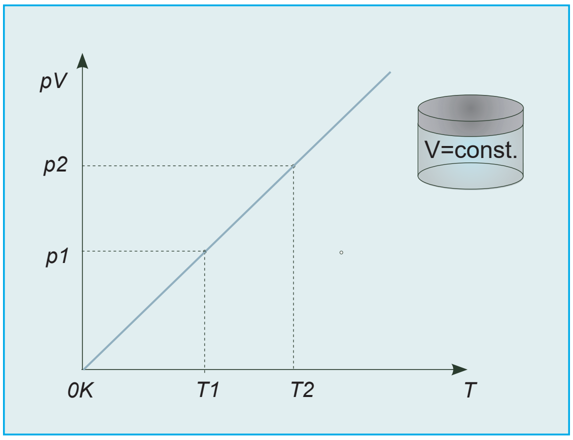


Fig. 7 Pressure temperature correlation of a gas

An ideal gas thermometer consists of a dilluted gas in a closed containment with a constant volume (Fig. 7). The term “ideal gas” stands for a theoretical gas fluid with ideal parameters. Under normal environmental conditions most common gases behave nearly like an ideal gas. Heating up an ideal gas in a constant volume container will lead to a linear increase of temperature parallel to a rise of internal pressure. The average kinetic motion of all gas particles is correlant to the temperature of the gas. In theory, the temperature could be lowered further to a point where all particles come to a complete standstill. This point is called **absolute zero** or **zero Kelvin**. At this point the molecules have no more kinetic movement and their thermal energy is zero. It also defines the starting point of the Kelvin scale (0K or -273.15°C) which is the standard unit for temperature of the international System of Units (SI).

Temperature has great influence on the physical well being and the human body can sense its changes quite well. The Fahrenheit scale (°F) relates directly to this phenomenon. 100 degrees Fahrenheit refer to the core temperature of the human body (37.7°C). The marker points of the Celsius scale are the freezing (0°C) and the boiling point (100°C) of water.

The main advantage of the Celsius and Kelvin scales is that both units have the same degree intervals. It is common practice to state temperature points in degree Celsius (e.g. 25°C ambient temperature) while temperature differences (written as ΔT or dT for Delta T) are defined in degree Kelvin (see Tab.3)

Tab.3 Use of Temperature Scales Kelvin and Celsius

Temperature Points [°Celsius]		Temperature difference [Kelvin]	
$T_{ambient}$	25°C	25°C - 5°C = 20K	ΔT
$T_{Thermo\ Box}$	5°C		

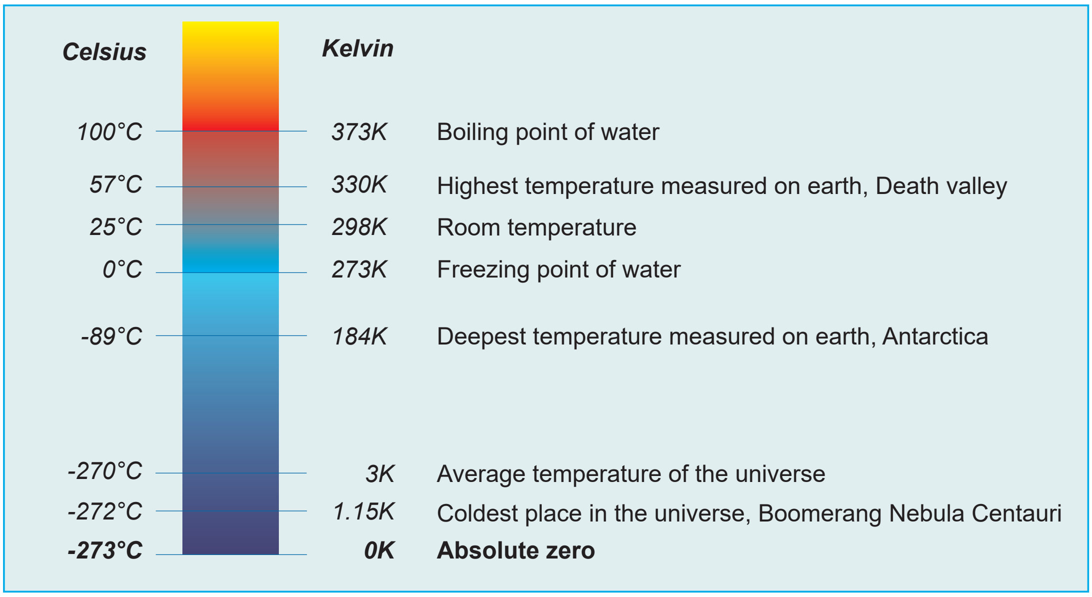


Fig. 8 Temperature recordings on an open scale starting with absolute zero

2.2 Zeroth Law of Thermodynamics

If two bodies are each in thermal equilibrium with some third body,
then they are also in equilibrium with each other.

Fig. 9 shows a container of water and a metal cube. They both have the same temperature. If the metal cube was cut in half it would still have the same temperature. Temperature is an **intrinsic property**, that means the temperature of an object is not dependent on its length, size or shape. Volume and mass are examples for **extrinsic properties**, their values are always dependent on their particular amount or size. If the intrinsic properties volume and mass are brought into relation, they become the new property density, which is an intrinsic property.

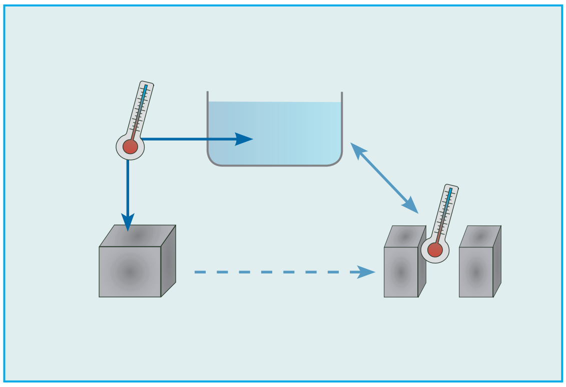


Fig. 9 Zeroth Law of TD relates to temperature

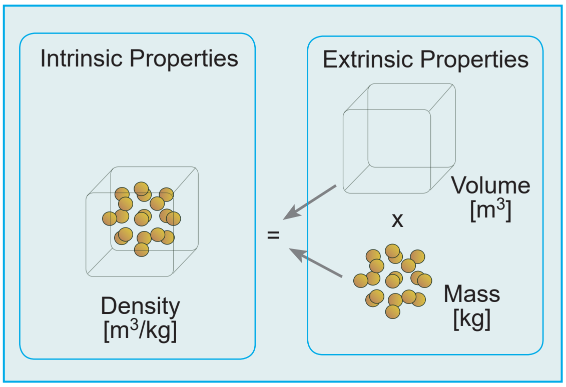


Fig. 10 Correlation between physical properties

2.3 Heat Transfer

The air molecules in the thermo box of the Solar Cooling unit contain a certain amount of kinetic energy. They are moving around randomly and whenever an air molecule hits the evaporator plate, it transfers a certain amount of kinetic energy to the evaporator plate. The impacted particles of the evaporator metal start to vibrate by the same amount as the colliding air molecules are slowed down.

This form of temperature or heat energy transfer is called **thermal conduction**. Whenever two physical mediums (solids, liquids or gases) with different kinetic energy levels come in direct contact, their molecules will bounce into each other until they've reached the same level of motion i.e. the same temperature, their **thermal equilibrium**.

Cooling down the air in the test arrangement (Tab.2: Internal air fan on) only needed approximately half the time since the circulation of air provided an additional form of heat exchange. **Convection** is the flow movement of fluid particles with different temperature levels. A warm fluid (liquid or gas) is less dense and will have the tendency to rise while a colder, more dense (and therefore heavier) medium will tend to sink down.

When an external force is exerted to the medium, the movement of the hot (or cold) fluid can be directed into a specified direction (**forced convection**). The movement of air inside the thermo box caused by the fan propeller improved the heat exchange and shortened the cooling time.The heat exchange by convection and conduction can be improved by two factors: **Enlarging the contact area** of heat exchange and a **higher temperature difference** between the two exchange mediums.

The vibration of atoms caused by an increase of internal thermal energy can emitt electromagnetic waves. Heat transfer by **radiation** requires no medium and can also move through a vacuum (sun rays). When heat radiation hits an object, its particles can be reflected, absorbed or they can penetrate the object (transmission). Heat radiation of the human body can be sensed when standing in a warm room near a cold window.

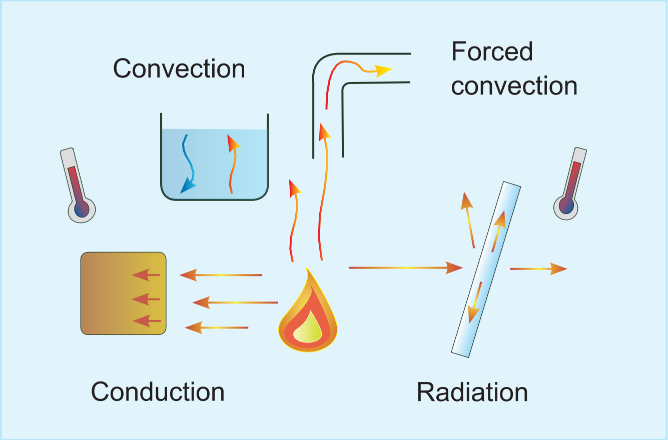


Fig. 11 Different methods of heat transfer

3 HEAT ENERGY AND MATTER

Prior to the next test arrangement (Tab.4) the approximate volume and mass of the air inside the thermo box needs to be calculated. The same mass amount of water is poured into a small container together with temperature probe T1. To compensate for the smaller surface, the bag is placed tightly to the evaporator plate (contact chilling). The temperature developments of both mediums are noted in Tab.4. The results show that it takes significantly more time to cool down the water than the same mass of air. Temperature difference (Δt) and mass (m) are therefore not the only factors to explain the transfer of heat energy.

The specific heat capacity (c) determines how much energy in Kilojoules (kJ) are necessary to heat (or cool) one kilogram of a specific substance by one degree Kelvin. It also shows the ability of a substance to store and release heat energy.

Thermo Box Dimensions

H [m]	W [m]	L [m]	Volume [m^3]
0.5	0.3	0.4	0.06

Volume to Mass Calc

Air		
Volume	0.06	m^3
Average density	1.224	kg/m^3
Mass	73	g

Mass to Volume Calc

Water		
Mass	73	g
Volume	0.7	dl

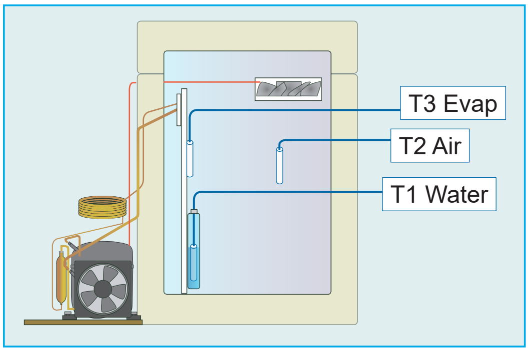
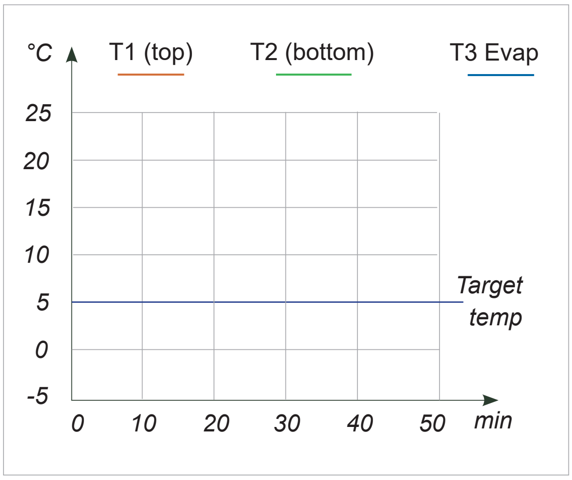


Fig. 12 Cooling of air and water

Tab.4 Chilling of air and water

Voltage		RPM	
Amps		Target temp	5°C
t [min]	T1 (Water)	T2 (Air)	T3 Evap
0			
10			
20			
30			
40			



Tab.5 Heat Capacity

$$c \times \Delta T \times m = Q$$

	c	ΔT	m	Q
	Specific heat capacity	Temperature difference	Mass	Heat
	kJ/kgK	K	kg	kJ
Air	1.004			
Water	4.175			

Note: 3,600kJ are equal to 1kWh

Water is an excellent medium for thermal energy storage. This particular effect can be observed on the mobile unit when the compressor is switched off and the thermo box lid is open. While the air will thermally equalize with the ambient temperature in a few minutes, the water will keep its low temperature for a much longer time. Kilojoules (*kJ*) and Joules (*J*) are SI units for energy. 3,600 Kilojoules equal 1 Kilowatthour (*kWh*), a unit that in most cases refers to electrical energy.

The lowest temperature point is zero Kelvin or minus 273.16 degrees Celsius. Every matter above 0 Kelvin has a kinetic movement of its molecules and therefore contains thermal energy. But it always requires a temperature difference to make use of this thermal energy. In most cases this temperature difference will refer to our natural environment which is the ambient daytime temperature of approximately 25°C. A hot plate with a temperature of 45°C will not really be useful for cooking since the temperature difference to heat the food will only be 20K. But the same 20K in the opposite direction (5°C) could be very well used for cooling the same food product.

3.1 Matter and States

Besides plasma, which is considered the fourth (but unstable) state of matter, the three classical states of matter that can be observed in our natural environment are gaseous, liquid and solid state.

On the **macroscopic** (μακρός, *gr.* large) level, plain sight observations and the most common types of measurements for volume, weight and temperature can be conducted to determine the momentary state of a substance. On the **microscopic** (μικρός, *gr.* small) level, the Bohr-Rutherford model is used to explain the characteristics and behaviour of atoms and molecules in different states of matter. Water is the only substance on this planet that can be encountered in all three phases under normal conditions.

Gaseous Phase

Air is a mixture of various gases like nitrogen, oxgyen, carbon dioxide and other chemical elements. The molecules of these elements are floating around randomly, sometimes bouncing into each other. The impact of these collisions is mainly kinetic (motional) energy and it defines the internal energy of a gas. The average distance between the molecules, which is much larger than the size of molecules themselves, is determined by the air pressure. When filled into a cylinder, air will usually float freely into this container, disperse and fill it up. Since gases are compressible, they can be pumped into high pressure containers to compress their volume for storage purposes. In any case, the gas molecules will always bounce against the walls of their containment and the total average of these impacts is defined as the temperature of the gas. A higher temperature means more internal energy caused by faster and more random motion of the particles. In the gaseous phase, pressure and temperature of a medium correlate (see Fig. 7).

The air in our troposhere also contains water. The gaseous phase of water is called water vapor and defines the moisture of air. Hot air is less dense because its molecules are moving around more freely and therefore leaving more space that can hold water vapor. One cubic meter of hot air with a temperature of 40°C can hold up to 63 grams of water vapor while the same amount of cold air at 20°C can only hold 18 grams of water vapor. When air cools down, the space between the air particles will become so dense that the water molecules will bind together and condensate i.e. they change their state from gas to small droplets of water. This point is called dewpoint and can be observed in nature as the formation of clouds or fog.

3.2 Psychrometric Charts

Psychrometric (ψυχρόν *gr.* cold) charts are used to determine how much water vapor is in the air at a given air pressure (for example at mean sea level, MSL). Generally warm air can carry more water vapor than cold air but at every temperature there is a point when the maximum holding capacity (100% absolute humidity) is reached and the vapor will condensate (dew point temperature). Fig. 13 shows an example of air at 20°C that contains 10g/kg of water vapor. Adding another 5g/kg (blue arrow) would lead to saturation and the air would condensate. Condensation could also take place if the air was cooled down to 14°C (red arrow). Dew point is the condensation temperature for air with a certain amount of H_20 (10g/kg). Relative humidity determines how much more water vapor the air could take before dew point condensation is reached. 10g/kg at 20°C equals a relative humidity of 70%.

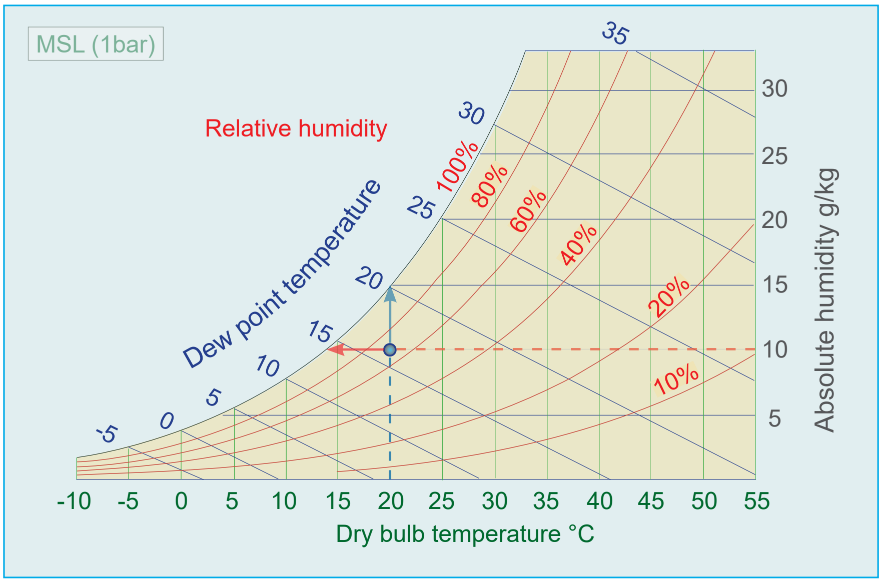


Fig. 13 Psychrometric charts determine the water content of air

Dry bulb temperature (DBT) is the mean temperature of the air taken by a thermometer which is not exposed to moisture or direct heat radiation (e.g. sun exposure). **Wet bulb temperature** (WBT) is the lowest temperature that can be achieved by evaporation. The drier the air, the more evaporation and hence cooling can take place. The higher the wet bulb temperature, the more humidity is in the air. Wet bulb temperature is always lower than dry bulb temperature (DBT = WBT equals 100% air humidity).

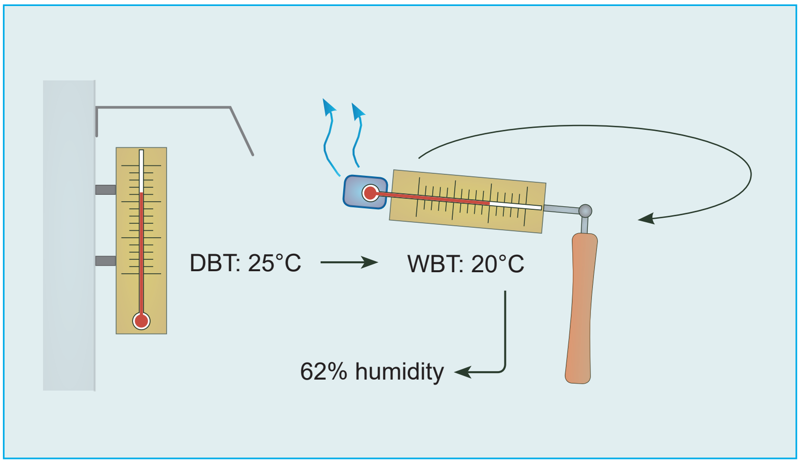


Fig. 14 Sling thermometer to measure wet bulb temperature

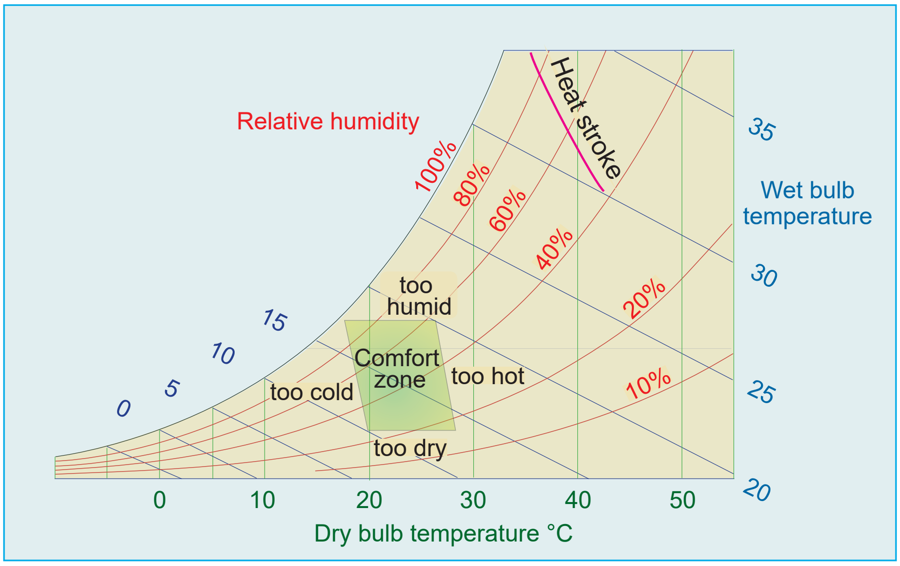


Fig. 15 Psychrometric charts determine the water content of air

Increased air humidity can already make moderate temperatures feel uncomfortable. An ongoing wet bulb temperature above 32 degrees already poses a dangerous health threat. Instead of releasing body heat (by sweating) to its surroundings, the human body starts to take up heat from the environment. Ongoing climatic changes could make certain areas of the world become inhabitable (e.g. DBT 45°C and 50% humidity). In many countries domestic cooling and air conditioning is already considered an indespensible utility and it is predicted that by 2060 the worldwide energy demand for cooling will outrun the one for heating.

Moist air contains more heat energy (enthalpy) and therefore requires more energy for cooling. This can be seen on a psychrometric chart by enthalpy lines which run almost parallel to the WBT lines. Air with a dry bulb temperature of 30°C and a relative humidity of 40% contains around 60kJ per kg. 30°C air with a relative humidity of 80% contains almost 90kJ per kg.

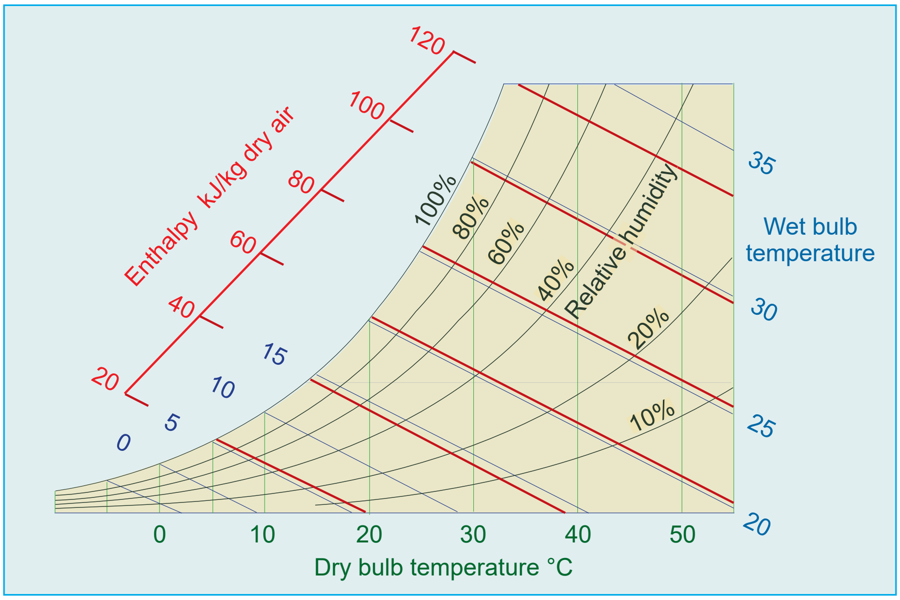


Fig. 16 Enthalpy lines on a psychrometric chart

Liquid Phase

In liquid state molecules can vibrate, rotate and move around but they are in close contact to each other, bonded by their intermolecular forces. Liquid substances have therefore a fixed volume and are almost incompressible.

A water molecule consists of two hydrogen and one oxygen atom. When separated these elements are normally gases at ambient conditions. But when chemically bonded, they start to share an outer electron and form a V-shaped polar molecule (Fig. 17) with a negative oxygen and a positive hydrogen side. This V-shape is called a **hydrogen bond** and it is the cause for the unique characteristics of water. By the electrostatic attraction of the differently charged ends (+/-), water molecules can easily connect together forming a constantly moving, light liquid. The negatively and positively charged sides are also the reason why water is an universal solvent.

At 4°C the water bonds condense to small plates (Fig. 18). This is why water has the highest density at this temperature. Even solid frozen water has a lower density. This is the reason why ice forms and floats on the top of water bodies.

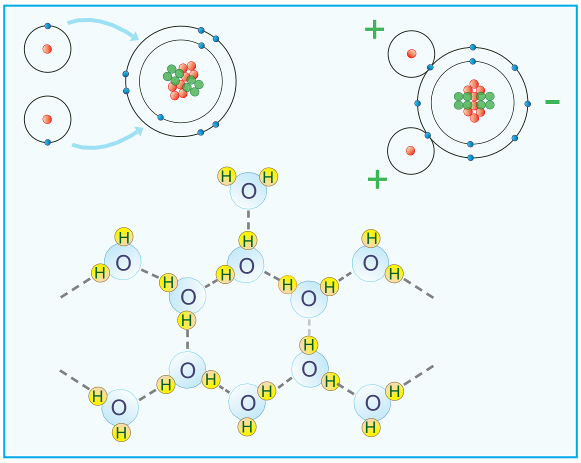


Fig. 17 Hydrogen bonds of water

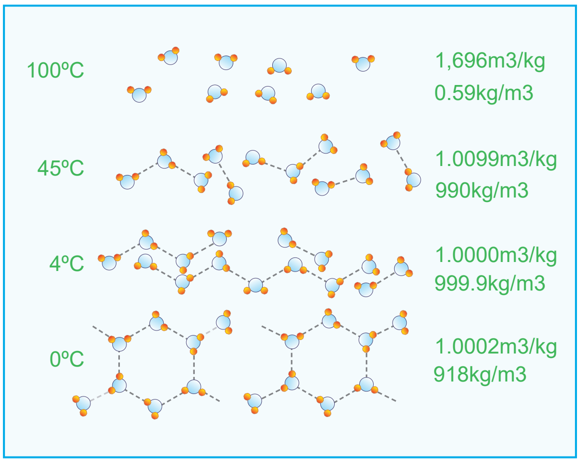


Fig. 18 Thermodynamic properties of water

Solid Phase

At 0°Celsius, the freezing point of water is reached. The molecules will form crystalline structures and the liquid will turn into solid ice. The molecules of substances in a solid state are arranged in a regular pattern (amorphic or crystalline) which allows them to retain their form and volume. Despite the fact that solids are arranged in a molecular structure, the particles still contain kinetic energy because of their internal vibrations. As long as there is kinetic energy there is also thermal energy.

Liquid Vapor Phase

The intermolecular ties of water are strong because of their hydrogen bonding but when enough heat energy (Δh_{Evap} = 2,257kJ/kg) is added, the hydrogen bonds can break up and the H_2O molecules can vaporize.

At low temperatures only a fraction of water molecules contain enough kinetic energy to break free from their hydrogen bonds. They appear as tiny scattered bubbles in the water that rises up to the surface and dissolves in the air (vaporization). The tendency of a liquid to vaporize is called **vapor pressure**.

An ongoing vaporization of water molecules into the air will lead to an increase of air pressure. This rise

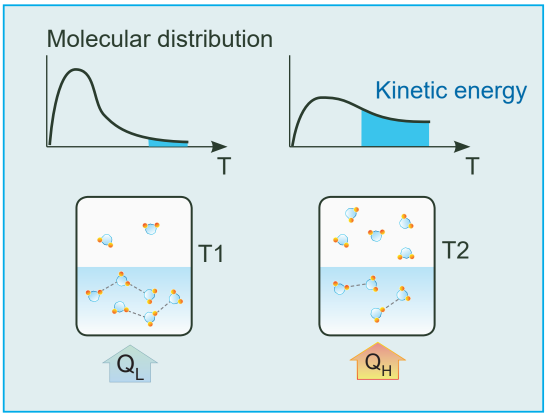


Fig. 19 Kinetic energy increases evaporation

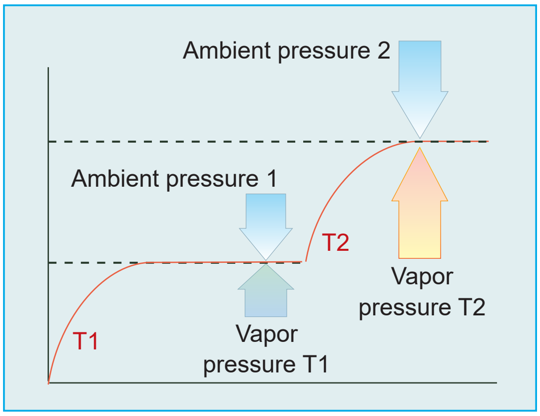


Fig. 20 Liquid vapor equilibrium

in ambient pressure will force H_2O molecules back into the water and the rate of condensation increases. When the rate of condensation reaches the rate of evaporation a dynamic equilibrium will form (Fig. 20).

Adding more heat will raise the temperature of the water and hence increase the internal kinetic energy of the liquid. More water molecules will be able to break free. A higher rate vapor pressure will consequently also lead to higher rate of condensation until a new level of dynamic equilibrium is reached.

Vaporization is the general definition for a change of state from liquid to vapor. **Evaporation** happens at the surface of a liquid. **Boiling** is the bulk phase change that happens at certain pressure-temperature- configuration.

4 LATENT AND SENSIBLE HEAT

4.1 Phase Change

In Fig. 19, 100ml water with a temperature of 2°C are poured into a glass fillled with 500ml of 25°C warm water, both liquids will mix until they have the same temperature (thermal equilibrium). In this case the new water mixture will have a final temperature of 21°C. The cooling effect of 4K is rather neglectable.

The experiment will be repeated but this time the 100ml of water are added to the warm water as frozen ice cubes. After the ice has melted the final temperature of the mixed liquid will be 7.5°C. The thermal energy required to break up the ice crystalls and melt the ice was taken from the warm water resulting in a significant cooling effect of 17K.

Fig. 22 shows the temperature-enthalpy (*Th*) diagram for water. Enthalpy is the measurement for the inter-

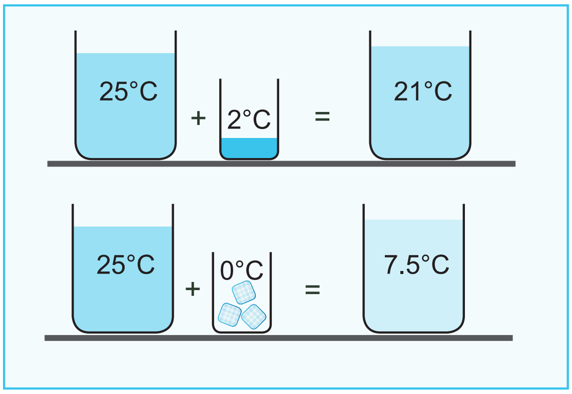


Fig. 21 Latent heat effect of ice

nal (thermal and mechanical) energy content of a substance. Its unit is kilojoules per kilogram (*kJ/kg*).

A change in enthalpy caused by temperature is measured in kilojoules per kilogram Kelvin (*kJ/kgK*). In solid (frozen) state 2kJ of thermal energy are required to change the temperature of one kilogram of ice per Kelvin (e.g. from -20 to -19°C). A change in temperature without phase change is called **sensible heat**.

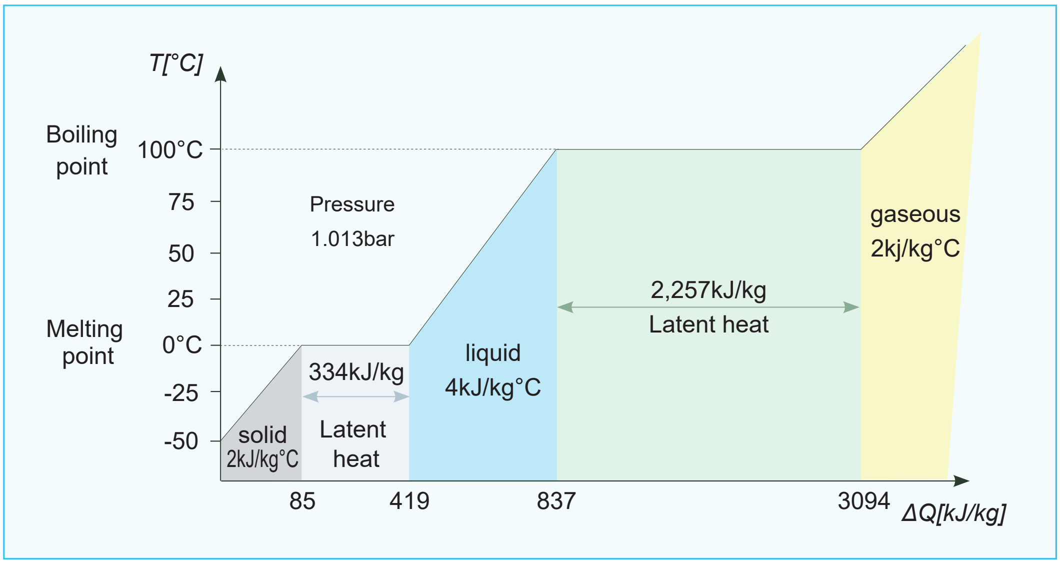


Fig. 22 Th diagram of water with phase change enthalpy

When the ice reaches zero degrees Celsius (0°C) it will take 334kJ per kilogram to change water from a solid to a liquid state. On the microscopic level, this energy is required to break up the crystalline structure of the ice molecules and to change them into free floating cohesive bonds.

During this phase change both ice and liquid water are present and temperature does not change until the process is finished. Energy absorbed or released during the phase change of a substance is called **latent heat**.

An even higher amount of latent heat is necessary for the phase change from the liquid to the gaseous phase. 2,257 Kilojoules of heat are required to break up the hydrogen bonds and change one kilogram of liquid water into hot water vapor. By then the molecules have absorbed enough kinetic energy to float around in the air as free gas particles.

Reversing the process and cooling down the water vapor back below 100°C (at *1bar*) would make the gas particles recondensate into liquid water. The temperature will not change until all the vapor has recondensated. The transformation of the H_2O molecules into a state of lower kinetic energy will release the same amount of heat (2,257*kJ/kgK*) to the environment.

Both fluid phase changes, the **latent heat release of condensation** and the **absorption of heat during evaporation** are the main techniques used in cooling to achieve an effective transfer of thermal energy.

5 THERMODYNAMICS

The science of thermodynamics evolved during the industrial revolution of the 19th century. Steam engines were the most advanced machineries in these days. But when it became clear that they only converted a fraction of their thermal energy input into useful mechanical energy, scientists and engineers began to take a deeper look into the realm of energy and matter.

5.1 Thermodynamic Systems

A specific object in the focus of a thermodynamic observation is called **system**. It has a solid boundary that physically separates it from the outer surroundings e.g. the environment or even the whole universe. In an **open system** the boundary is permeable or has openings for an exchange of energy and matter. A **closed system** does not allow the exchange of matter but energy in form of pressure or heat can enter or leave the system. An **isolated system** does not allow any exchange of energy nor matter. Since a total, close to a 100% isolation is only possible for a limited time span, isolated systems are more of theoretical nature.

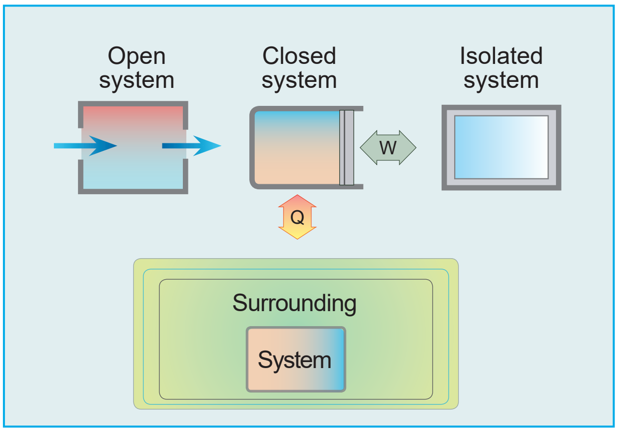


Fig. 23 Thermodynamic systems

Thermal Reservoirs

A heat engine can convert thermal energy into mechanical work. In order to do this, the engine must be placed into a heat flow between two thermal reservoirs. The energy input comes from a hot reservoir or source. It can provide an unlimited supply of heat energy (Q_H) without changing its temperature. The cold reservoir or sink can absorb an infinite amount of waste heat (Q_L) from the heat engine with any change in temperature.

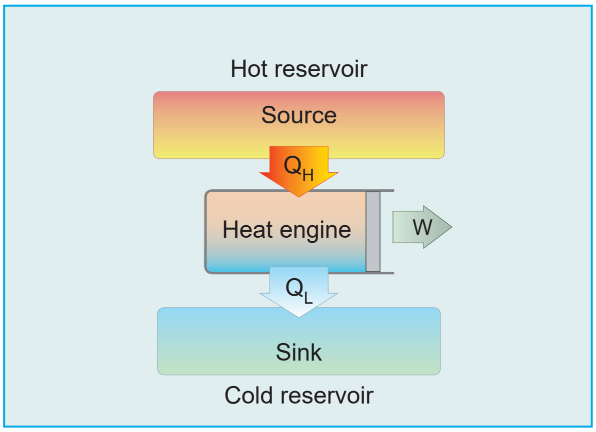


Fig. 24 Thermal reservoirs

5.2 First Law of Thermodynamics

The first law could be described as the thermodynamic law of strict bookkeeping. Every systems contains a certain amount of internal energy. This is the total amount of kinetic (motional) and potential (gravitational, centrifugal, electric, magnetic) energy of all the particles (atoms and molecules) within the boundaries of that system. Any change in internal energy (ΔU) must be equal to any amount of mechanical or thermal energy leaving or entering the system.

The first law of thermodynamics is also known as the conservation of energy law. Energy cannot be created or destroyed. It can only be converted into other forms of energy and the total amount of energy in the universe remains constant. The first law also states the impossibility to build a perpetual motion machine of the first kind, a machine that can do work without any energy input.

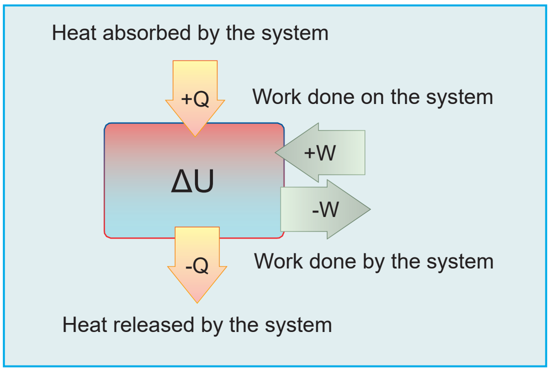


Fig. 25 First law of thermodynamics

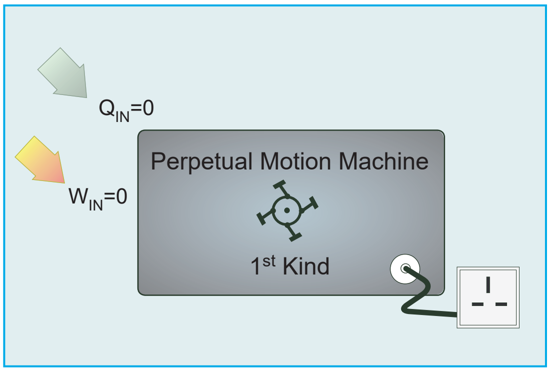


Fig. 26 Perpetual motion machine 1st kind

5.3 Second Law of Thermodynamics

A bowl of marbles thrown on a table will disperse in the order of their color. A copper cube dropped into a bucket of luke warm water and will heat up to 100°C by absorbing the enthalpy of the surrounding water (Fig. 27).

Both events do not contradict the first law of thermodynamics since the total energy balance at the end of the process will still be the same. But they totally contradict the natural observation and understanding of nature that energy and matter will always have the tendency to disperse.

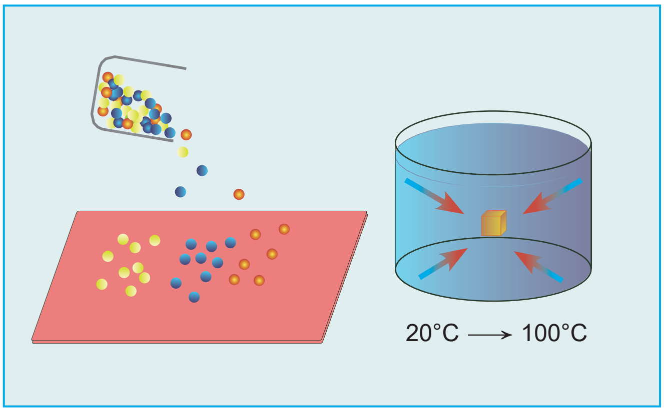


Fig. 27 Events that do not contradict 1st law of TD

5.4 Statistical Entropy

A first way to proof that matter and energy in the universe will always have the tendency to dispere is probablity. In general, the momentary condition of an object can always be described by its physical parameters like volume, pressure, mass, temperature etc.

Once determined, the specified condition of an object is called a (visible) macrostate. But since all matter is build up by atomic particles and these particles are in constant motion, one macrostate can have multiple numbers of (invisible) microstates.

Fig. 28 shows a cylinder which is separated by a permeable barrier into two sections. Two gas particles are put in the cylinder and in the beginning they are both in the left section. This momentary position is defined as a microstate. Since gas particles are constantly moving, there are three different microstates (Ω) in total. Microstate 2 and 3 are the same since particles are not distinguishable.

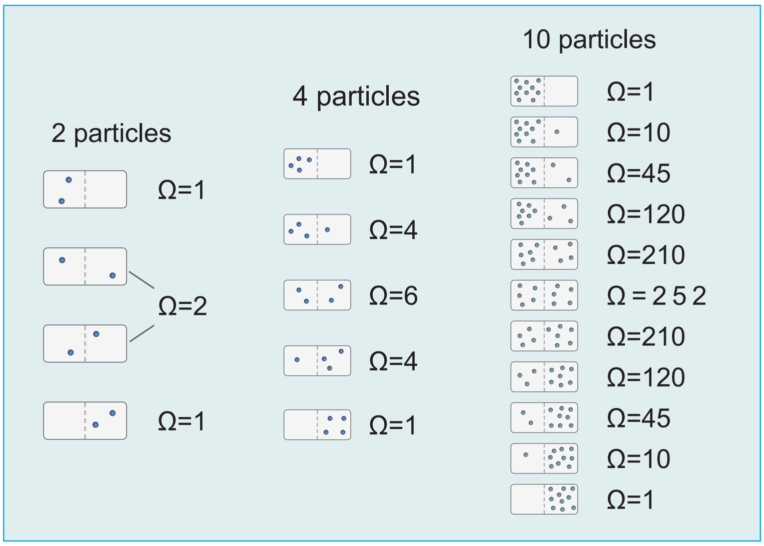


Fig. 28 One macrostate and its possible microstates (Ω)

When the number of gas particles is increased to four, the possible number of microstates increases to five. The chance where all particles will be on either section of the box still remains one (Ω=1) while the chances of an equal distribution of particles rise significantly.

This tendency increases exponentially the more particles are added. In a box with ten gas particles the chance that all particles are found in one section is still one (Ω=1) but the chances of a random (chaotic) distribuition has risen to 254. If the cylinder only contained one gram of hydrogen gas, the number of particles would already go up $6x10^{23}$.

The microstate where all particles are gathered in one section can be compared with a low temperature macrostate since it represents a certain kind of order while the random (chaotic) distribution of particles can be seen as a macrostate of a high temperature. In mathematical terms, the possibility that a cold copper cube would heat up in a warm water bath (Fig. 26) or that thrown marbles would order themselves by theor color is not completely impossible but the chances are so outrageously low that it will never happen in reality.

5.5 Chaos, Information and Entropy

The concentration of all particles in one section of a cylinder can be seen as a high grade of information while the random distribution of particles can be compared to a state of chaos or disorder (i.e. less information). The same analogy can be done with temperature distribution. Cold milk and hot coffee that are still separated contain more information about their state as if the two were mixed together.

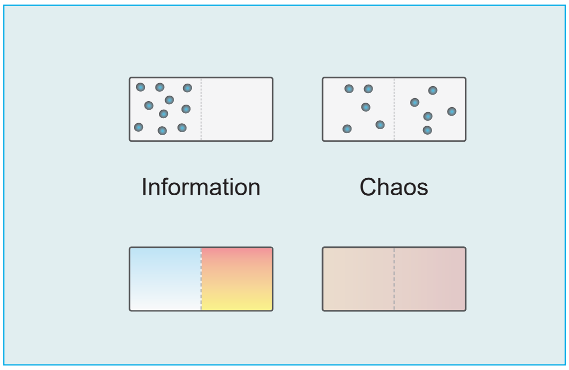


Fig. 29 Information and temperature comparison

This unavoidable change to disorder is described in the second law of thermodynamics with the term Entropy. In an isolated system entropy change can be zero or increase but it can never decrease. In an open system entropy can decrease but only if the entropy is shifted to the outside environment.

This also explains why a perpetual motion machine of the second kind (a machine that converses thermal energy completely into mechanical work) cannot exist. It would lead to an entropy decrease of the universe and therefore it would violate the second law of thermodynamics.

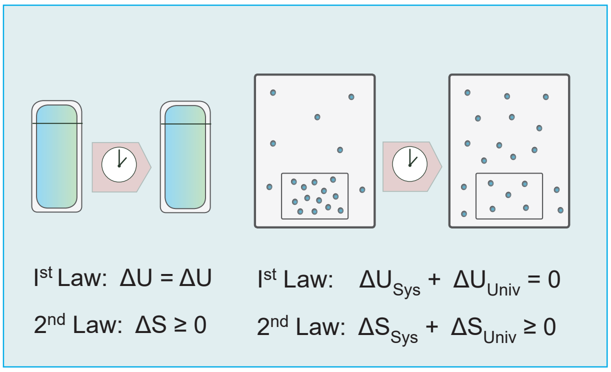


Fig. 30 Entropy change in an isolated and open system

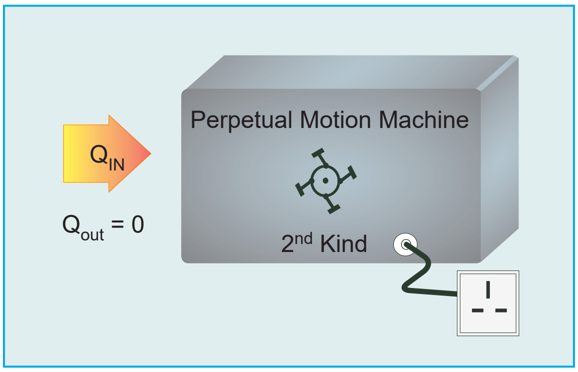


Fig. 31 PMM contradicts the 2nd law of TD

> ***- There is no device whose sole effect is to transfer heat from a cold body to a hot body -***
>
> Second Law of Thermodynamics (Clausius statement)

5.6 Cycle Processes

Fig. 32 shows a gas cylinder with a moveable piston which is submerged in a heat reservoir. Thermal energy (+Q) from the reservoir will enter the piston and heat up the gas. The gain in internal energy would lead the gas to expand and exert pressure on the piston. In this case the whole amount of heat energy would be transferred into mechanical work.

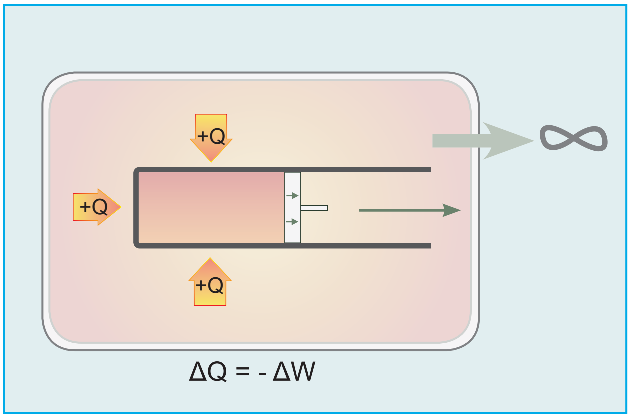


Fig. 32 Non cyclic process of heat conversion

This experiment seems to contradict the second law of thermodynamics in the Kelvin-Planck statement:

> ***-There is no device whose <u>only</u> effect is the conversion of heat completely into work-***
>
> Second Law of Thermodynamics (Kelvin, Planck statement)

But the piston in the heat reservoir can actually only continue to transfer heat completely into work if it was perpetually expanding as well. So the conversion of heat into work would not be the only effect. Besides that such a device would be useless for practical applications. A heat engine has to generate work and always return into its initial state. Such an operation is called a work cycle and is shown on Fig. 33. The Kelvin-Planck statement is therefore often rephrased as: "There is no machine that **can operate in a cycle** and whose sole effect is to convert heat into an equal amount of work".

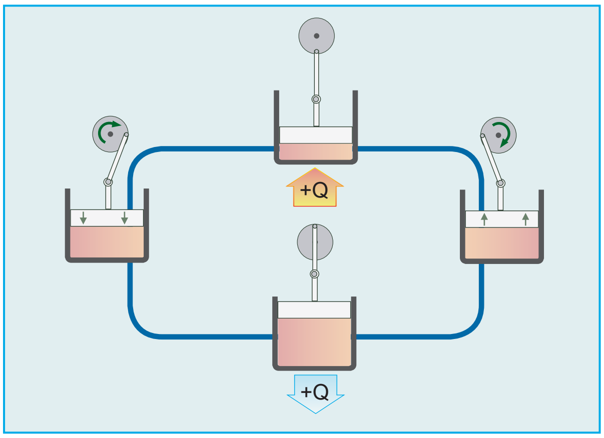


Fig. 33 Cycle process of a heat engine

5.7 Pressure Volume Diagram

A good way to visualize the thermodynamic process of a system is the pressure-volume (pV) diagram. Isolines (*isos*, “equal”) are lines or curves on the diagram that depict the constant value of a certain parameter (e.g. pressure) while other properties (e.g. volume and temperature) can change. The graph in Fig. 34 shows a gas cylinder with a moveable piston.

Isobaric Process

Isobars (*baros*, “weight”) refer to lines of equal pressure. When the piston is moved down by the crankshaft, work is done on the system (+W) and the internal energy of the gas increases. The opposite effect (right) would happen when the internal energy would expand the volume of the gas and the exerting force would move the piston upward. The internal energy of the gas will then decrease by the amount of work done by the system (-W). The area under the isobaric line equals the total amount of work (*W=pxΔV*), either done (-) or gained (+). In both processes the pressure of the gas remains constant.

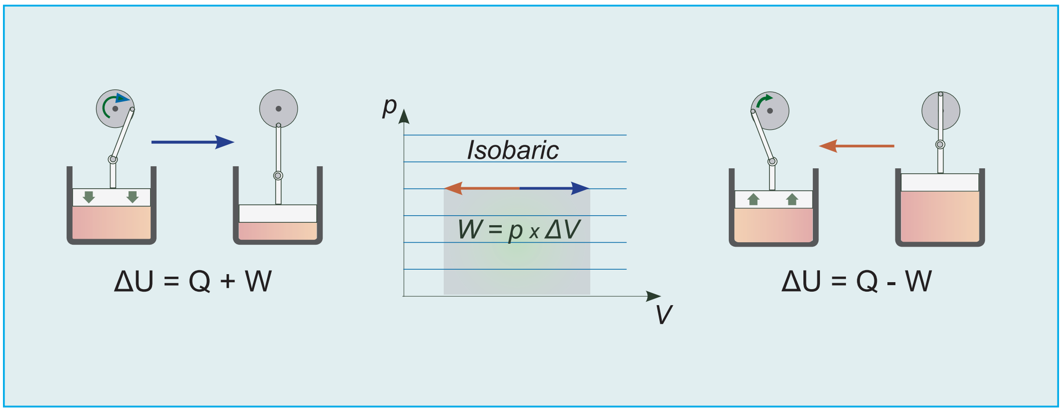


Fig. 34 Constant pressure run along the isobaric lines

Isovolumetric Process

This refers to a process of constant volume and can be imagined by putting a lock on the piston wheel. No work can be done on or by the system and the volume won’t change. Any heat leaving (-Q) or entering (+Q) the system will result in a change of pressure and a rise or decrease in internal energy (ΔU). Isovolumetrics lines are sometimes also called isometrics or isochors (*khora* “space”).

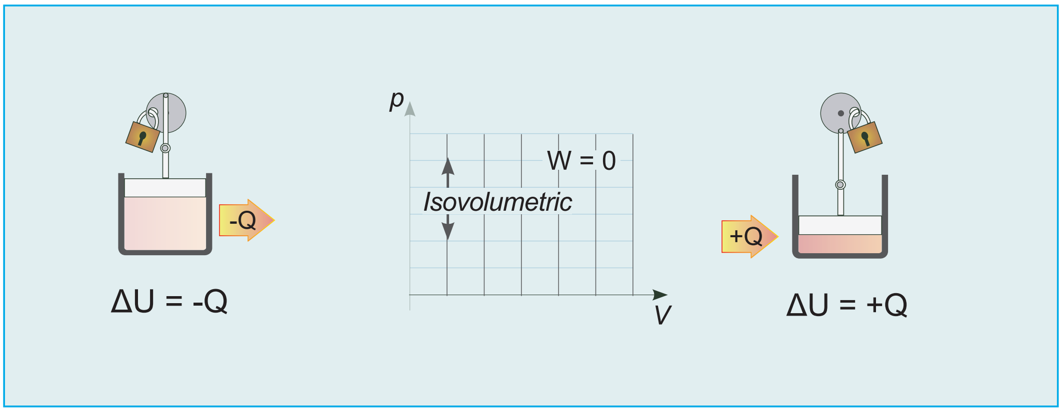


Fig. 35 Isovolumetric process

Isothermal Process

A process with no change in temperature also means no change in internal energy is allowed (T is proportional to U). Every bit of energy (W or Q) must immediately leave the system, either as work (expansion) or heat (compression). The piston walls must be diathermic (to allow optimal heat transfer). Isothermal processes are also infinitesimally slow.

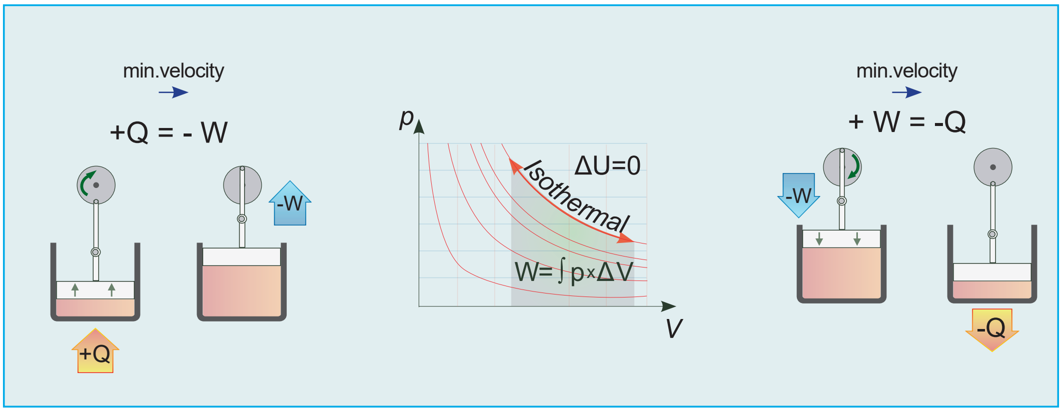


Fig. 36 Isothermal process

Adiabatic Process

(*a*=not, *dia*=through, *batos*=passable) No heat exchange between the system and its surrounding takes place (Q=0). Temperature and internal energy can change but only by an exchange of mechanical work. One way to achieve an adiabatic process is to thermally isolate the piston from its surrounding. Another requirement is that an adiabatic process has to happen very fast (e.g. fire piston). Adiabatic curves (or adiabats) are steeper than isotherms. They intersect all other isolines which means during an adiabatic process pressure, volume and temperature can change.

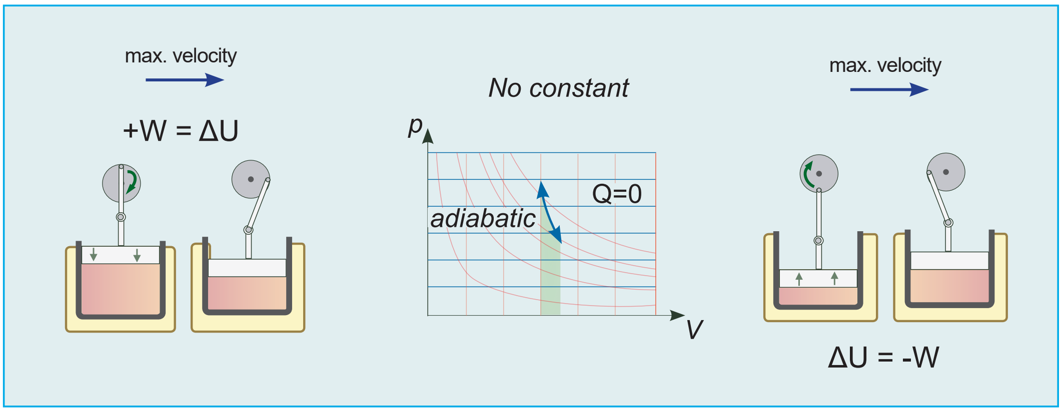


Fig. 37 Adiabatic process

5.8 Carnot Engine

In 1824 French engineer Sadi Carnot came up with the generic model of a heat engine of which he claimed that no other engine could beat his engine in efficiency. The carnot engine is of theoretical nature and represents the mathematical limit of an engines efficiency. Fig. 38 shows the flow diagram and the cycle process on a pV diagram of a Carnot engine.

Isothermal expansion (1-2): Starting from point 1, constant heat energy (Q_H) from a high temperature reservoir is applied to the gas cylinder. Since the temperature remains constant (isothermal), the volume of the gas must expand, pushing the piston upwards to do work. The entropy of the gas increases ($\Delta S_1 = \Delta Q_H / T_H$).

Adiabatic expansion (2-3): The cylinder is removed from both reservoirs. The gas continues to expand doing work on the piston and the gas cools down. The thermal insulation ensures that there is no heat exchange with the environment. The entropy remains unchanged.

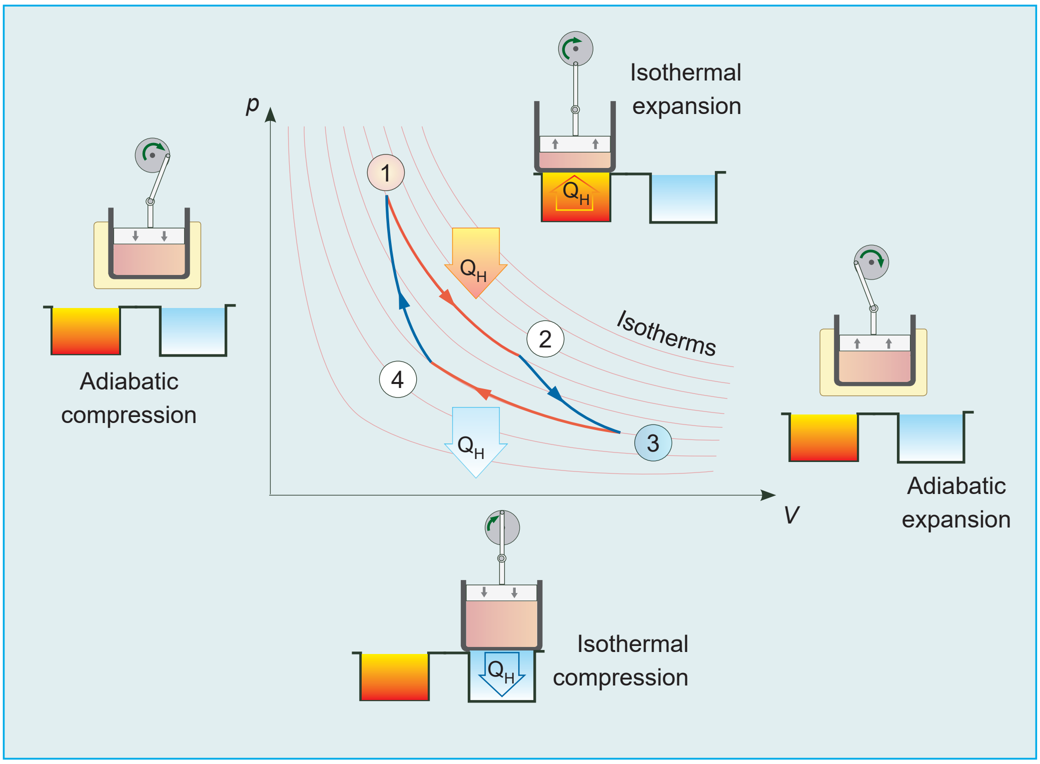


Fig. 38 The carnot cycle represents the theoretical max. efficiency of a heat engine

Isothermal compression (3-4): The cylinder gets in contact with the cold reservoir. Outside work pushes the piston down. The pressure increases but since heat energy Q_L is transferred to the cold reservoir, the gas temperature remains constant. The entropy decreases ($\Delta S_2 = \Delta Q_L / T_L$) by the same amount as it was increased between step 1-2.

Adiabatic compression (4-1): The thermal insulation allows no heat exchange with the environment and again, there is no change in entropy. The only energy input comes from the external force that keeps pushing the piston down, bringing the internal energy back to the level of step1.

In real life a Carnot engine wouldn't be of much practical value. It would require a large heat transfer area and its speed would be very slow. Nevertheless, the Carnot theorem still represents the theoretical maximum efficiency for all heat engines.

5.9 Engine Efficiency

Simple put, efficiency is always ”What do you get?” which in the case of a heat engine is the mechanical work output (W) over “What do you pay?” which is the required heat input (Q_H). According to the first law of thermodynamics, system input (Q_H) equals output ($W+Q_L$). Therefore W must equal to $Q_H - Q_L$.

With the enthalpy equation ($Q = c \times m \times \Delta T$), Q_H and Q_L can be replaced by the temperature values T_H and T_L .Note that the carnot efficiency is always calculated with absolute temperatures (Kelvin). The greek letter μ "eta" is the formula sign for efficiency. In real life modern heat engines can reach an efficiency of 25%.

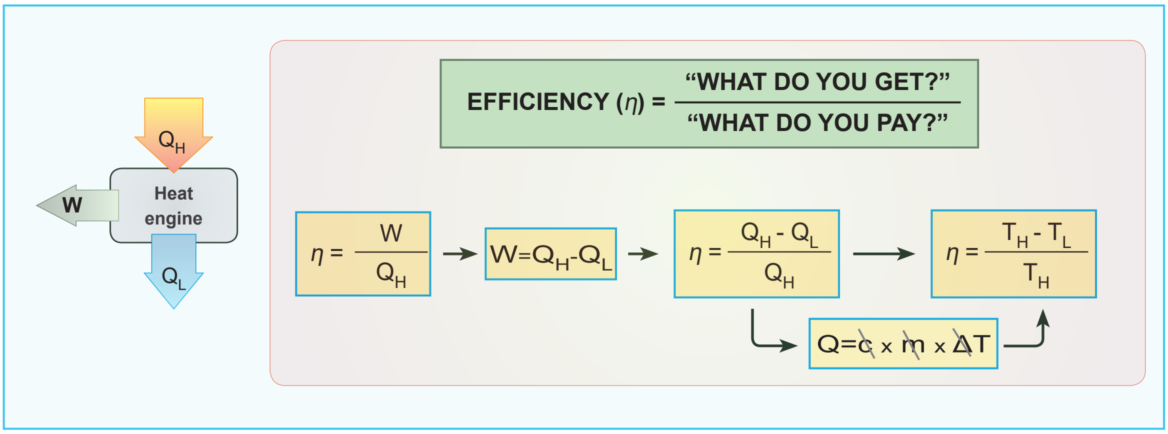


Fig. 39 Carnot theorem of the theoretical maximum heat engine efficiency

5.10 Reversed Heat Engine

A heat engine generates mechanical work (W) by converting thermal energy from a high temperature reservoir (Q_H) and releasing the non-convertible heat into a low temperature reservoir (Q_L). The whole process can be reversed. By applying mechanical work, the natural entropy flow of heat (2nd law) can be inverted and heat can be drawn from a low temperature reservoir and released into a high temperature reservoir.

Heat pumps use the natural enthalpy of air, water or soil to provide low temperature heating for buildings with a good thermal insulation. By using a four way valve, heat pumps can reverse their heat flow and operate as an AC cooling system.

The efficiency of a heat pump is also determined by outcome over input but it is expressed as the **coefficient of performance** (**COP**).

Reversed heat engines do not convert mechanical energy directly into heat. An electrical pump is used to transfer heat from an ambient source (e.g. outdoor air) into an enclosed space providing heat as a utility. Good heat pumps have a COP of approximately 4. That means for one part of electrical (pump) energy four parts of heat energy can be transferred.

Refrigerators and heat pumps work on the same technical principle. A compressor pump draws heat enthalpy from a thermally insulated space, lowering its temperature and thus generating the cooling effect. The collected heat is dumped into the ambient air.

When a heat pump and a refrigerator operate in the same conditions (T_H and T_L), the heat pump will always have a higher COP (+1) than the refrigeration system because the energy output of the heat pump will include the mechanical input of the compressor pump as heat. For refrigeration systems the term EER (Energy efficiency ratio) can be used instead of COP.

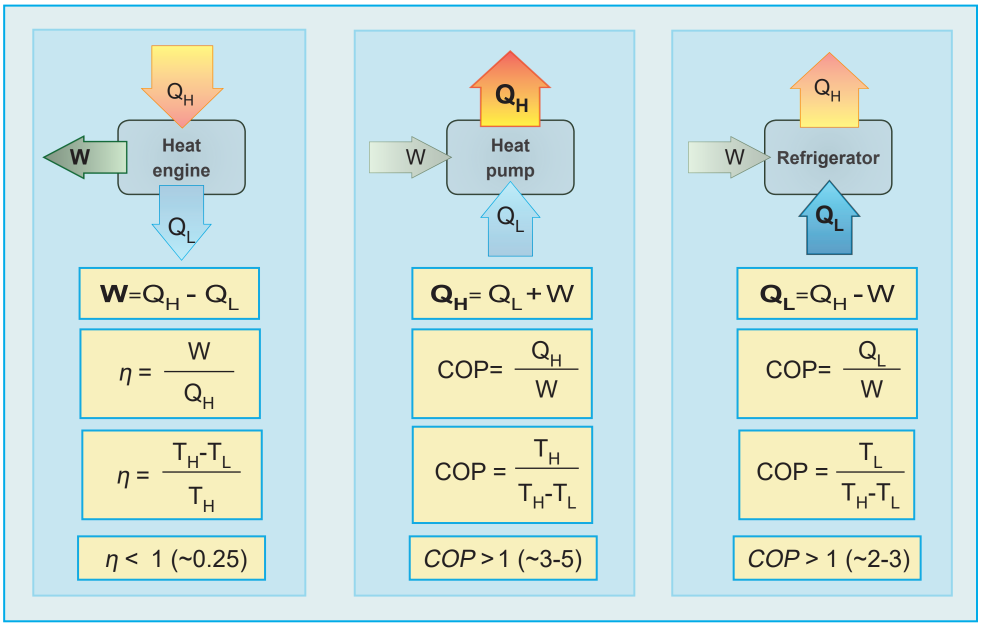


Fig. 40 Comparison of efficiency factors for heat engines

SEER (Seasonal energy efficiency) or SCOP (Seasonal coefficient of performance) are standardized energy efficiency labels for heat pumps and cooling systems up to 12kW. They take into account the annual performance of a system including operation under different temperature conditions, full and partial load performance as well as standby consumption.

5.11 Proof of the Carnot Theorem

Assuming a Monsieur Tonrac would show up and claim that his heat engine can reach a better efficiency than a Carnot engine. He could be proven wrong by combing his alleged machinery with a reversed Carnot engine, since its work output (400kJ) matches the required work input of the reversed Carnot engine. The flow diagram of Fig. 40 shows that a net amount of 200kJ would flow from the cold reservoir to the hot reservoir. A scenario which is impossible due to the second law of thermodynamics.

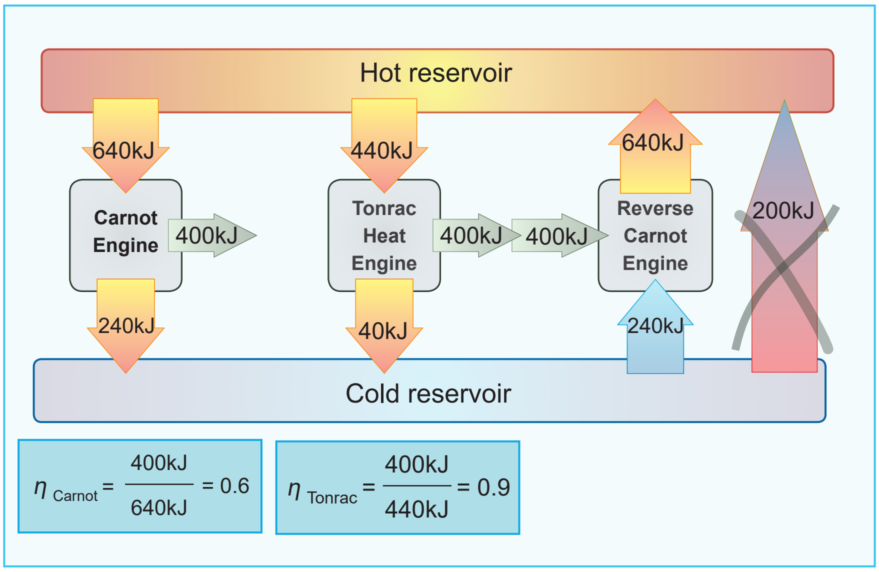


Fig. 41 Experimental proof of the Carnot theorem

6 THE REFRIGERATION CYCLE

The refrigerant is the work fluid of a cooling circuit. It absorbs heat energy from a thermally insulated source and releases this heat into the ambient surroundings. An optimal efficiency can be achieved when this heat transfer takes place during a phase change. During **evaporation** the refrigerant is **gaining latent heat** by absorbing heat from the fridge box. **Condensation** means that the refrigerant **cools down** while the accumulated enthalpy is released as **latent heat i**nto the environment (Fig. 42).

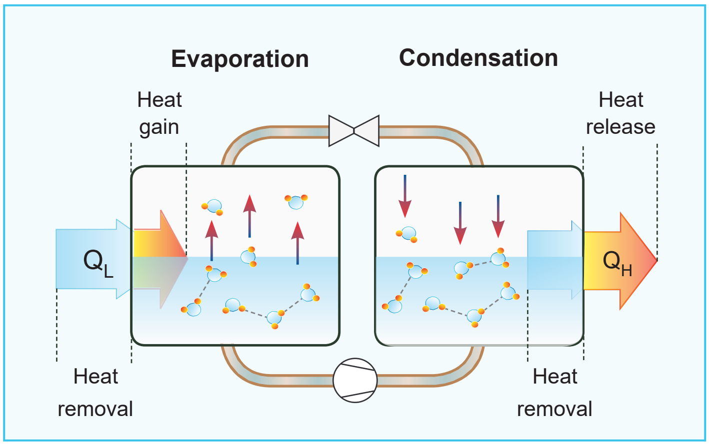


Fig. 42 Heat transfer by phase change

All previous scenarios of latent heat exchange referred to water as a transfer medium. Due to its hydrogen bonds, water has excellent heat storage capabilites and is used as a cooling medium in a wide range of industrial applications e.g. heat engines and power generation. But because of its relatively high boiling point (100°C at 1bar), water is generally not suitable as a refrigerant (R718) for commercial and domestic cooling.

Volatile liquids have the advantage that they already evaporate under ambient pressures at cooling temperatures (4°C to -20°C) and they recondensate when the pressure is raised by a few bars. The mobile training units use isobutane (R600a) as a refrigerant.

6.1 Enthalpy Diagram

One of the most helpful tools to understand the cycle process of heat transfer for refrigeration is a pressure-enthalpy (pH) diagram. Fig. 43 shows the pH-diagram for isobutane. Pressure in bars is indicated on the y-axis in form of a log-scale, the x-axis shows the changes in enthalpy by kJ/kg.

The red lines represent equal temperatures (isotherms) in degree Celsius. Starting on the top, a refrigerant with a temperature of -20°C at 30bar pressure would contain an enthalpy of 160kJ/kg. At this point the refrigerant would be 100% liquid. Following down the red -20°C line, the refrigerant would keep its temperature but the pressure would decrease. At 0.7bar the refrigerant would reach the liquid-vapor dome or **mixed region**. The refrigerant will now gradually start to change its phase and evaporate. The liquid-vapor ratio can be seen by the slanted dryness fraction curves. When the red (-20°C) line intersects the slanted x=0.2 line, the refrigerant consists of 80% liquid and 20% vapor. The vapor ratio gradually increases as the isotherm moves towards the vapor region.

The mixed region is also the latent heat region. Isotherms (temperature lines) and isobars (pressure lines) move parallel and don't change but the enthalpy increases with the phase change from 160 to 550kJ/kg. This is the heat energy that the refrigerant would normally absorb from the cooling box.

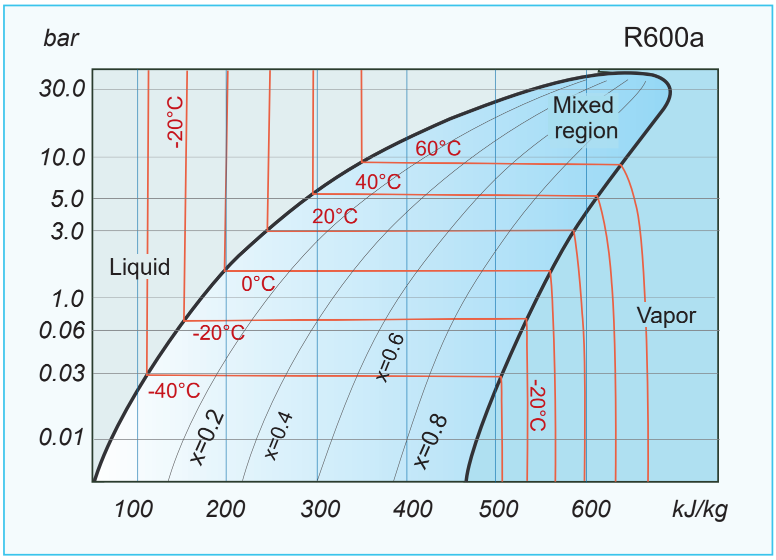


Fig. 43 Ph-diagram of Isobutane with vapor dome

The boundaries of the mixed region are called saturation lines. When reaching the right end of the mixed region, the refrigerant becomes 100% (saturated) vapor. Isotherms and isobars will no longer run parallel.

If the refrigerant would now continue to absorb heat from its surrounding, the continuing gain in enthalpy would no longer be needed for the phase change. The pressure lines would start to cross the isotherms. With a further raise in pressure, the temperature of the gas would increase. The gas would become **superheated**.

The same but inverted effect will take place with an opposite direction through the pressure dome. Fully saturated isobutane with a temperature of 40°C at 5.2bar pressure has an enthalpy of approx. 610kJ/kg. When the gas starts to release thermal energy to the outside it will reach the saturation line of the pressure dome and phase change to liquid will start. Temperature and pressure will not change until the refrigerant has fully recondensated. By then the refrigerant has released over 300kJ/kg of accumulated thermal energy to the outside. The fluid has passed the saturation line and will be 100% liquid. Further loss of heat energy will now result in a drop of sensible temperature. The liquid will be **subcooled**.

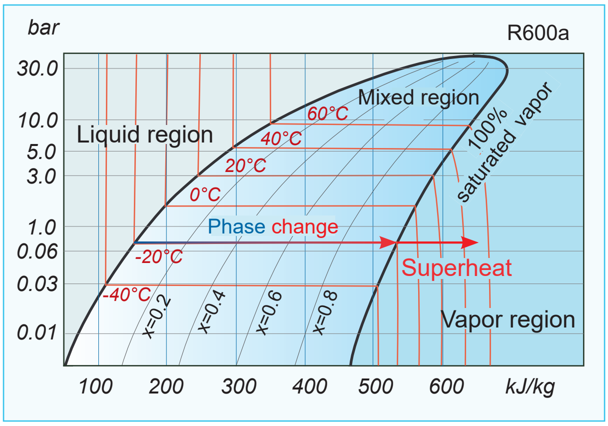


Fig. 44 Phase change-saturation-superheat

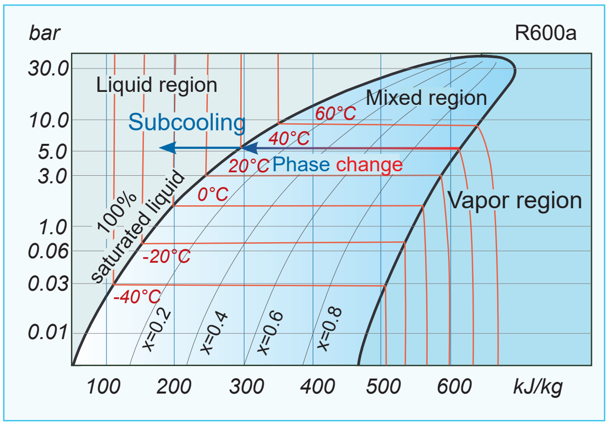


Fig. 45 Phase change-saturation-subcooling

Fig. 48 shows the practical cooling circuit of a refrigerant on an enthalpy (pH) diagram. At point 1 the refrigerant evaporates in the evaporator and is taking up heat from the content of the fridge box. After taken up enough enthalpy the refrigerant will be fully evaporized (passing the saturation line). It enters as a low pressure, low temperature, superheated vapor the compressor (2) where it will be compressed to a high pressure, high temperature vapor. The refrigerant enters the condenser coil (3). Since its temperature will be higher than the environment, it will release the accumulated heat changing its state back to a liquid. Finally the liquid refrigerant passes through the metering device which leads to a sudden drop of pressure indicated by the vertical line. As liquid vapor mixture (4) the refrigerant is then sprayed into the evaporator where new heat accumulation from the fridge box can take place.

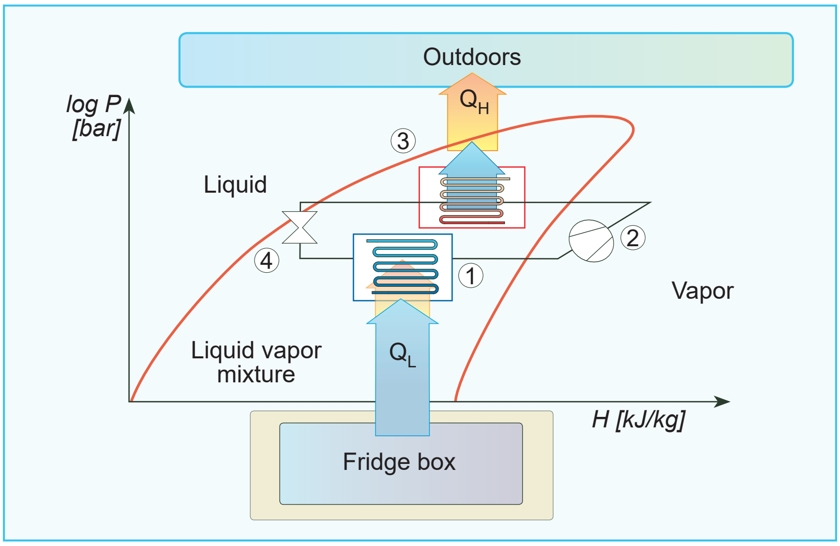


Fig. 46 R600a refrigeration circuit on a pH-diagram

6.2 The Compressor

The mechanical power input required to transport and pressurize the refrigerant is done by the compressor or vapor pump unit. Gas compressors can be categorized into the group of **dynamic compressors** where rapid rotation converts velocity into pressure. In radial flow compression the fluid is pushed out sideways while in axial flow compressors the fluid travels along the rotational axis of the compression (jet engines).

Positive displacement compressors draw the gas into a compression chamber and compress the fluid by volume reduction. In the group of rotary compressors, scroll compressors (Fig. 48) are becoming more present in the HVAC market but for small commerical and domestic refrigeration systems reciprocating piston pumps are still the dominant type for vapor compression.

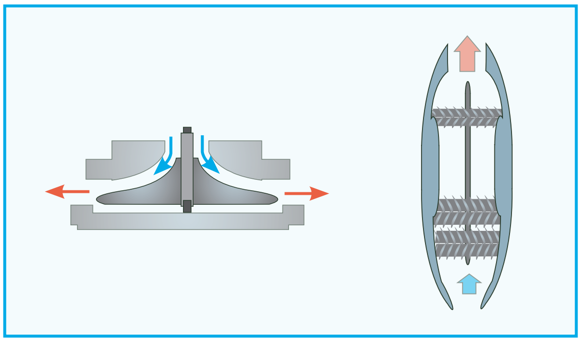


Fig. 47 Axial and radial flow compression

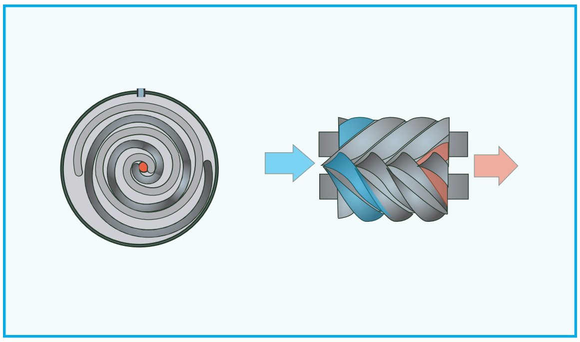


Fig. 48 Scroll and screw compressor

6.3 Piston Compressors

An important classification for compressors is determined by the motor position. **Open compressors** have their motor drive separated from the piston housing. This faciltitates access for maintenance. But the power transmission has to go through a sealed shaft that can cause leakage problems. **Semi-hermetic compressors** are usually used for larger cooling units. Motor and compression are housed in one bolted chamber that can be opened for servicing.

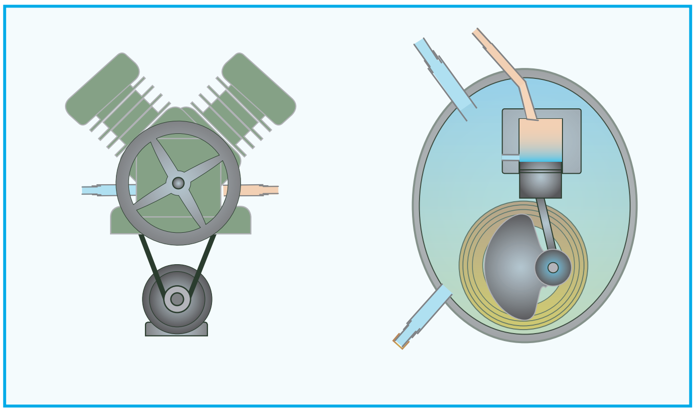


Fig. 49 Open and hermetic compressor

Hermetic compressors represent the largest group of compressor types used in domestic and small commercial cooling. They have a compact design where the motor drive and the crankcase are constructed as a single unit. Load springs minimize vibrations and the whole unit is sealed in one housing (compressor shell). The sealed housing is filled with refrigerant vapor that enters the via the suction line.

The refrigerant vapor gets compressed in the reciprocating piston chamber and leaves as a high pressure, high temperature gas via the discharge line. The third valve opening is the process tube line which is sealed off by a valve or cramping.

Low temperature, low pressure gas enters the compression chamber via the manifold intake from the suction line. The suction is generated by the retraction of the piston that expands the volume of the chamber. The excentric mounting of the piston rod on the top of the rotating crankshaft leads to the reciprocating movement. After the retraction the piston moves forward and compresses the fluid. The in and out flow of the fluid is controlled by the alternating opening and closing cycle of the self acting suction and discharge valves.

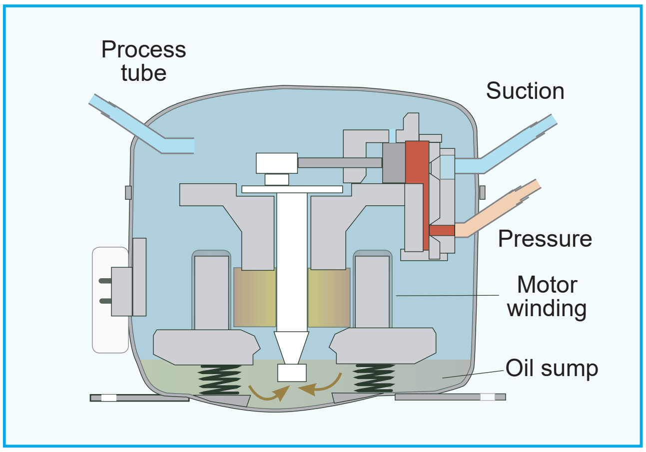


Fig. 50 Open and hermetic compressor

The mechanical moving parts of the compressor require lubrication. Polyoester (POE) oils are used with modern refrigerants. POE oils can mix with the refrigerant and travel through the cooling circuit. In reaction with water, they can become accidic. Therefore correct purging and air evacuation (humidity) of the cooling circuit before charging with refrigerant is important.

Flooding the compressor with liquid refrigerant can dillute the oil and obstruct sufficient lubrication. Since liquids are not compressible, ingression of liquid refrigerant (flooding) can also damage the piston mechanism of the vapor pump and is actually one of the most common mistakes for refrigerator damage.

Sufficient superheat will provide that the refrigerant has fully evaporated before it enters the compressor chamber. Though too much superheat should be avoided since the refrigerant also serves as a cooling medium for the compressor. The right amount of refrigerant charge and lubricant is given in the design part of the data sheet. Correct amount of refrigerant can be checked by subcoling and superheat measurements.

Data sheets define which refrigerant must be used and determine the designated application of the compressor. LBP (low back pressure) refers to low evaporation temperatures (typically -45°C to -15°C) mainly used in refrigerators and deep freezers. Medium back pressure (MBP) applications are water coolers and display cabinets (-25°C to -5°C) and low back pressure (LBP) for dehumidifiers (-15°C to +5°C).

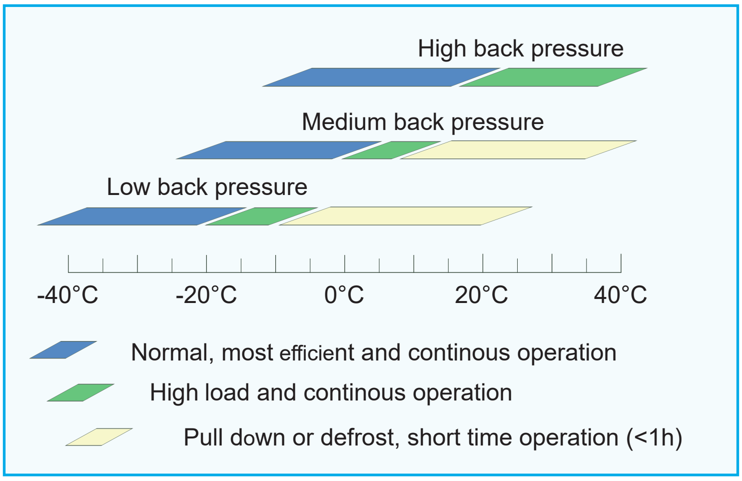


Fig. 51 Compressor lubricants

6.4 Expansion Valves

The expansion device can be seen as the antagonist to the compressor in the cooling cycle. It changes the high pressure, medium temperature subcooled liquid into a low pressure, low temperature,vapor liquid mixture. Expansion devices (or metering devices) are situated between the liquid line which is leaving the condenser and the inlet of the evaporator.

Capillary Tubes

Smaller cooling units with a relatively stable temperature range use capillary tubes as an expansion device. Copper tubing with a length of 2-4 metres and a view milimeters internal diameter is coiled up to several turns. The longer the tube and the smaller the diameter, the lower will be the pressure drop of the refrigerant. Tube length, diameter and hence the mass flow in the capillary tube is determined by the pressure difference between the condenser and the evaporator.

Capillary tubes have no closing mechanism. High side (condenser) an low side (evaporator) equalise in pressure when the refrigerator is not running. This facilitates the start of the compressor and allows a motor start with low starting torque.

But the pressure equalisation also leads to accumulation of liquid refrigerant at the bottom of the evaporator. Since the long thin tubbing makes it prone to clogging, a filter drier with loose desiccant is mounted prior to the device. When refrigeration circuits with capillary tubes are emptied, they need suction pump evacuation on both pressure sides.

Fixed Orifice

Another non-regulating expansion device is the fixed orifice (*french*: opening). Its basically just a small piston with a precisely drilled hole in a brass cylinder. The refrigerant enters the orifice as a high pressure liquid but when it ejects the nozzle, the rapid expansion leads to a pressure loss. The refrigerant immediately turns into a liquid vapor mixture known as flashing. Too much vapor flashing is not efficient because it minimises the latent heat exchange in the evaporator (liquid to vapor). It also increases superheat. The advantage of a fixed orifice is that the piston can be exchanged or cleaned easily. Some fixed orifices allow reverse flow of refrigerant when the unit is used in reverse mode as a heat pump (see Fig B).

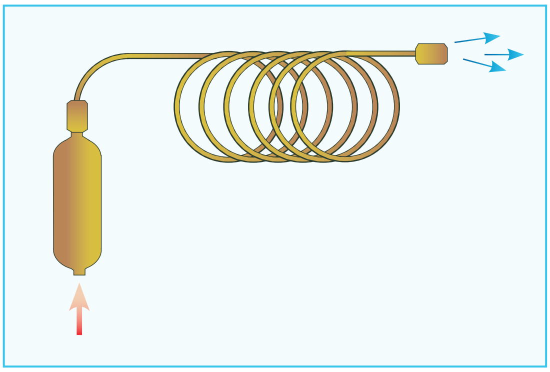


Fig. 52 Capillary tube with filter drier

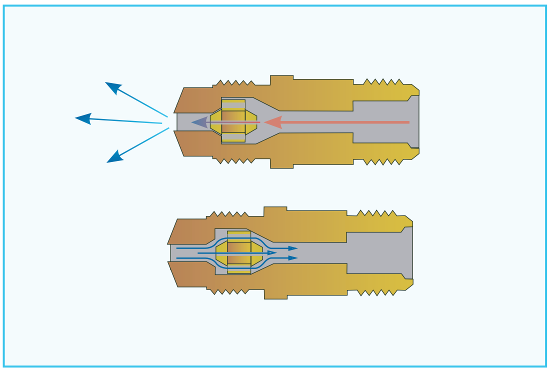


Fig. 53 Fixed orifice in reverse flow (below)

6.5 Filter Driers

Besides the four core elements of a cooling cycle (Compressor-Condenser-Expansion device-Evaporator) every refrigeration unit has a fifth mandatory element in their circuit, the filter dryer. As the word implies this equipment has two main functions, moisture absorption and contaminant removal.

The primary cause for the ingress of moisture is that air has entered the refrigerant cycle due to improper handling during installation, refrigerant refill or maintenance works. Polyolester compressor lubricants are also highly hydroscopic, though a complete avoidance of moisture in the circuit is hardly possible.

The high temperatures in the cooling cycle can enhance the chemical reaction of the refrigerant or the compressor lubricants with water into acid formation. Corrosion of metals can shorten the total life span of the refrigerator or even lead to a vapor pump failure (compressor burn out). Another potential hazard is internal ice blockage because of subzero temperatures on the low pressure side.

The filter drier contains desiccant material, small beads made of silica gel or Aluminium oxide beads. These materials have extremely small pores (3×10^{-7}mm). Refrigerant molecules are too big to fit into this pores but water molecules can get trapped. The surface of the desiccant is also positively charged with cations that attract bipolar H_2O molecules. Corrosion caused by acid formation can chip off parts of the copper tubing and desintegrate polymer fittings. Other solid contaminants like oxydated metal chips or flux particles can come from insufficient cleaning and evacuation after soldering works.

Filter Dryer Types

Smaller cooling units usually contain a copper spun filter drier that is soldered into the discharge line right before the capillary tube. The molecular sieve is made of loose desiccant beads. The desiccant is kept in place by a baffle and an additional filter screen. When installed correctly copper spun filters can last the lifetime of the refrigerator. They are used in systems up to 10kW. Their burst pressure should be at least 3-5 times the max. operating pressure.

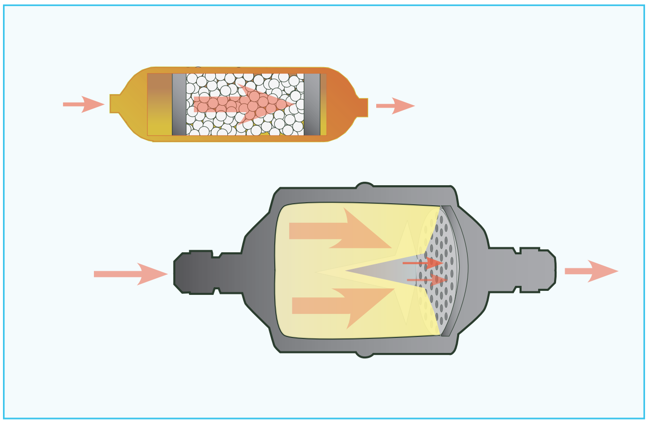


Fig. 54 Copper spun and welded steel type filter dryers

Larger systems use welded steel shell design filter dryers. The refrigerant is pressed through the solid molded core which acts as a molecular sieve made of composite hydrocarbons and activated alumina to capture moisture and eventual acid contents. The refrigerant then collects in the groove from where it passes through a final polyester mat screen that retains dirt particles down to 25microns. A load spring on the entrance side keeps all the components in place. Steel shell filter dryers can work with multiple refrigerants and have a maximum burst pressure of 50bar.

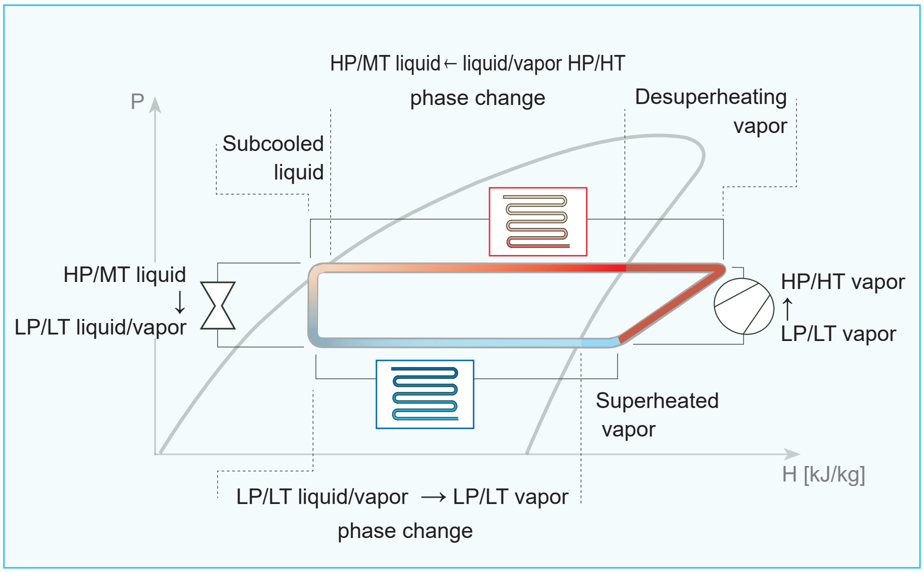


Fig. 55 Refrigerant phase changes in the cooling circuit

6.6 Thermostatic Expansion Device

Larger refrigeration units, especially those with larger heat load fluctuations like HVAC's, require an injection device with an automatic adjustment mechanism for the refrigerant flow. Thermostatic expansion devices (TXV or sometimes TEV) are also called constant superheat valves.

When the heat load drops, full phase change from liquid to vapor in the evaporator coil will be delayed and the temperature in the suction line will decrease. Attached to the suction line is a probe cylinder that is connected to the TXV head via a capillary tube. Cylinder tube and head are filled with a separate refrigerant which is not connected to the main cooling circuit.The valve head houses a flexible diaphragm. The low head pressure retracts the diaphragm which narrows the attached injection valve, letting less refrigerant into the evaporator.

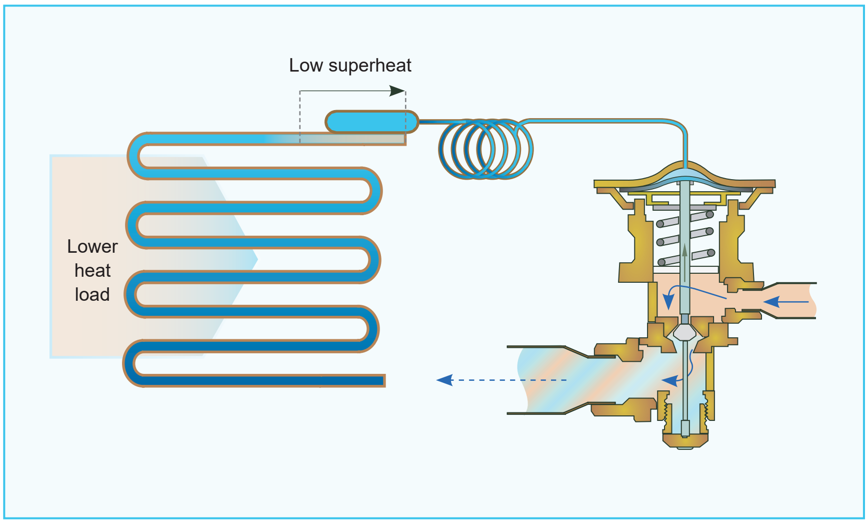


Fig. 56 Low superheat requires less refrigerant flow

With an increased heat load the refrigerant will evaporate at an earlier stage. Sensible heat will produce more superheat. The increased superheat warms up the probe and the expanding liquid pushes down the diapragm. The attached injector piston drops down and widens the refrigerant valve. More refrigerant can enter the evaporator coil and the superheat will decrease again.

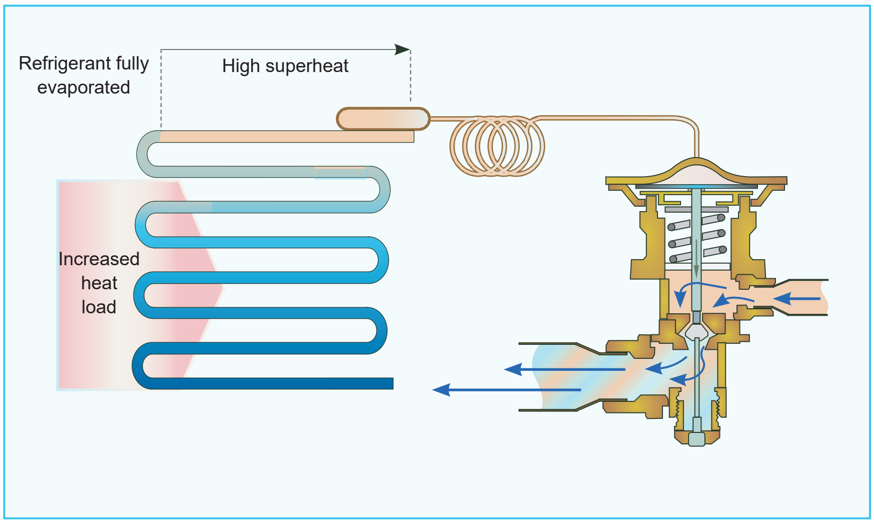


Fig. 57 Increased flow of refrigerant decreases excessive superheat

6.7 The Evaporator

Heat exchangers are devices that handle the heat transfer of fluids (liquids or gases) by forced convection. Since the refrigerant is physically separated from the air in the cooling box by a diathermic wall (usually metal plates of copper or aluminium) the evaporator of the refrigeration unit can be classified as closed, phase change, turbulent flow heat exchanger.

Evaporator phase change takes also place on the outside area since the air of the fridge box will condensate when cooled below its dew point (see chapter 3.2). When the temperature drops below 0°C ice will form on the evaporator plate. Commercial freezers do need frequent removal of ice build-up (defrosting) since ice decreases the heat transfer coefficent significantly.

In domestic and small business applications the most prevailing type is the rool bond evaporator. A special coating (weld stop) in the form of the refrigerant serpentine pattern is applied between two aluminium sheets. When the sheets are put into the rolling mill, heat and pressure weld the two sheets together except at the areas where the coating was applied. The unwelded aluminum can then be inflated by hydraulic air pressure creating a channel. The openings of the channel are then connected with the inflow and outflow of the refrigerant line. Roll bond evaporator plates can also be bent into a particular shape to increase the contact area. Deep freezing compartments in domestic refrigerators have a U-shaped evaporator plate that can cover top, bottom and rear side of the compartment.

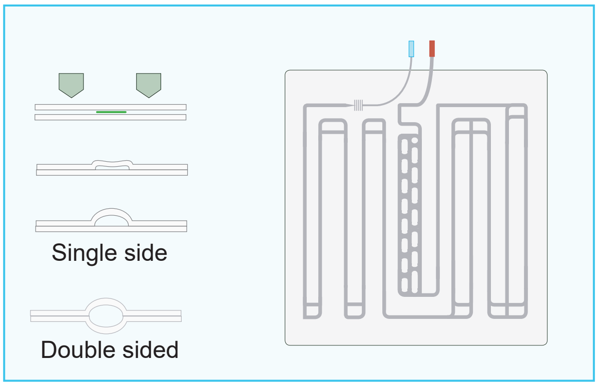


Fig. 58 Manufacturing of roll bond evaporator

Tab.6 Evaporator Capacity			
$Q_{Evap} = A \times \Delta T \times k$			
Evaporator capacity	Q_{Evap}		W
Evaporator surface area	A		m^2
Temperature difference	ΔT		K
Heat transfer coefficient	k		W/m^2K

The refrigerant leaves the metering device as a spray mist of approximately 25% vapor and 75% liquid ($x=0.25$). The main objective of an evaporator is to transport this liquid vapor mixture through its channels so an efficient heat uptake by the refrigerant can take place. The phase change of the refrigerant from liquid to vapor is the most effective way of heat absorption. This is caused by the sudden drop in pressure (expansion valve) and the temperature difference between the refrigerant and the content of the fridge box (Tab.6).

Empirically the evaporator capacity can also be measured and calculated by the enthalpy removal times mass flow (see chapter 7). The total capacity of the evaporator must match the cooling power of the refrigeration circuit at a specified evaporation temperature. A smaller evaporator must run at a higher temperature difference to achieve the same refrigeration effect. Larger evaporator area can operate at a smaller ΔT.

6.8 Condenser

The condenser is the heat rejector of the cooling unit. The refrigerant enters the condenser from the pressure line of the compressor as a high temperature, high pressure vapor. The main function of the condenser is to release the accumulated thermal energy into the environment. The refrigerant passes through three different temperature zones at a constant pressure, entering the condenser as a superheated gas. It then undergoes a phase change where it releases the bulk amount of enthalpy and leaves the condenser coils as a subcooled liquid.

Air cooled condensers reject their heat into the ambient air. Most domestic refrigerator systems use natural convection and radiation. Therefore they need a relatively large surface area for the heat exchange. Wire and tube condensers are installed at the backside of a refrigerator. Thin wires that are welded to a serpentine coil tube act as fins to increase the heat transfer area. Hot wall condensers have the condenser plates integrated between the thermal insulation and the outer metall casing of the refrigerator and use all three vertical walls as their heat transfer area.

Forced air cooled condensers can be smaller in size since an axial fan provides improved heat exchange by forced air convection. Aluminium fins brazed to copper tubing in the direction of the air flow support the heat exchange. The area of the condenser that faces the air flow is called face area. The air velocity (~2 to 4m/s) that hits the face area is called face velocity.

The required enthalpy that must be absorbed by the passing air flow can be calulated with the total amount of heat (cooling plus compressor power) compared to the total capacity of air flow.

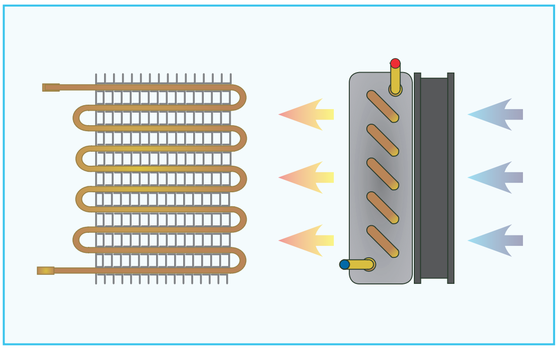


Fig. 59 Face area (left) of a forced air flow

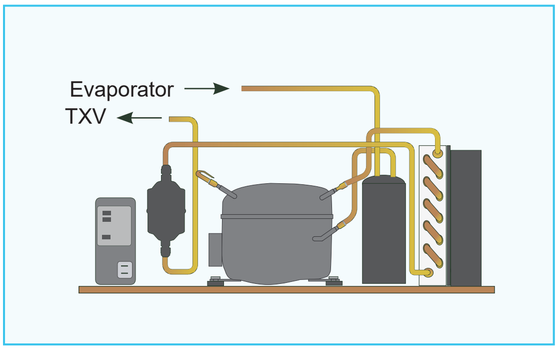


Fig. 60 Condensing unit with accumulator

The term condenser unit refers to a complete set of components that are already connected and assembled on a common base plate. In HVAC the condensing unit will be outdoors while the evaporator (i.e. the cooling unit) can be placed anywhere indoors. In most cases the condensing unit consists of the electronic control unit, the compressor and condenser, fan cooling, filter drier and very often an additional accumulator that can prevent liquid refrigerant floodback to the compressor.

Flooded evaporators in larger cooling appliances use the full range of latent heat exchange. The accumulator allows liquid refrigerant to settle down at its bottom, so only vapor refrigerant can enter the compressor. In **dry type evaporators**, the refrigerant is already fully saturated in the evaporator coils so only superheated vapor can enter the compressor chambers.

Condensers always need to be placed in an area with suffient natural air exchange and protected from direct sun radiation. In practice the saturation temperature of the condenser should be 10K above ambient temperature. Higher saturation temperature leads to higher pressure and reduces the efficiency of the system.

7 NET REFRIGERATION EFFECT

Measurement of the actual pressure and temperature values of the refrigerant flow is the best way to determine the efficient performance of a cooling unit. Larger applications like HVACs have pre-installed service valves that allow the direct connection of measurement gauges. Smaller cooling units need the installation of an additional piercing valve to conduct operational P/T measurements.

7.1 Piercing valves

The installation of a piercing valve is an actual penetration of a pressure line. Once again all relevant safety instructions and regulations must be followed when conducting such a professional maintenance work. The hollow piercing needle of the valve is pushed down by a thread until it penetrates the copper tubing. A rubber gasket seals the hole pressure tight. Once installed, the pressure line can be accessed over the Schrader valve outlet.

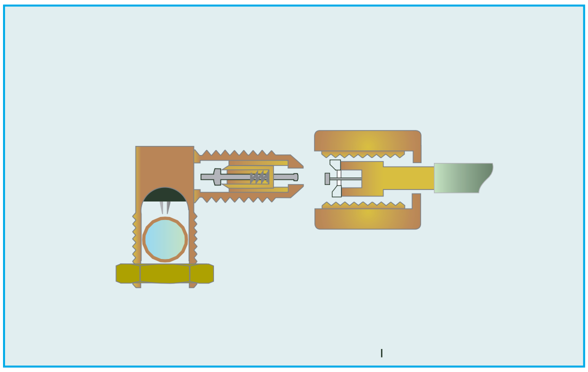


Fig. 61 Piercing unit with Schrader valve

For superheat measurements, a suitable point with sufficient space must be selected at the low pressure return line from the evaporator, as close as possible to the compressor inlet (Fig. 61). Additional space next to the piericing valve should be left for the clamp of the temperature gauge.

For subcooling a straight section of copper tubing should be selected between the condensor outlet and the entry of the filter drier cartridge. Once the piercing valves are installed, no excessive force should be exerted on them.

Prior to any pressure measurement, pressure gauges should always be zeroed to ambient pressure for calibration. The pressure gauge can be connected hand-tight to the Schrader access valve. The clamp of the temperature gauge should also sit tightly on the copper tubbing.

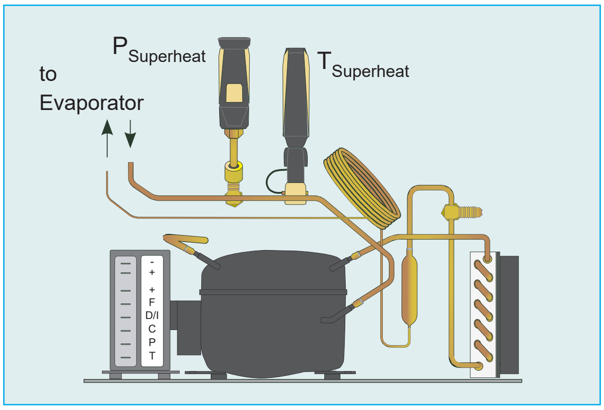


Fig. 62 Gauges for superheat measurements

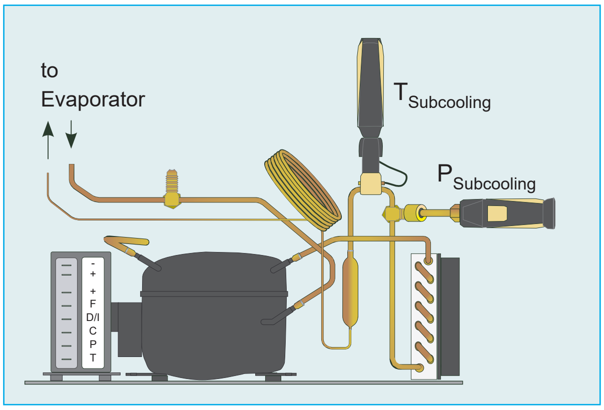


Fig. 63 Placement of gauges for subcooling

Digital instruments have the advantage that the refrigerant type can be specified in the settings menu and then all readings are already adjusted to R600a. When the refrigerator is turned off, suction and pressure line will be close to ambient pressure. After a certain run-up time, superheat, subcooling and additional measurements can be made.

Measuring Superheat

- Pressure measurement on suction line
- Corresponding saturation temperature (on display or from chart)
- Temperature measurement on suction line
- Saturation temperature minus suction line temperature gives superheat (Tab.7)

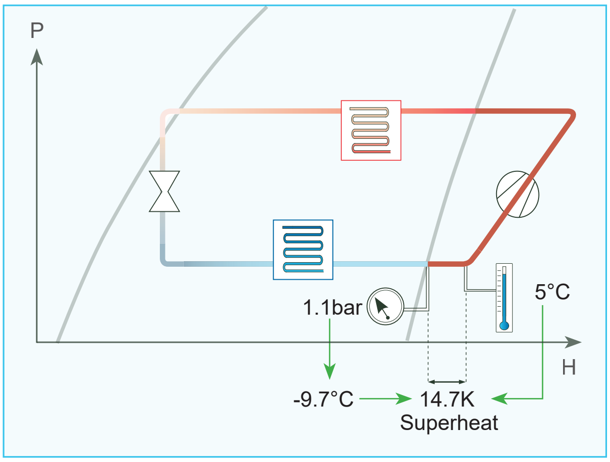


Fig. 64 Superheat calculation

Tab.7 Superheat Measurement			
Saturation pressure	1.1bar	Saturation temperature	-9.7°C
Suction line temperature			5°C
Difference			
Superheat			**14.7K**

Measuring Subcooling

- Measurement of saturation pressure between compressor and filter drier
- Corresponding saturation temperature on display or from chart
- Measurement of pressure line temperature
- Pressure line temperature minus saturation temperature gives subcooling (Tab.8)

Tab.8 Subcooling Measurement			
Saturation pressure	4.2bar	Saturation temperature	31.3°C
Pressure line temperature			20°C
Difference			
Subcooling			**11.3K**

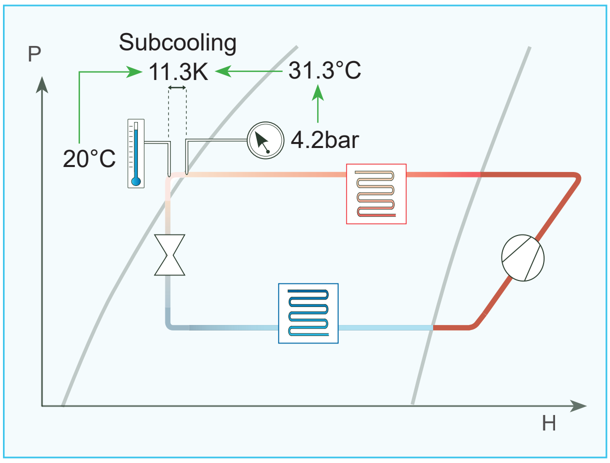


Fig. 65 Subcooling calculations

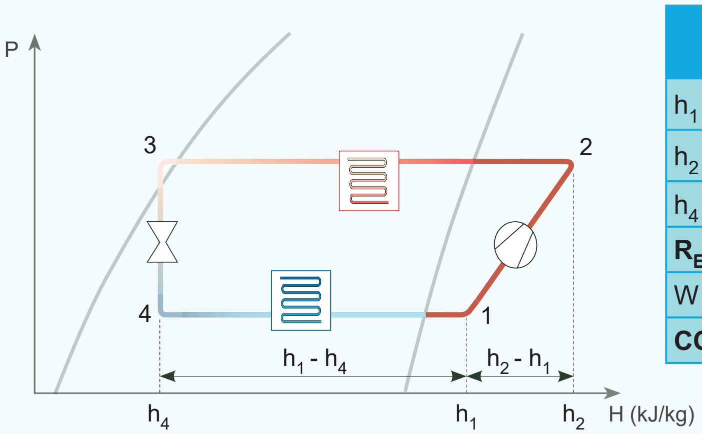
7.2 Refrigeration Effect

The enthalpy values (kJ/kg) on a pH-chart can be used to calculate the efficiency of the cooling unit. The **net refrigeration effect** is the amount of enthalpy leaving the evaporator (h_1) minus the amount of enthalpy entering the evaporator (h_4). The mechanical input (W) that is necessary to transfer heat from the interior cooling space to the warmer outside environment can be calculated by h_2-h_1. The coefficient of performance (COP) is the ratio of refrigeration effect compared to the required mechanical input (“What do you get, what do you pay...”)

$$R_E = h_1 - h_4$$

$$W = h_2 - h_1$$

$$COP = \frac{R_E}{W}$$



Tab.9 Calculation of COP

h_1	556	kJ/kg
h_2	680	kJ/kg
h_4	250	kJ/kg
R_E	**306**	**kJ/kg**
W	124	kJ/kg
COP	**2.5**	

Fig. 66 Coefficient of performance calculation with enthalpy values

7.3 Refrigeration Capacity

Another important value is the actual amount of cooling that is produced by the cooling unit. It can be calculated as the product of RE times the actual amount of refrigerant flow. The mass flow rate (ṁ *pronounced* m-dot) should be available from the compressor specifications.

Tab.10 Refrigeration Capacity

$$R_E \times \dot{m} = R_C$$

Refrigerant mass flow rate	$\dot{m}$	0.86	kg/h	**Refrigeration capacity**	**R_C**	**263**	**kJ**
Refrigeration effect	R_E	306	kJ/kg				

7.4 Effects of Increased Subcooling

Fig. 67 shows the effect that an increase in subcooling would have on the effficiency of a refrigeration circuit. More subcooling of the liquid refrigerant (h3 to h3') will also increase the cooling effect ($R_E' = h_1 - h_4'$). Since the work input ($W = h_2 - h_1$) remains constant, COP will also increase. The refrigerant has a certain constant capacity to remove heat (R_C) which is refrigeration effect times its mass flow rate ($\dot{m}$). Since R_E increases, mass flow rate will decrease.

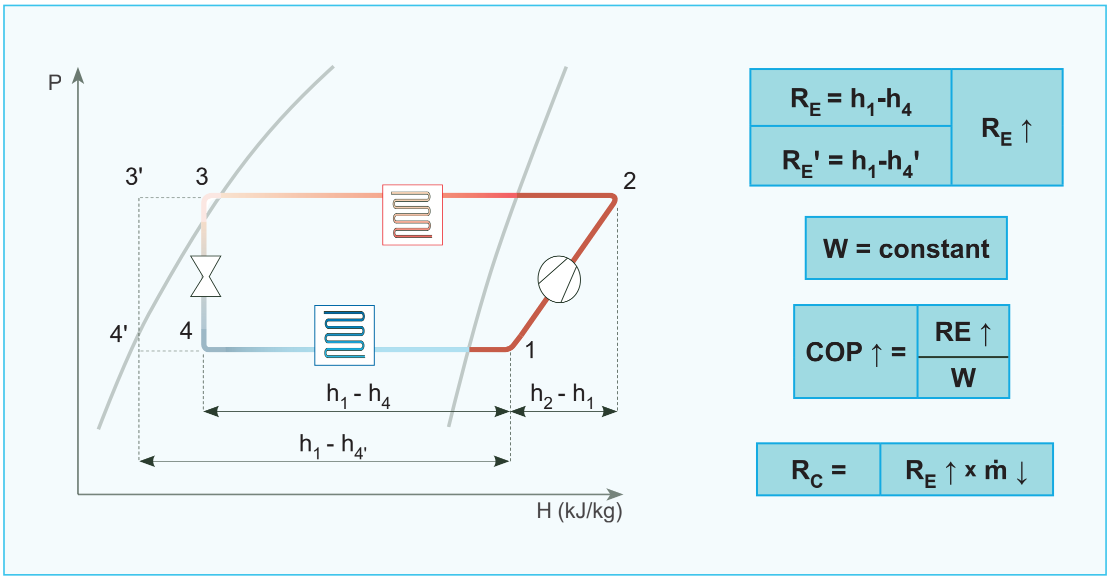


Fig. 67 Effects of increased subcooling

7.5 Effects of Increased Superheat

Similar to an increase of subcooling an increase of superheat will also lead to an improved efficiency ratio of the cooling unit. More superheat will increase the refrigeration effect but will bring a slight increase of the work input. In total, the COP of the cooling unit will increase.

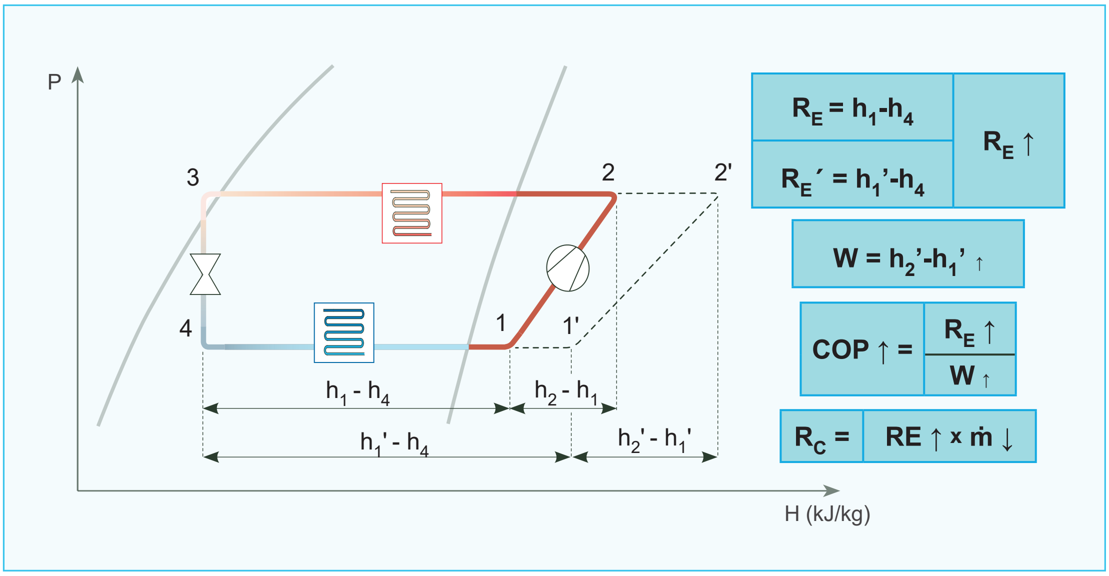


Fig. 68 Effects of increased superheat

7.6 Effects of Lower Evaporator Pressure

The refrigeration effect (R_E) will slightly decrease but the amount of mechanical work (W) will rise significantly. COP will therefore decrease at the same rate and since R_E decreases mass flow rate will increase.

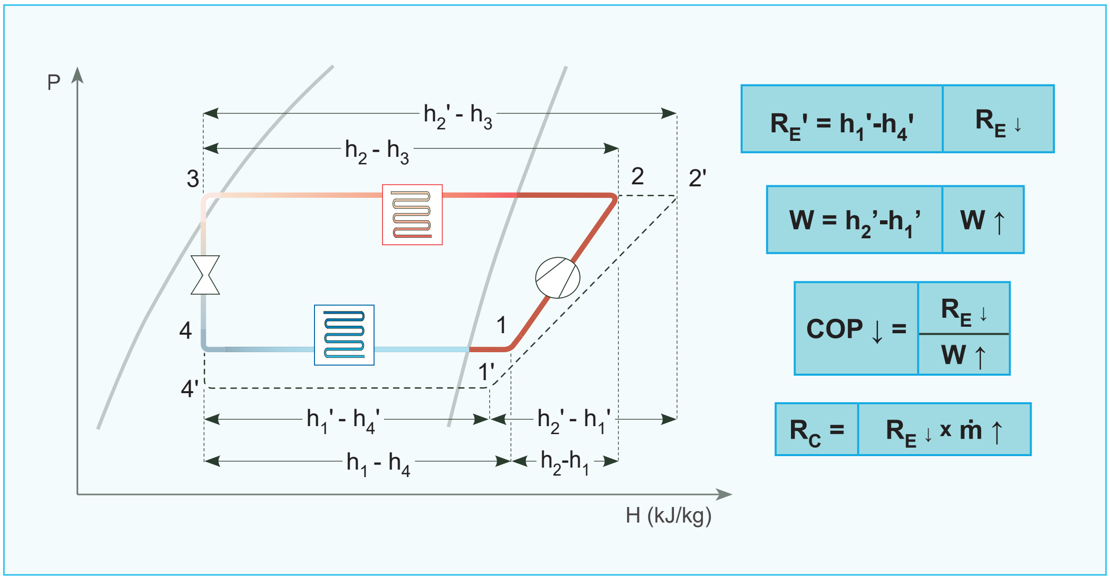


Fig. 69 Effects of lower evaporator pressure

7.7 Effects of Higher Condenser Pressure

An increase in condenser pressure will decrease the refrigeration effect and increase compressor power. Overall COP therefore decreases as well. With R_C as a constant, mass flow rate will also increase, which explains the increased work demand.

The effect of an increase in condenser pressure can be observed when the axial air fan of the condenser is switched off during operation. After noting the pressure and temperature values in Tab.11 under normal conditions (fan on), the axial ventilator is switched off and the gradual changes of the pressure and temperature values can be observed and noted.

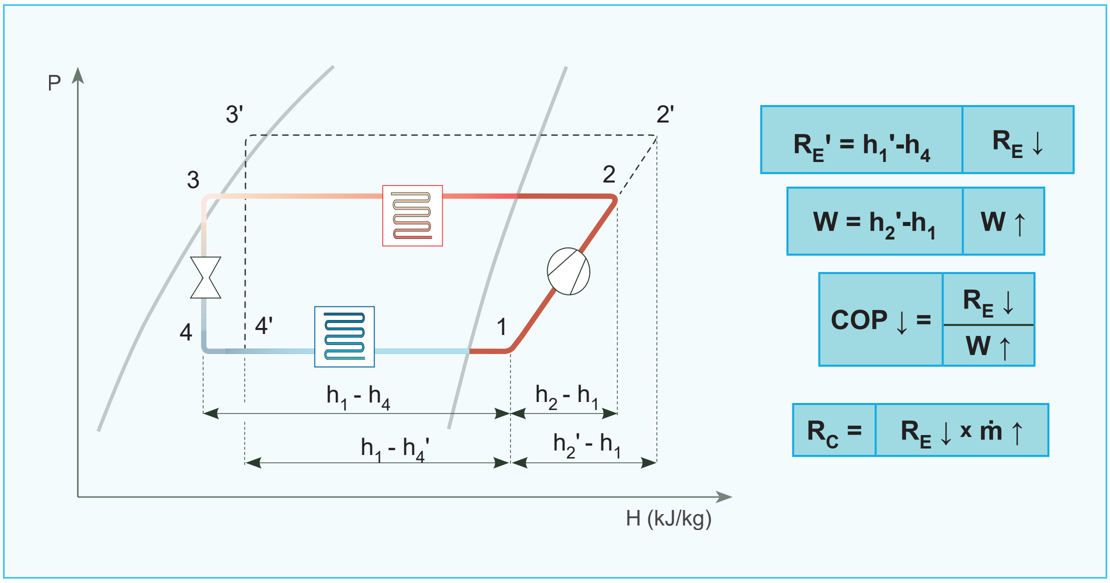


Fig. 70 Effects of higher condenser pressure

Tab.11 Increase of Condenser Pressure

Condenser fan on			Condenser fan off		
$P_{Subcooling}$		bar	$P_{Subcooling}$		bar
$T_{Subcooling}$		°C	$T_{Subcooling}$		°C
$P_{Superheat}$		bar	$P_{Superheat}$		bar
$T_{Superheat}$		°C	$T_{Superheat}$		°C

8 REFRIGERANTS

After the invention of the first vapor compression refrigerator by J.Perkins in 1834, natural chemicals like ether, ammonia (NH_3), carbon dioxide (CO_2) or sulpur dioxide (SO_2) were used as refrigerants. Most of these substances have certain major disadvantages like corrosiveness, low efficiency or toxicity that made them unfit for a broader commercial use.

8.1 Flourinated Refrigerants

In the 1930s scientists thought that they had discovered the ideal refrigerant in synthetic halogens, hydrocarbons where the hydrogen atoms are partially or completely replaced by halogen atoms like chlorine or florine. Chloroflourocarbons (CFCs) and partially derived hydrochloroflourocarbons (HCFCs) were non toxic, non flammable, non corrosive and highly efficent.

But their strong chemical stability proofed to be fatal in the long run. When released into the environment, global wind patterns (e.g. the polar vortex) made them travel up as far as into the upper regions of the atmosphere. Up in the stratosphere, they were finally reacting agressively with the O_3 molecules of the oxone layer, the protective shield that bounces off the sun's cytocidal UV radiation. One chlorine atom can react with 100,000 ozone molecules and such an average “journey” of a CFC molecule into the stratosphere can take about 15 to 30 years.

With a few exceptions (e.g. fire retardants in submarines) CFCs are globally banned and HCFCs are planned to be phased out from the global market by 2030. HFCs contain no more ozone depleting chlorine atoms but it was discovered that some HFCs retain very persistent in the lower parts of the atmosphere and contribute significantly to global warming.

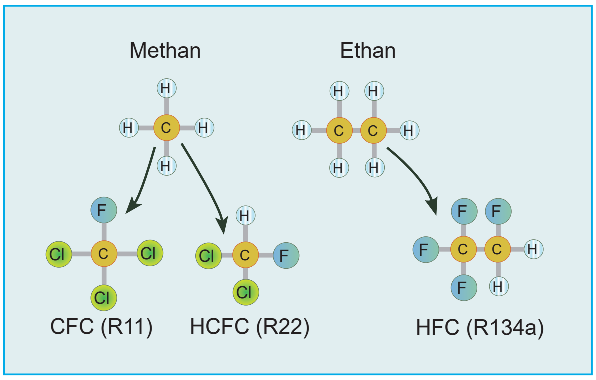


Fig. 71 Halogenation of hydrocarbons

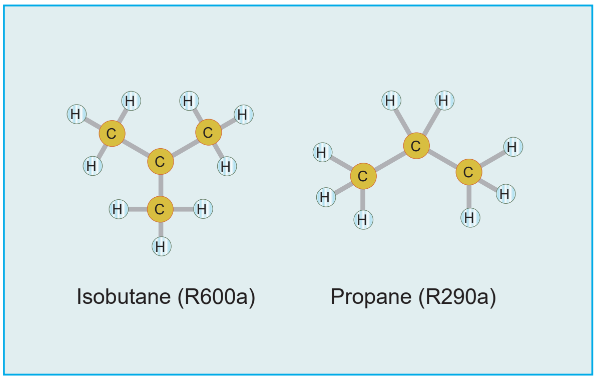


Fig. 72 Natural hydrocarbon refrigerants

Ozone depletion potential (ODP) and Global Warming potential (GWP) are the main environmental threats caused by refrigerants (Tab.12). The total equivalent warming impact (TEWI) is a broader approach to the topic of climate hazard since it also includes the negative contributions generated by manufacturing and disposal.

HFCs with a tolerable low GWP will remain in the market for the forseeable future. In the moment they are the most dominant category of regrigerants in the global market (e.g. R134a). HFCs can also be mixed with hydrofluoroolefins (HFOs). Hydrofluorooelefins are unsaturated organic refrigerants with low GWP, zero ODP and are considered the fourth generation of refrigerants.

Tab.12 General Quality Requirements for Refrigerants

Efficiency	**Environmental**
Chemical stability under the ocurring pressure and temperatures in the refrigeration cycle	Non persistent and biodegrable
Non corrosive to equipment materials and non reactive with lubrication oil and humidity	Zero ODP
Condensation and evaporation at appropriate temperatures (no evaporation under vacuum and no condensation above 30bar)	Very low GWP
Mixable but also dissoluble with/from lubrication oil	**Health Safety Standards**
No or low glide	Non toxic
Low viscosity	non flammable

8.2 Refrigerant Blends

Refrigerant blends are a mixture of two or more refrigerants. They are classified by the most critical individual refrigerant of which they are composed. For example, if a blend contains HCFC, the blend is also classified as an HCFC. There are three major groups. Blends that retain their properties like specific boiling and condensation points during all operations are called **azeotropics**. When exposed to atmospheric pressure the components will not separate.

Refrigerant mixtures where the particular components will condensate and boil off at their own individual points are called zeotropic blends. A **zeotropic** blend can separate into its individual components. When liquid is lost (e.g. by leaking), the refrigerant cannot just be refilled but it must be completely recovered.

The temperature at which a zeotropic blend will first boil off is called **bubble point**. The temperature at which a zeotrope will first condense is called **dew point**. Since a blend has different boiling and condensation points, zeotropes show a slope on the dome region of the pH-diagram (temperature glide). **Near azeotropes** are blends with different bubble and dew points but in a closer range.

8.3 Hydrocarbons

Natural refrigerants like propane (R290a) or isobutane (R600a) have excellent thermodynamic properties. They are suitable for many cooling applications and offer an environmentally friendly alternative for domestic and commercial refrigeration systems. They are also compatible with most refrigerant oils and lubricants.

Legislation of some countries restrict their use to smaller systems with a maximum filling volume of 150 grams, due to their potential flammability. Only technicians, competently trained with safety restrictions and regulations should handle and maintain refrigeration cycles with hydrocarbons. Compressors with R290a and R600a need to have a warning label for flammable substances. Isobutane is a colorless and odourless gas. Its autoignition temperature is at 460°C. Explosive limit concentration in air is between 1.4 Vol.% (37g/m3) to 8.3%Vol % (219g/m^3).

The ASHREA (American Society of Heating, Refrigeration and Airconditioning Engineers) designation is a list of approved refrigerants. An alphanumeric key provides information about the chemical composition (number and type of hydrocarbon and derivate atoms), the toxicity (A-B) and flammability (3-1) of the refrigerant.

Tab.13 Sample List of Common Refrigerants

ASHRAE			Chemical group	Common name	Boiling Point (1bar)	Glide	ODP*	GWP**
R11, R12	A	1	CFC	Freon	-29.8	-	1	11,547
R22	A	1	HCFC	Freon	-40.8	-	0,05	2,106
R502	A	1			-45.6	azeotrop	0.23	4,657
R134a	A	1	HFC	Tetraflourethane	-26.3	-	0	1,430
R600a	A	3	HC	Isobutane	-11.7	-	0	3
R290	A	3	HC	Propane	-41	-	0	3
R718	A	1	H_2O	Water	100	-	0	0.2
R407a	A	1	HFC		-45.8 to 39.2	6.6 zeotropic	0	2,107
R1233zd	A	1	HFO		20.8	-	0,00034	1-4.5
R717	B	2L	NH	Ammonia	2.22	-	0	0

* in relation to Trichlorflourmethan (R11)

** in relation to CO_2

9 COOLING LOADS

The total amount of thermal energy that has to be removed from the interior of a fridge box to retain a certain low temperature is called **cooling load**. The majority of this load is generated by the content of the cooling specified as **product load**. The additional factors that need to be taken into account mainly depend on the size, design and the way how the cooling unit is operated.

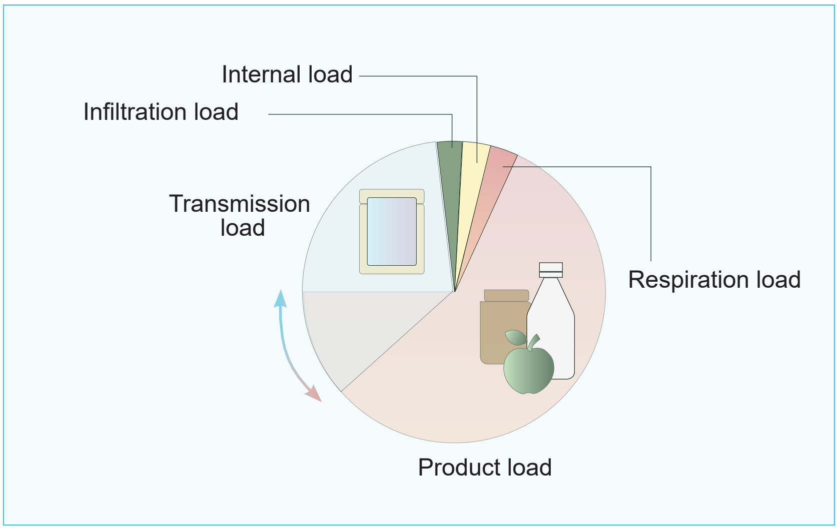


Fig. 73 Specific components of the total cooling load

9.1 Transmission Load

Transmission load is the heat ingression which transcends through the walls of the cold room or the cooling box. It mainly depends on the quality of the thermal insulation but also on the temperature difference (ΔT) between the outside environment and the cooler inside air, Poor insulation will lead to a constant heat ingress into the fridge box for which the compressor has to compensate with additional cooling.

Transmission load is the sum of heat that gradually transgresses through the insulation material, wall joints and gaps of the opening mechanism. Good thermal resistance of quality insulation material, an appropriate wall thickness, well sealed joints and a tight door closing mechanism can reduce the transmission load. Negative impact on the transmission load is caused by poor thermal insulation and a large Δt. Choosing an appropriate location for the cooling unit with sufficient air exchange, shading protection and away from other heat sources (ovens, machineries) can help to decrease the amount of transmission load.

Thermal resistance

The thermo box of the Solar Cooling unit is made of extruded (XPS) or expanded (EPS) polysterene foam boards. Widely used as an insultation material in the construction sector, polysterene is lightweight, easy to cut and moisture resistant. Its biggest disadvantage is its non-biodegradability. Polysterene foam consists of 95% air, encapsulated in tiny polymer beads which makes it a material of extremly low thermal conductivity (see Fig. 74).

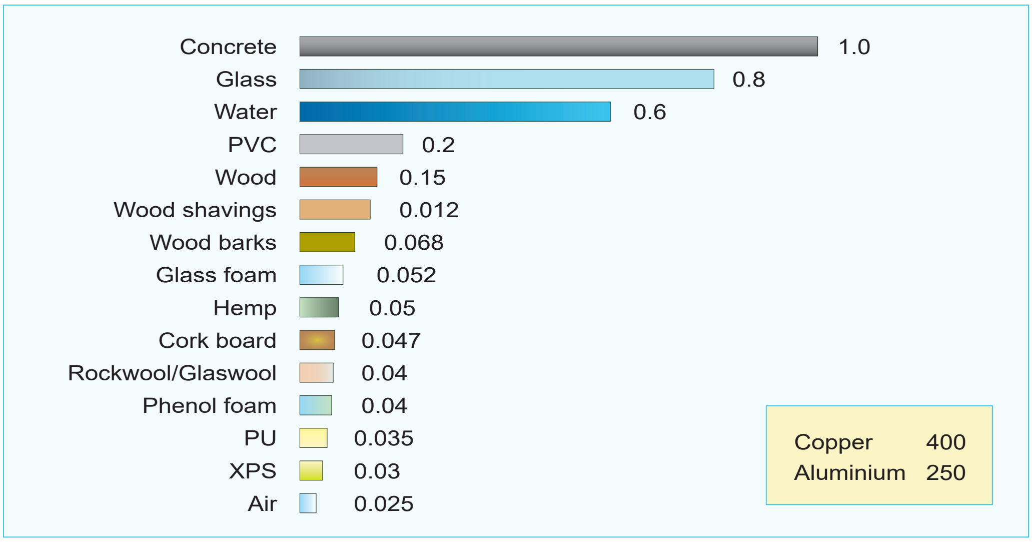


Fig. 74 Thermal conductivity (W/mK) of building materials

Tab.14 shows that the lower the thermal conductance (λ) of a material and thicker its wall diameter (d), the better the thermal resistance (R) of a material will be.

Tab.14 Thermal Resistance of XPS Foam Board

$$\frac{d}{\lambda} = \mathbf{R}$$

Material thickness	d	0.1	m
Thermal conductivity	λ	0.035	W/mK
Thermal resistance	**R**	**2.86**	**m^2K/W**

The total transmission load (Q_T) is the outside area (A) of the fridge box times the temperature difference (ΔT) divided by the thermal resistance (R). The higher thermal resistance, the lower will be the transmission load. An estimated loss factor needs to be added as well to compensate for air gaps in wall joints and doors (thermal bridges).

Tab.15 Transmission Load

$$\frac{A \times \Delta T}{R} = \mathbf{Q_T}$$

Total surface area	A	0.1	m^2
Temp difference	ΔT	26	K
Thermal resistance	R	2.86	m^2K/W
Transmission load	**Q_T**	**0.9**	**W**

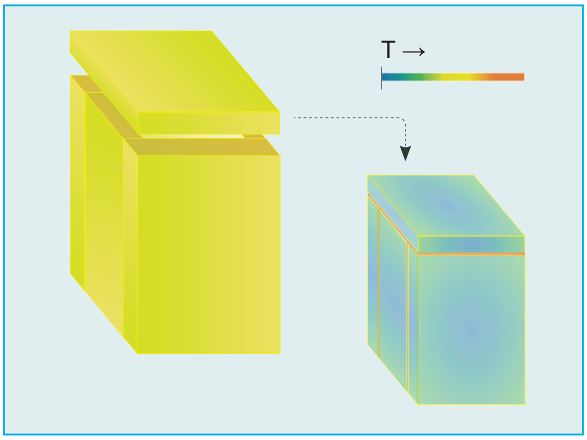


Fig. 75 Heat ingress by thermal bridges

R-Value of Multiple Materials

Cooling boxes are very often constructed of multiple materials. In this case the R values of every single material needs to be calculated separately and then the sum of all individual R values can be taken for the final calculation of the transmission load.

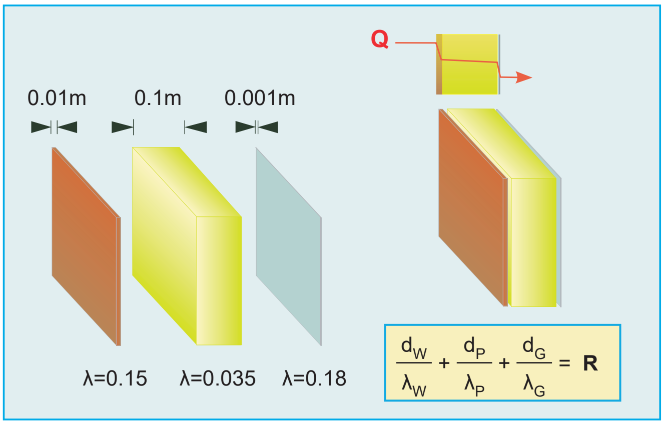


Fig. 76 Insulation materials with different R-values

Tab.16 Transmission Load

Material	d [m]	λ-value [W/mK]	R-value [m^2K/W]
Plywood	0.15	0.01	0.07
Polysterene	0.035	0.1	2.86
Acryl glas	0.18	0.001	0.01
Total R-value			**2.93**

9.2 Infiltration Loads

Cooling units are frequently opened for a product exchange and maintenance. This can lead to an ingress of warm air from the outside which increases the total heat load. For cooling units with operating temperatures above freezing (0°C), the infiltration load can be calculated by the additional enthalpy (Tab.17).

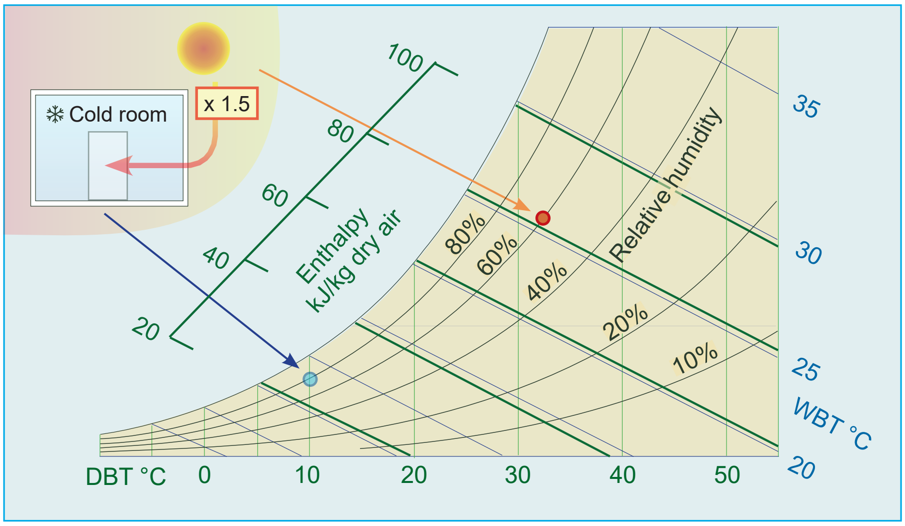


Fig. 77 Psychrometric chart for enthalpy calculation

Tab.17 Additional transmission load enthalpy

	Cold room	Outdoor	
Dry bulb temp	10°C	32°C	
Air humidity	80%	60%	
Mass enthalpy	25.46	78.52	kJ/kg
Volume enthalpy	5.81	17.81	Wh/m^3
Additional enthalpy per day*		324.86	Wh

*Cold room with $18m^3$ and an air mass exchange of 1.5 per day

$$\frac{\text{Mass enthalpy [kJ/kg]}}{3.6 \times \text{Density}} = \text{Volume enthalpy } [Wh/m^3]$$

$$\frac{78.52 kJ/kg}{3.6 \times 1.225 kg/m^3} = 17.81 Wh/m^3$$

Cooling units that operate below freezing, air humidity and its latent heat content must be taken into account as well. Larger cooling units with frequent product exchange use PVC strip curtains as a cooling protection barrier. In smaller cooling units top drawers have a better protection against ingress of warm air than refrigerators with horizontal hinge or slide doors.

Internal Loads

Electrical appliances like fan motors or lights are generating dissipation heat. In larger cooling units with actively working personnel (butcheries) the heat dissipation of the human body has to be considered as well. These factors are summarized as internal loads.

9.3 Product Loads

The heat enthalpy of food products that enter the cold room account for the major part of the cooling load (50-75%). Commodities that just need to be chilled i.e. the final temperature stays above their initial freezing point T_f just require the calculation of quantity, specific heat, respiration heat and the frequency of product exchange.

Fig. 78 shows the influence of product exchange on the cooling load. In case A 10kgs of food items are cooled down from ambient temperature to 4°C (ΔT=20K). The whole amount is then replaced by a new batch. The cooling load remains the same.

Case B shows that 50% of the cooled product is taken out for distribution and replaced by the same amount of new product. In this case the initial cooling load accounts for ten kilograms but then the cooling load decreases to 5kg.

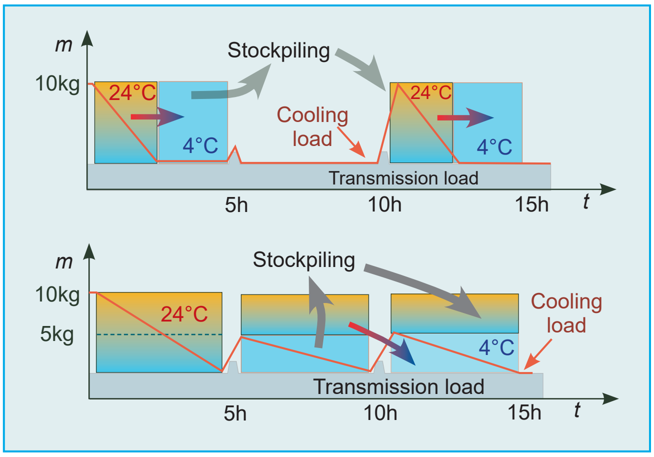


Fig. 78 Stockpiling determines cooling load

Tab.18 Product load above freezing

$Q_T = C \times m \times \Delta T$

Specific heat (Bananas)	C	3.35	kJ/kgK
Mass	m	10	kg
Temp difference	Δt	21	K
Heat load	**Q**	**703.5**	**kJ**

9.4 Freezing Product Load

Moisture content determines the freezing characteristics of organic products, though water is often not present in its pure form but in solution with other substances like proteins, carbohydrates and salts.

Therefore food products do not freeze at a single temperature but gradually change their state into solid frozen. For example fruits with a high sugar content have a very low freezing point. The heat load required for freezing can be calculated by two methods.

The first method in Fig. 79 calculates the enthalpy change of three stages and adds them together. The sensible heat (chilling) load above freezing (same as in Tab.18), the latent heat of fusion which is determined by the water content of the product and the sensible heat (freezing) load of the product at temperatures below 0°C.

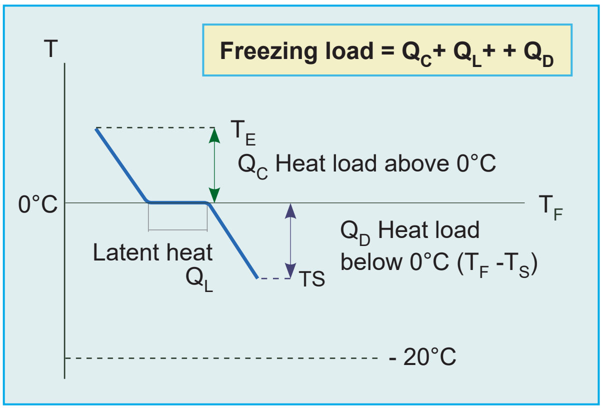


Fig. 79 Conventional freezing load method

The enthalpy method (Fig. 80) takes the usual chilling load Q_C for temperatures above 0°C and for subzero temperatures the enthalpy difference ($T_{0°C}$ - T_S) is calculated. Both methods require charts for thermal properties of food to determine the specific values. In the range of +5 to -20°C both methods will give close results. When the entering temperature or the final storage temperature is close to zero degrees the enthalpy method should be used.

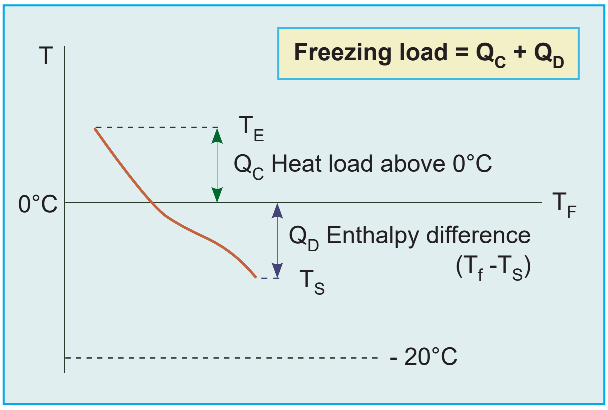


Fig. 80 Enthalpy method to calculate freezing load

9.5 Respiration Heat

One notable biochemical activity that continues after harvesting is respiration. This process is the dominant cause for the deterioration of fruits and vegetables during storage. Respiration consumes oxygen and gives off carbon dioxide, water vapor and thermal energy. The amount of heat that is released depends on the type of fruit and the storage temperature.

Fig. 81 shows two cooling curves for ripe banana fruits. The brown curve represents a slow cooling process that takes four hours to cool down from 25 to 4°C. For every hour the average respiration heat at a certain temperature is taken from a chart and counted together giving a total of 0.197W/kg. The green line shows a rapid cooling curve of one hour for which the average cooling rate can be taken. A fast one hour cooling process decreases the respiration rate down to 0.092W/kg.

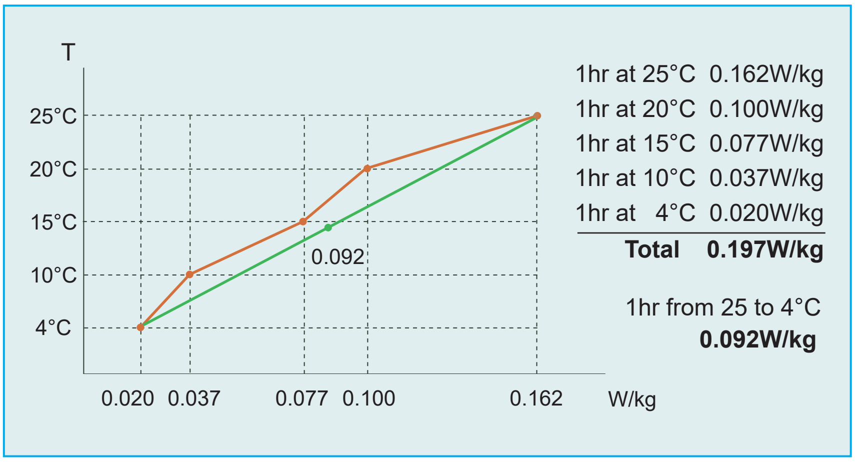


Fig. 81 Respiration load of bananas at different temperatures

Packaging Load

Another load factor that must be taken into account at larger refrigeration plants is the heat load by packaging material. Charts inform about the specific heat capacity (kJ/kgK) of various packaging materials (wood palettes, wrapping foil, enclosed air etc.). This value must be multiplied by the mass of the material (kg) times the difference between the product's initial temperature and the intended storage temperature.

9.6 Cooling Time Curve

Cooling time calculations are based on Newton’s law of cooling. It states that the rate of heat loss is always proportional to the temperature difference between the body and its surroundings (see chapter 2.3 Heat Transfer).

Starting with a large Δt the cooling curve will gradually flatten out the more the product reaches the temperature of the cold room (Fig. 82). This is shown in the formula by *t* (min) as a negative exponent. The additional factor K summarizes all the physical properties of the food product that influence the rate of cooling.

A large exposed surface area with a good heat convection can accelerate the cooling process. The total mass (volume x density) and specific heat capacity of the product will increase the required cooling time. The base number *e* (2.718...) in the cooling formula is a natural growth constant.

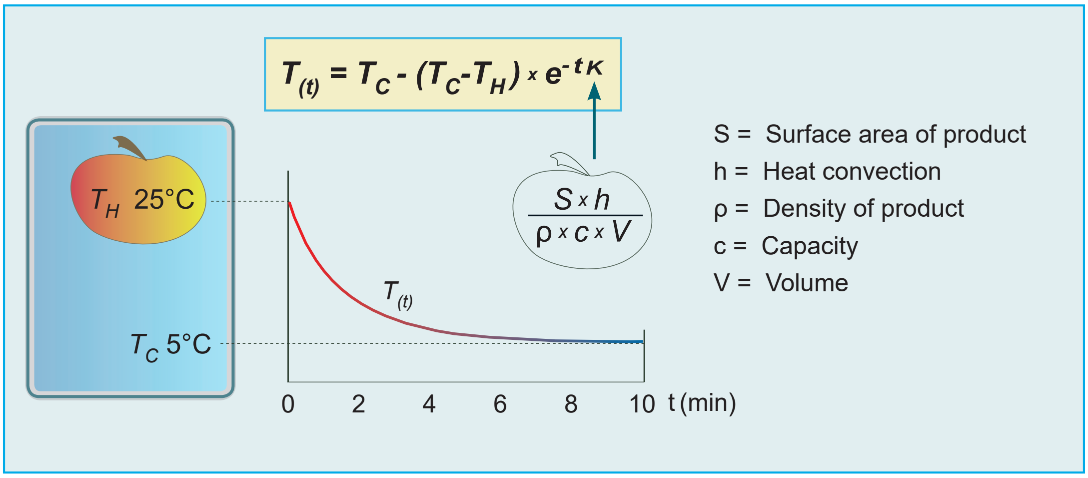


Fig. 82 Cooling time curve and influencing factors

10 FOOD PRESERVATION

The preservation of food products by refrigeration is based on the fact that low temperatures decrease the molecular movement and therefore decelerate the internal biochemical processes of the product. Other than sterilization or chemical treatment, refrigeration cannot improve the quality of edible products. Hence the storage time of cooled or even frozen foods is definetly limited. It is also important that sufficient cooling should be provided from the initial point (i.e. harvesting, slaughter, catch) of the production process.

Most food products continue with their metabolic activity after harvesting. Cellular respiration takes oxygen from the air to convert glucose into energy while water and carbon dioxide is being released. Respiration is an exothermic process and must be taken into account when calculating cooling loads (see chapter 9.5).

Refrigeration also minimizes the growth rate of microorganisms in food products. Warm temperatures are the primary factor for premature degradation and spoilage of foods. Most microorganisms like bacteria or mold grow best at temperatures between 20 and 60°C. A further raise in temperature will decrease growth and eventually lead to heat death of most microorganisms.

Most microorganisms also require oxygen for their growth (aerobic bacteria). Industrial refrigeration uses controlled atmosphere (CA) to reduce the oxygen content in the air below 5%. This also decelarates the ripening process for storage or transportation. Before market distribution, stored fruits and vegetables can be gassed with additional ethylene as a ripening agent. Vacuum packing is another method to extend the shelf life by deoxygenation. It also reduces the storage volume.

Moisture control is an important factor for food preservation since high humidity in cold rooms can lead to mold buildup. On the other side fresh food products like vegetables and fruits require a certain relative humidity during storage to maintain their texture and weight. The loss of moisture in food commodities is caused by respiration (Fig. 81). Besides lower quality, a five percent moisture loss equals five percent weight loss (saleable mass).

Lowering the temperature below 4°C decelerates microorganic growth and respiration to a degree that fresh food is considered to be safe for storage and further processing. Organic decay cannot be stopped completely and is sometimes even desirable (dry aging of meat or ripening of cheese).

10.1 Cooling, chilling, freezing

Refrigeration can be summarized as the technical process to remove heat from an object or space in order to lower its internal and surface temperature. In food processing agricultural goods are transformed into edible food products and refrigeration is used to preserve and extend the shelf life of perishable products for further processing, distribution or storage.

Tab.19 Refrigeration Temperature Applications

Normal room temperature	>15°C
Cold temperated rooms	+8° to 12°C
Cold rooms (Plus cooling)	+4° to 0°C
Fast Cooling, defrosting	-8° to -12°C
Deep freezing rooms	-18° to -25°C
Cyrogenic refrigeration	-153°C and lower

Chilling is the (preferably) fast cooling of food products to a temperature above freezing, in most cases between 0-4°C. Every food product has an optimal temperature and a relative humdity at which it can be stored for a maximum possible amount of time. Cooling below the specific optimal temperature can lead to **chilling injuries**, negative physiological changes of the product like loss of color, soft scald or tissue damage.

Refrigeration above freezing is not limited to food preservation. It is also used for other forms of food processing e.g. hardening (butter), drying or concentrating. And finally the vast field of indoor air quality and climate control systems (HVAC). It is predicted that by 2050 the global energy demand for domestic and vehicular cooling will overtake the energy demand for heating.

Freezing does not only refer to refrigeration below subzero temperatures, it also includes the physical alterations of phase change (fusion). Refrigeration by freezing therefore needs to be divided into three stages.

The blue line in Fig. 83 shows the behavior of pure water when its temperature is lowered at ambient pressure. After a temperature drop during the chilling phase the temperature of the water reaches 0°C. Now the vapor pressure of liquid water is equal to frozen water. A continuing removal of heat leads into the latent phase with no further drop in temperature. When all the water is completely frozen a consecutive removal of heat energy leads to further drop in temperature.

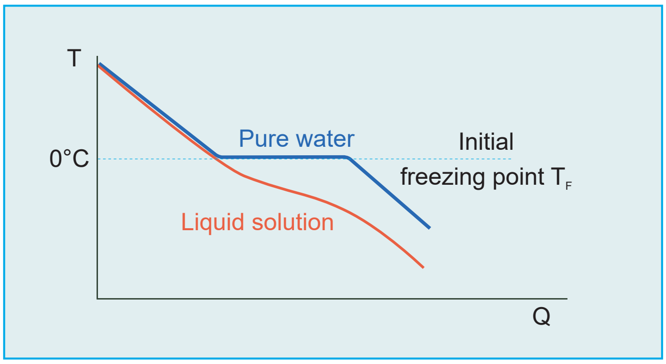


Fig. 83 Freezing of pure H_2O and water content

In food products water is not only present in pure form but also as a mixture with other liquids. The vapor pressure of these liquids is lower, they will not freeze together with water. Their temperature will continue to decrease (red line) without phase change. Actually the more the water portion decreases by formation of ice, the non-aqueous part of the solution will concentrate even further. As a result food products do not a have a sharp point but a zone of freezing that starts with the initial point of freezing, T_F.

The cells of animal and vegetal tissue are surrounded by an extracellular fluid which has a different concentration than the fluid inside of a cell, the protoplasma. To uphold the difference of osmotic pressure the cell walls need to have a certain tension known as turgor (*latin*: bloated). It causes the crispness of fresh fruits and vegetables and the solid appearance of meat.

During freezing the extracellular fluid becomes more concentrated. The drop in osmotic pressure also causes a drop in turgor and the protoplasma can dissipate through the cell walls. This liquid cannot reenter the cells walls and appears as unsightly drip of mushy food during thawing. The formation of large ice crystals with their sharp edges and their volumetric expansion can also damage cell tissue and increase these unwanted effects of **freezing injury**.

Fast freezing can counteract the negative effects of freezing injury to a large extent. The vast freezing of all tissue fluids at the same time can uphold the cellular osmotic pressure and the velocity of freezing leads to the formation of smaller ice crystalls. There are various technical methods for fast freezing used industrial refrigeration.

Blast cooling uses low temperature (-30°C) air as a cooling medium. Temperature exchange happens through forced convection. The food can be stored in stacks or it passes through a forced convection ventilation zone on a conveyor belt.

Immersion freezers use cooling fluids that have better heat conduction properties than air. The food products are sprayed or sometimes even dipped into a mixture of glycol or brine. **Contact freezers** are quite effective and have certain hygenical advantages but their use is mostly limited to flat food products like fish fillets or leafy vegetables.

Cyrogenic freezing uses liquid nitrogen (boiling point at minus 196°C) or carbon dioxide (dry ice) as evaporate cooling mediums. This very effective but expensive technique is often used in combination with other methods.

Larger food processing plants with refrigeration storage very often contain processing rooms. They are used to prepare the commodities for transportation, selection or packaging. Temperature and humidity are controlled to achieve optimal intermediate conditions and also the make it more suitable as a working environment. Temperatures are usually around 15°C. If they are adjacent to cold rooms and freezers they can also serve as a kind of temperature sleuce between cold storage and the outside.

10.2 Thermal Properties of Food

Fruits and Vegetables

Fruits and Vegetables are organic products and will continue with their biotic activity after harvesting. The main indicator for this biochemical process is respiration. Carbohydrates like glucose react with oxygen and produce energy in the form of heat and release water plus carbon dioxide

$$C_6H_{12}O_6 + 6O_2 \rightarrow \text{energy} + 6CO_2 + 6H_2O$$

The higher the rate of respiration, the faster the process of deterioration and decay will take place. Certain factors can influence this chemical process. High **temperatures** increase the rate of respiration almost exponentially until a certain maximum temperature is reached and the plant tissue is destroyed (thermal death). Physical stress like cuts and crushes increase the respiration. Unlike most edible plants, some commodities, particulary tropical and subtropical fruits, can actually increase their respiration when refrigerated.

A **lower oxygen content** (below 2-3%) in the air will decrease respiration while a total depletion of oxygen leads to anerobic conditions which in the long term will cause fermentation and decay. A higher percentage of **carbon dioxide** in the air will have positive effects on some commodities while it can have an adverse impact with other products.

Ripening is the biochemical process that make edible plants more palatable in texture, taste and aroma. Certain fruits and vegetables are **climacteric**, they can continue their ripening process after they have been harvested. **Non-climacteric** fruits and vegetables can only ripen as long as they are still attached to their stem or roots.

Some plants release ethylene gas with their respiration. **Ethylene** can accelerate the ripening process but it can also cause damage to certain commodities. Therefore ethylene producing plants should not be stored with fruits and vegetables that are sensitive to ethylene (see Tab.20).

Tab.20 Characteristics of Fruits and Vegetables

	Respiration (mW/kg)					Ethylene		Climacteric		Optimal storage		
	0°C	5°C	10°C	15°C	20°C	production	sensitive			Temp °C	Humidity	Shelf live days
Very slow												
Nuts	2.4	4.8	9.7	9.7	14.5	none	none		no	2-7	55-70%	180
Slow												
Apples	9	18	25	60	80	high	yes	yes		1-4	90-95%	30-360
Citrus fruits	9	18	36	62	89	very low	moderate		no	7-10	90-95%	7-28
Potatoes	-	15	25	30	60	very low	medium		no	7-10	90-95%	21-270
Moderate												
Banana (green)	-	-	-	90	120	low	yes	yes		20	85-95	7
Bananas	-	-	-	100	200	medium	none	yes		14	85-95	3
Lettuce	35	50	90	120	200	no	yes		no	0	98-100	14-21
Tomatoes (green)	-	-	-	60	100	low	yes	yes		16	90-95	14
Tomatoes	-	-	-	80	120	medium	none	yes		16	90-95	4
Fast												
Strawberries	40	70	200	250	450	very low	none		no	0	90-95	3-7
Avocados	-	-	-	300	600	high	yes	yes		7	85-95	
Very fast												
Mushrooms	100	210	-	-	800	none	yes		no	0	95%	3-4
Spinach	60	150	250	-	660	very low	high		no	0	95-100	10

Meat and Poultry

The core body temperature of an animal is about 39°C but it may be higher after slaughter by induced stress. After dressing, the meat carcasses should be cooled down rapidly to 1-2°C to reduce the risk of bacterial growth. 70% of the meat carcass is water, hence the temperature drop is mainly caused by evaporative cooling which will also lead to a certain loss of salable mass.

Meat muscles consist of tiny muscle fibers bundled in strings and held together by connective tissue. Lesser active muscles near the lower part of the spine (sirloin, filets) are more tender than the active parts like the neck or the shanks.

After slaughter the energy supply to the muscles seizes and the tissue stiffens (rigor mortis). Fresh meat should not be frozen before rigor mortis has passed. After 12-36h an enzymatic reaction sets in and tenderizes the muscle tissue again.

This process can be continued for several days when the carcass is kept at 2°C. For long term storage meat must be frozen as fast as possible to avoid freezing injury. Meat carcasses with an internal temperature between -1 and -4°C can be stored around a week. Long term storage requires deeper temperatures (see Tab.21).

Tab.21 Recommended storage times for frozen meat in weeks

	Beef	Lamb	Veal	Pork	Poultry
-12°C	4-12	3-8	3-4	2-6	1-3
-18°C	6-18	6-16	4-14	4-12	12-24
-23°C	12-24	12-18	8	8-15	

Poultry can be stored for a week when cooled at -2°C. Long term storage requires requires freezing temperatures of -18°C. The body temperature of a slaughtered chicken lies around 30°C. Most regulations require to cool down poultry to 4°C in a time between 4-8 hours depending on their weight.

Poultry is suspectible to bacterial contamination like salmonella and liquid refrigeration methods can require desinfection of the fluid medium (chlorination). Properly packaged poultry can be stored for one year when frozen below -17°C. Insufficient humidity for long term storage can cause freezing damage by dehumidification. Frozen poultry meat does have a tendency to turn rancid.

Dairy products

In the early days of mankind milk consumption by humans was limited to nurture infants by breastfeeding. Adults did not have the ability to produce lactase, an enzyme that is necessary to digest milk. Through a genetic mutation around 8,000 years ago, the human body started to produce this enzyme. With the exception of some Asian cultures, milk and dairy products have become one of the most essential food commodities.

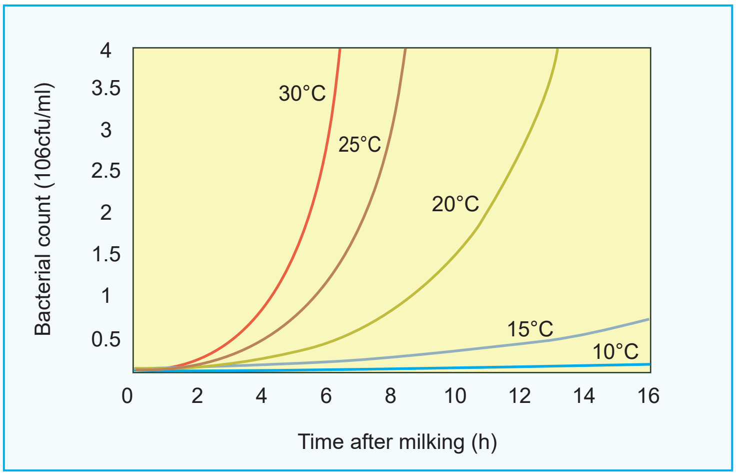


Fig. 84 Bacterial growth in fresh milk

Milk is a butterfat water emulsion with dissolved carbohydrates, proteins, lactose and minerals. The fresh raw milk fat content of the predominantly domesticated ungulates (*lat. ungula* hoof) like cows, sheep and goats ranges from 4-8% depending on their feed and keeping. The highest fat content of land mammals comes from reindeer (18%), baby seals get fed with milk of almost 50% fat content.

Fresh raw milk contains several antimicrobial agents that prevent bacterial growth for a limited time right after milking. But being a substance of high temperature (36°C), high water activity and nutritional source make milk a perfect breeding ground for pathogens. The health condition of the cattle, the hygenical conditions during milking and a warm climate can accelerate these negative effects (e.g. mastitis).

To ensure safe conditions for further use, raw milk needs to be cooled down to 4°C within 3 hours after milking. When brought to another location the maximum temperature during transportation must not exceed 10°C. When refrigeration storage temperatures can be kept below 4°C, raw milk can be stored for up to one week.

Fish

Fish is a highly perishable commodity and needs to be preserved immediately after catch. At temperatures between 0-2°C fresh fish can have a shelf life of 1 to 2 weeks. The requirements depend on the type and size of fish. Large fish are usually eviscerated which enlarges the cooling surface.

An effective and very common way to preserve fresh catch is icing. Granular ice is made in auger drums and can be produced in different sizes ranging from micro ice or fine ice to macro ice or flake ice which consists of flat, thin ice plates suitable for layering.

A sufficient quantity of ice provides good surface contact for heat exchange and more space between the fish bodies. Ice storage vessels should have drainage, so meltwater which carries blood, bacteria and slime can rinse off. It also avoids refreezing and the formation of ice lumps when temperatures can not be kept at a stable level.

For ice production both freshwater or seatwater can be used but both should come from relatively clean sources. Seawater ice has the advantage that its melting point is a around -2°C (depending on its salinity) so the lantent heat transfer of fusion takes place at the same temperature as the freezing point of fish.

Frozen fish should be kept at a temperature around -20°C. Then it can have a shelf life of a year or longer. Some fatty fish types like mackerel can turn rancid when frozen. They should be used for other types of long term preservation like pickeling or smoking.

11 SOLAR POWERED COOLING

11.1 AC Compressors

Hermetic compressors for small commercial and domestic applications are usually powered by single phase alternating current (AC) motors. Since single AC phase can only generate a pulsating but not a rotating electromagnetic field, a phase shifted auxillary winding is need to initiate the rotation of the motor. The three access terminals for the main and the auxillary coil windings on an AC compressor casing are labelled with the letters C (common), S (start) and R (running).

RSIR - Resistance Start Induction Running

The auxillary starting winding is made of thinner wire and has fewer turns. Thus having a lower inductance the auxillary coil has less phase shifting than the main winding. Once the initial torque is created the starting winding is disconnected by a current relay or a PTC (positive temperature coefficient) switch. RSIR compressors have a low starting torque (LST) and are used in smaller refrigerators (240 Watts) with capillary tubes where a pressure equalization takes place in the system before startup.

CSIS - Capacitor Start Induction Run

Similar to RSIR this motor uses a capacitor in series to the starting winding to create an initial phase shift. CSIR have a high starting torque and are commonly used in larger refrigerators up to 500 watts. Once the motor is reaching its rated speed, the starting capacitor is switched off from the circuit.

CSR - Capacitor Start and Run

CSR or CSCR motors have a capacitor in the starting cicuit and in the running circuit. After the run-up is reached, the starting capacitor must be turned off by a switch or a relais. They have a high starting torque (HST) and are used for larger refrigerators and air conditioning systems (3.5kW).

PSC - Permanent Split Capacitor

After run-up the capacitor and the starter winding stay in the circuit for normal operation. PSC motors are used in lager applications and air conditioning systems (3-5kW). No starter relais or switch is needed and it can be used in systems with capillary tubes or automatic regulator valves (TXVs).

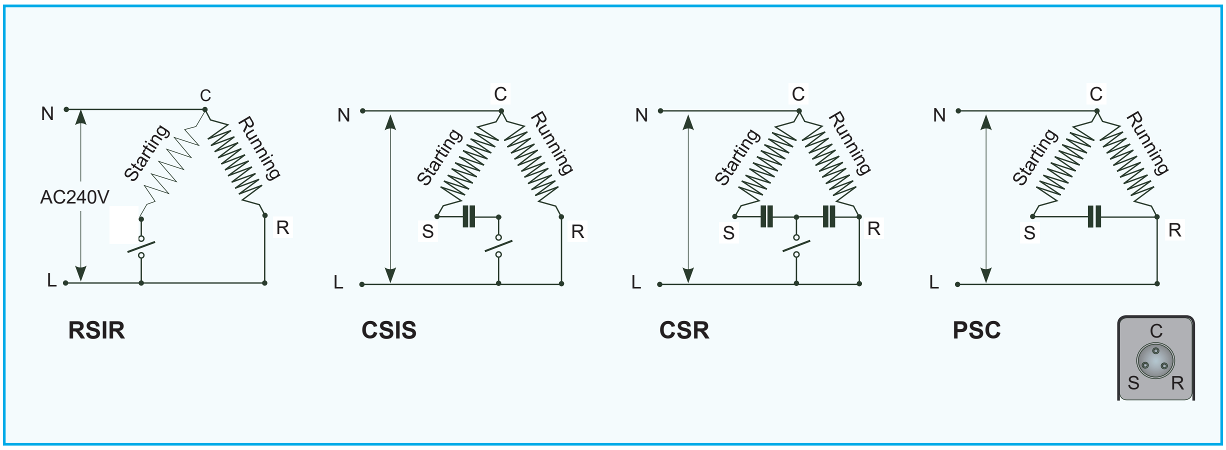


Fig. 85 Start and running coils in AC compressor motors

11.2 AC Compressor Control

The majority of the almost 1.5 billion refrigerators and freezers used worldwide for domestic and small commercial applications are controlled by a mechanical thermostat switch (Fig. 86). A sensing bulb which is usually attached to the evaporator plate is connected to a capillary tube that leads to a diaphragm inside the thermostat switch box.

The whole tube is filled with alcohol. A rise in temperature leads to an expansion of the fluid causing the diaphragm to move downwards towards a lever. The lever mechanism closes an electrical contact and the compressor of the refrigator starts to run.

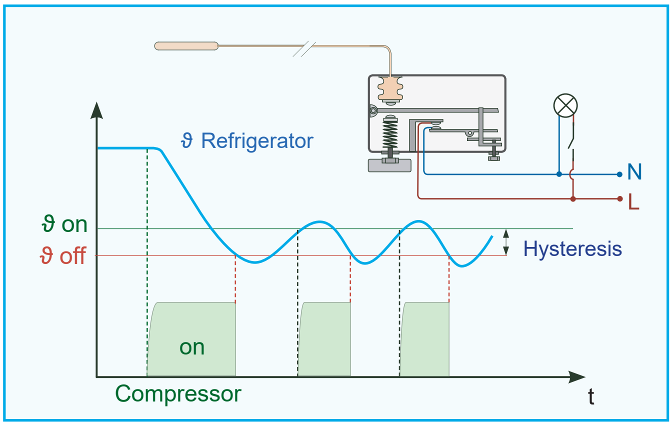


Fig. 86 Thermostat switch to control cooling circuit

The graph shows the initial start of a cooling process. The temperature inside the fridge is around room temperature. The compressor will start and run as long as a certain set point, the cut-out temperature (e.g. -6°C) is reached. At this temperature the decreasing volume of the capillary fluid will retract the diaphragm causing the lever to open the electrical contact. The compressor will stop the cooling cycle.

Depending on the thermal insulation of the refrigerator, how often the door is opened and how many uncooled items are added, the refrigerator will be able to keep the low temperatures for a certain time. When the temperature level rises above a defined point, the cut-in temperature (e.g. +2°C), the thermostat will start the compressor cycle again.

Different cooling ranges (e.g. -6°C to +2°C or -13°C to -5°C) can be set by an adjustment knob. In order to avoid a too close on and off switching (tacting) the thermostat must have a sufficient temperature difference between the two setpoints (hysteresis).

Some thermostats have an additional knob where the hysteresis can be changed. Parallel to the thermostat, an indoor light with a seperate door switch can be connected to the circuit.

Common refrigerators can only regulate their temperature control by this on-off setting of the thermostat. Once the compressor has started it will rotate at a fixed speed determined by the frequency of the utility grid (50-60 Hertz).

Since the compressor will always run at that speed, additional cooling load will increase the input current and therefore electrical energy consumption. VCC (variable capacity compressor) refrigerators use variable frequency drives that can adapt the compressor speed to the cooling load.

11.3 AC Refrigerators and PV Systems

When an AC motor is connected to the grid voltage, the copper coils of the stator basically react like a short circuit creating a high current flow, called **inrush** or **surge currents**. These surge currents might be ten times higher than the nominal current ratings.

A 200 watt motor can create starting currents of 10 Amps with an apparent load of 2.4kVA or higher. Insufficient pressure equalization in the refrigerant circuit can also lead to a surge of the starting current.

Off-grid PV powered stand-alone systems generally have a DC/AC inverter as their central unit, so common AC household appliances like lights, televsion or PCs can be used. These low power consumer units usually do not have any surge currents.

The user manual or the specifications of the AC inverter should provide information how much peak currents the unit can provide for a defined time period (Table in Fig. 88). A common AC domestic refrigerator with starting currents will require a stronger inverter that can handle these power surges.

Smaller inverters usually cannot handle the large flux caused by high currents because their magnets will go into saturation. Including a common domestic AC refrigerator into a PV stand-alone system will require a high power AC inverter while all other AC consumers could go along with a smaller inverter. This increases the initial costs of the whole system significantly.

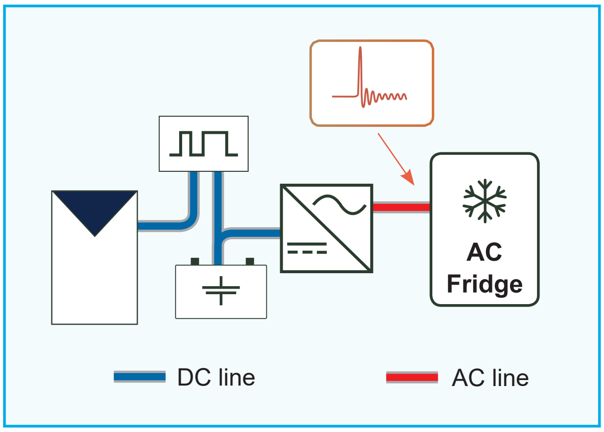
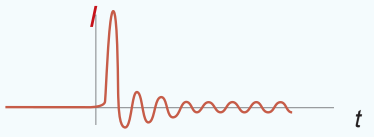


Fig. 87 PV system with DC/AC inverter



Inverter peak currents	
Power 5sec.	21kVA
Power 30sec.	10kVA
Continous power	5kVA

Fig. 88 Example for inverter surge capabilities

11.4 Brushless DC Motors

The motor drive covers more than 30% of the costs for a compressor. This and the increasing worldwide demand for cooling led to the development of new efficient compressor technologies like brushless direct current (BLDC) compressors.

BLDC motors create their alternating magnetic induction by electronic commutation. Over an IGBT transistor bridge, the coils of the stator are alternately energized to produce a constant torque. In order to trigger the transistors in the right sequence, the logic control needs to permanently receive information about the position and speed of the rotor e.g. by a Hall sensor.

One common method that requires no additional magnet and sensor installation is the zero crossing detection by back EMF measurement. Brushless DC motors show a high efficiency across their whole operating range (rpm) which makes them very suitable for Solar applications.

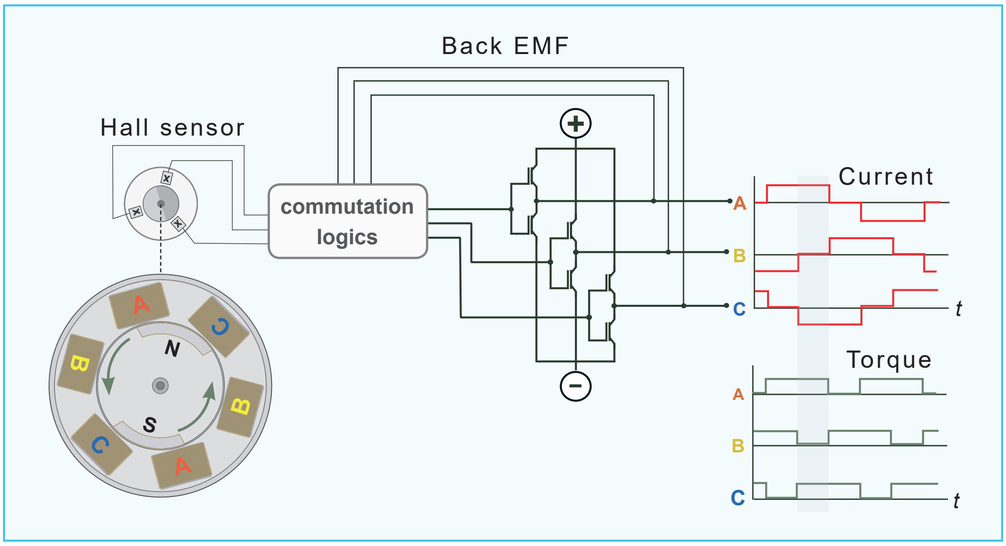


Fig. 89 BLDC Motor with electronic commutator control

11.5 Electronic Control Unit

The three current pins of the BLDC compressor are connected to the socket of the commutator unit. The power supply of the commutator can either come from a 12/24V battery or directly from a PV panel with a maximum open circuit voltage of 40V (60 cells). The appropriate program with temperature and voltage levels can be uploaded via EPROM with an insertable SD memory card.

The control unit receives its cooling parameters by the three temperature sensors. T1 for the product load, T3 for the evaporator temperature. The temperatures from sensor T2 are also logged but its use is optional (e.g. inside or ambient temperature, ice accu packs etc.). The cooling programs are designed to run a Solar PV powered refrigeration unit. Compressor speed, cut-in and cut-off temperature thresholds are mainly oriented on the charging levels of the battery bank.

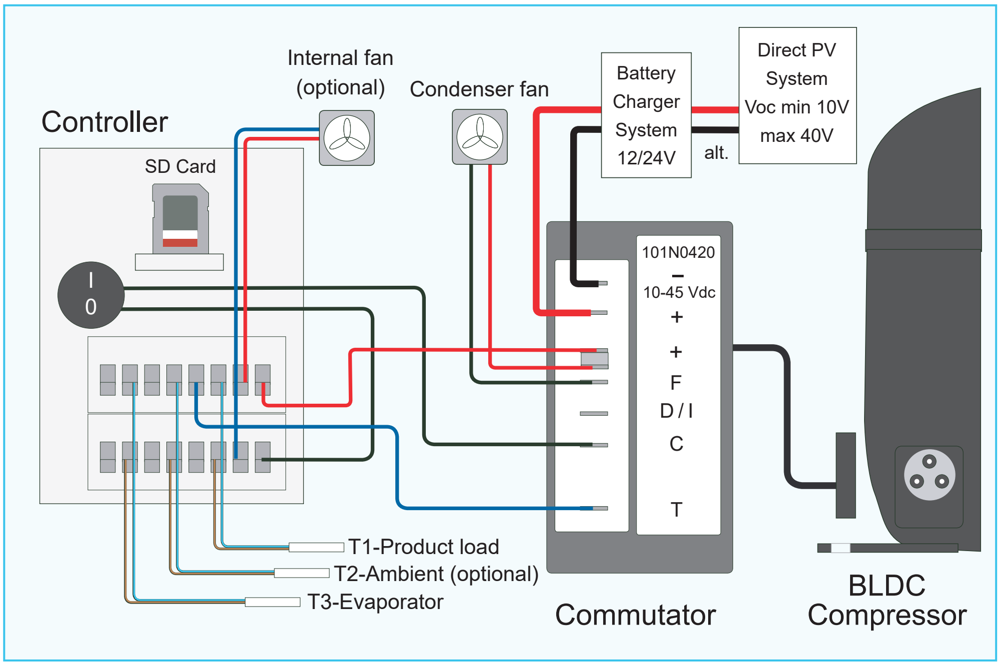


Fig. 90 Electronic control compoments of a DC compressor

11.6 EPROM Cooling Program

Fig. 91 shows a typical preset program for the cooling unit. A battery voltage of 12.7V or above equals maximum compressor speed and therefore maximum mass flow of refrigerant and maximum cooling performance. When the temperature sensor T3 logs a product temperature of 1°C, the system would have reached its cut-off temperature. Assuming that 1°C is the required temperature to keep the product on its best storage, the unit will try to supply enough cooling to keep this temperature.

When the voltage level drops below 12.7V (e.g. during nighttime) the system would go into efficiency mode not exceeding 3,500 rpm. After a further voltage decrease below 12.2V the system automatically turns into energy saving mode. 11.7V is determined to be the low cut-off threshold to shut down the compressor. The remaining battery power will only support the control unit until the PV panels will start to recharge the battery.

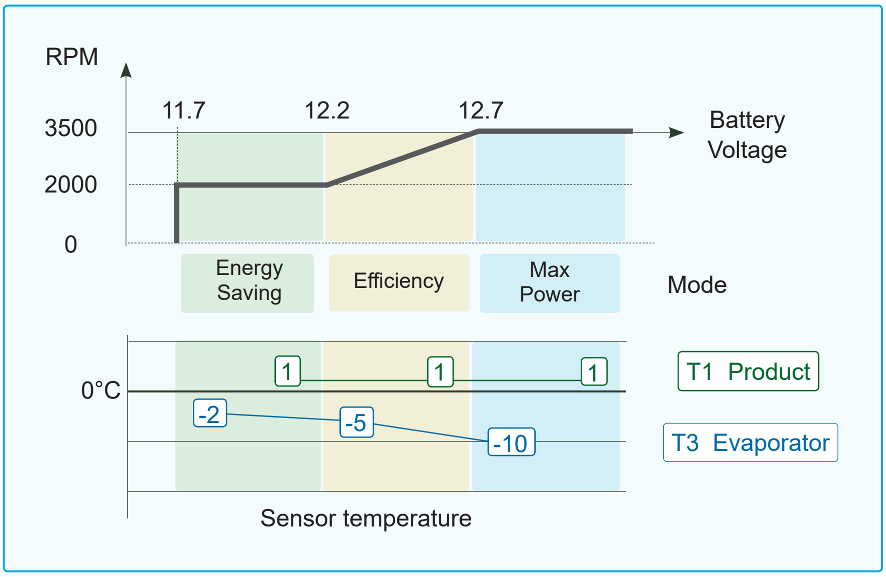


Fig. 91 Temperature controlled compressor voltage level

11.7 PV System Configurations

The possible configurations how a BLDC cooling unit can receive its electrical power from a PV system are shown in Fig. 92. In the frist option a charge controller forms the central unit of the system. Some MPPT controllers can log and compare the consumer discharge together the PV charge and determine an individual state of charge program for battery management.

Charge controllers of larger PV system very often do not have a designated output for consumer loads since it is based on the assumption that all loads will be AC units and therefore receive their power from an inverter. In this case the DC cooling unit must be connected directly to the battery and hence low discharge protection and battery management soley depend on the controller of the cooling unit. Some DC compressors have an extra inbuilt rectifier. Then the cooling unit can be connected to the AC power supply of the inverter (dotted magenta line).

The last graph shows the most economical option which is a direct connection of a PV panel with a DC cooling unit. The controller of the DC compressor must allow this connection and caution must be made not to exceed the maximum input voltage (V_{OC} max).

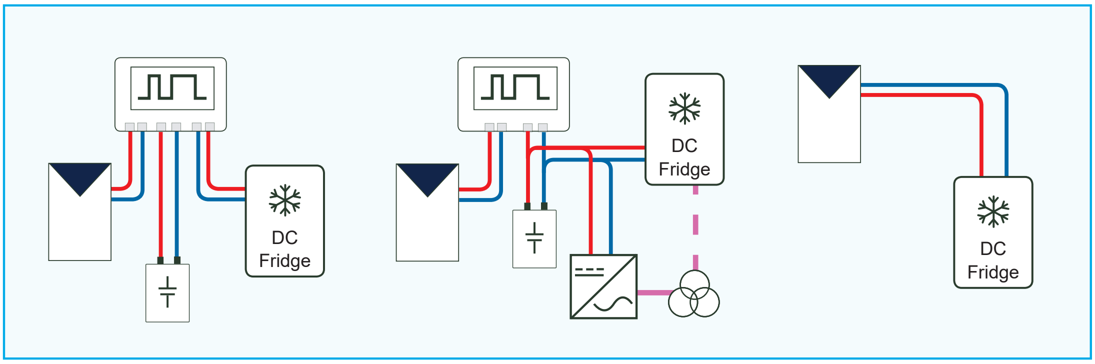


Fig. 92 Configuration of a PV stand alone system and a BLDC cooling unit

12 ENERGY STORAGE

The possibility to consume Solar energy throughout the whole day and night requires some sort of electrical energy storage. Lead acid accumulators are still the first choice for Solar systems. They represent a reasonable cost-performance value and are very reliable when kept in good maintenance. Coming rom the portable electronics and the e-mobility market, Lithium-Ion batteries are now entering the renewable energy realm as well. For a safe and efficient operation Li-ion cells require to a certain degree some kind of a battery management system. Electrochemical cells can store energy in a chemical form and release it as electrical energy. To raise their capacity and voltage output, cells are stacked up in series, hence the name batteries.

Primary cells are non rechargable batteries because the chemical reactions that lead to a flow of electrons disintegrate the cell materials. **Secondary battery** cells can be recharged, thus they are also referred to as accumulators (lat. accumulare: to heap). A battery cell always consists of two electric poles (electrodes). When connected to a load, the closed electrical circuit triggers the internal chemical reaction and electrons are being drawn from the positive side (chem. oxidation, loss of electrons) to the negative side of the cell (*chem.* reduction, gain of electrons) and leave the cell through the electrode which is called **anode** (“electrons go **A**way”).

The positive pole where the electrons are returning from the load is called the **cathode** (“electrons **C**ome in”). Since the terminology is determined by a discharging cycle this always applies to primary batteries. For secondary batteries the designation changes during recharge since the flow of electrons reverses. Inside the cell, electrons leave from the negative pole (oxidation) to the positive pole (reduction), from there the voltage source (e.g. the PV module) draws the electrons from the plus pole making it the anode. The electrodes return into the cell via the negative pole making it the cathode.

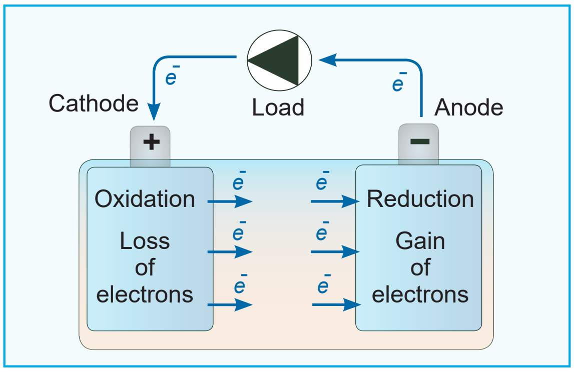


Fig. 93 Discharge cycle of a battery cell

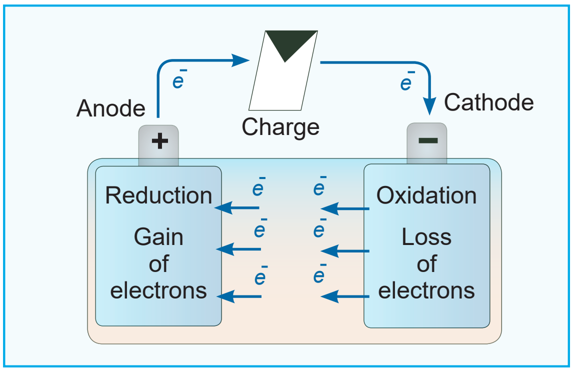


Fig. 94 Charging cycle of secondary batteries

12.1 Lead Acid Batteries

A lead acid accumulator cell consists of two plates. Lead oxide (PbO_2) paste pressed into a polymer grip plate forms the negative anode and a grid plate with sponge lead (Pb) as the positive cathode. Between the plates, separators of perforated isolation material prevent a short circuit but allow dissolved ions to pass through.The plates are stacked up into an acid proof containment which is flodded with an electrolyte, a mixture of distilled water and sulfuric acid (H_2SO_4).

The lead electrodes react with the sulfuric acid. Positively charged hydrogen ions and negatively charged sulfate ions create a charge separation. When an external consumer is connected, the accumulated electrons are drawn into the circuit creating an electrical current. One byproduct of this reaction is lead sulfate ($PbSO_4$) that builds up as a layer on both electrodes and another one is H_2O. The fluid mixture of a discharged battery contains more water and the acid concentration of the electrolyte drops.

One lead acid cell has a nominal voltage of 2 volts. The voltage between charge and discharge varies between 1.8 and 2.4 volts. Six 2 volt cells connected in series form a 12 volt battery (Fig. 97)

Putting a higher voltage potential on the outside terminals recharges the battery and reverses the chemical process. Lead sulfate dissolves from the lead plates and the acid concentration of the electrolyte mixture goes up again. The charging and discharging of a battery is called a **duty cycle**.

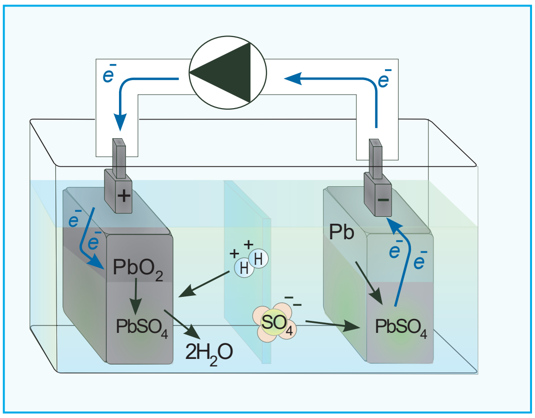


Fig. 95 Discharge cycle of a lead acid battery

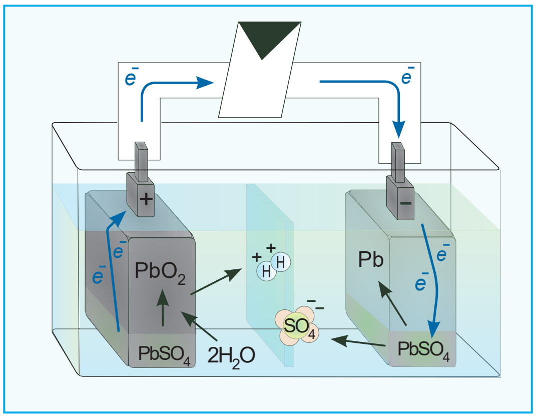


Fig. 96 Recharging of battery by a PV panel

12.2 Functional Classification

Starter batteries represent the largest product type of lead acid accumulators. They have to supply a high current (up to 1,000A) for a short time range. This can be achieved by a high number of relatively thin sheet plates (large surface = high current). The ability for high peak loads minimizes the duty cycle stability. A starter batterie that is continously discharged for more than 50% will reduce its life time significantly.

Traction batteries are used as a primary energy source for the propulsion of short range vehicles. In forklifts their weight can be used as counterbalance to lifting loads. They must be leak proof and resistant against vibration.

Stationary batteries are used as energy back-ups of UPS (Uninterrupted Power Supply) in hospitals or power stations and as an energy storage for off-grid signal and communication units. If they are designed as **deep cycle batteries** their average discharge level is at 50% or even lower. The internal design of deep cycle batteries consist of thicker electrodes to increase energy density, more space between the electrodes and room on the bottom of the battery so lead sulfate debris can accumulate.

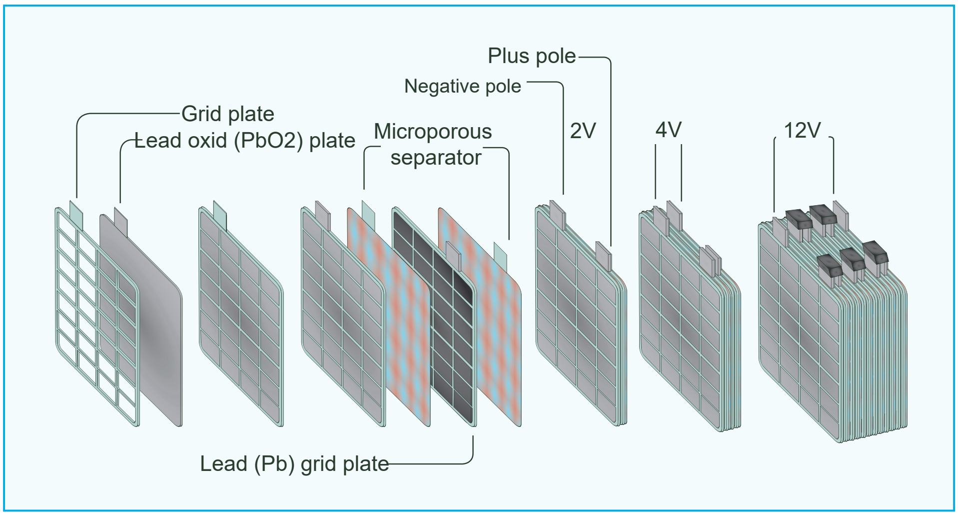


Fig. 97 Alternating lead oxide and lead plates form a rechargeable lead acid battery

12.3 Constructional Classification

Lead Accumulators with Liquid Electrolytes

Compared to starter batteries, accumulators for Solar applications are built with more solid lead plates and a weaker acid concentration of the electrolyte fluid. This extends the batteries life and increases the cycle stability. Exceeding the terminal charging voltage can liberate hydrogen (electrolysis of water). Together with oxygen it forms a highly explosive gas. Therefore good ventilation of battery rooms should always be provided and the lugs on the terminals must be secured tightly (spark prevention).

Occassional gasing, on the other hand, can stir up the electrolyte mixture and prevent the separation of water and acid. Because of the vaporization, open lead acid batteries must be periodically refilled with destilled water.

AGM-Accumulators

Absorbed glass matt (AGM) or valve regulated lead acid (VRLA) batteries are sealed accumulators. The electrolyte is absorbed in a fiber glass matt separator. These batteries are spill proof and can be stored in slanted positions. Oxygen and hydrogen that forms at the plates can recombine to water in the structure of the glass matts. Because of their solid construction, sealed batteries can use a higher acid concentration allowing higher capacities.

Gel-Batteries

The electrolyte is dissolved into silica dust forming an viscous gel. They are also spill proof and the gelified electrolyte is resitant to shock and vibration which qualifies them as traction batteries. They have a long life cycle and are more resistant to temperature changes. The closed construction does not allow any water refillment which is normally not necessary when used in a correct manner.

OPsZ Tubular Plate Accumulators

These low maintenance, long life cycle stationary battery types are used for bigger UPS back-ups like telecommunication and utility systems. Tubular electrodes consist of pasted flat plates divided by porous separators for insulation. They are also equipped with vent plugs and acid level indicators. Tubular accumulators have a better cycle stability and a higher life span which justifies their use in professional systems despite their high initial costs.

12.4 Cycle Stability

A cycle is defined as a discharge and recharge process of an accumulator. Manufacturers recommend a maximum **depth of discharge (DOD)** of 50%. According to Fig. 98 a battery with such a DOD has around 500 duty cycles. A smaller depth of discharge would prolong the lifetime of the battery.

The **cycle stability** defines how often a battery can be charged and discharged until its capacity underruns a certain value. Usually the life span of a battery is reached when it can only provide 80% of its nominal capacity. The accumulator is still fit to use but after this point the capacity will drop further and chances for a complete failure or a short circuit are more likely.

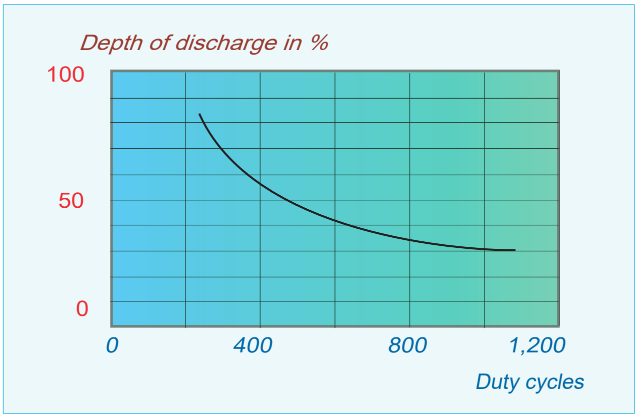


Fig. 98 Depth of discharge and battery life

Battery Capacity

The capacity of a battery defines how much energy can be stored in an accumulator. If the voltage of a battery system is not specified, the capacity can be given in Watt hours (Wh). Once the system voltage is defined, the capacity usually will be determined in Ampere hours (Ah). A 12V battery with 100Ah equals 1,200Wh. Batteries are chemical systems and therefore their discharge and charging performance are always time dependent. The C-rate or capacity rate defines a nominal charging or discharging current over a specified period of time.

Fig. 99 shows the real capacity available from a 100Ah battery. Since maximum DOD should be 50% actually only 50Ah are available. Most manufacturers will give C/20 as their nominal capacity rating since it usually provides an efficient discharge rate. In that case C/20 means the battery will only provide an average current of 5A. Larger battery banks in parallel configuration can handle bigger loads with a C20 rate. But a small battery with a high load of C5 or even C1 the nominal capacity of 100Ah will drop to a real life value of 35Ah.

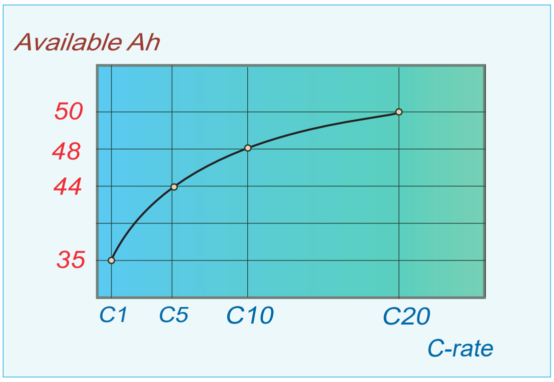


Fig. 99 Usable capacity of a 100Ah battery

Battery capacity	C-rate	Discharge time	Discharge current	50% DOD discharge time
100Ah	C/20	20hrs	5A	10hrs
	C/10	10hrs	10A	5hrs
	1C	1hr	100A	1/2hr
	2C	1/2hr	200A	1/4hr

Note: Quite often the divison slash is omitted and C/20 is written as C-20 or C20 or stated as a factor (0.05).

This loss of capacity is mainly due to internal heat losses caused by the higher discharge currents. Battery data sheets should provide the information about available capacity at various C-ratings. Eventual discharge load spikes are of course possible. C relates to the average discharge rate.

Ambient Temperature Influence

Discharge and charging currents will generate a certain amount of internal heat but under normal conditions the ΔT should not exceed more than 10% of the ambient temperature. Excessive heat generation can be a sign of malfunction like short circuiting.

Extreme ambient temperatures can also negatively influence battery performance and its lifespan. Low temperatures will decrease capacity output. Freezing caused by excessively low sub zero temperatures can damage a battery especially during discharge (water content in the electrolyte). Higher ambient temperatures can even increase capacity output but continous exposure to heat will shorten the battery life.

Solar charge regulators should compensate charging voltages for ambient temperatures. A temperature sensor as closely as possible attached to the electrode will provide reliable values for the charge algorithm. If the Solar charger contains a proprietary temperature sensor, charger and battery should always be installed closely together under the same ambient conditions. Peak voltage for constant current stage and float voltage should always be compensated for temperature.

Worst case scenario for a battery malfunction could be thermal runaway. A rise in temperature decreases internal resistance and thus leads to an increase of charging current creating a positive feedback loop. Recombination of oxygen at the negative electrode can even further increase exothermic heat generation which can lead to damage or even explosion of the battery.

Self Discharge

A lead acid battery that will not be charged for a longer time period discharges itself. Starter batteries are more prone to be damaged by this effect. Solar batteries should not loose more than 5-10% of their capacity per month by self discharge. Deep temperatures slow down the effect. A temperature raise of 10°C can double the rate of self discharge.

Accumulators are voltage sources. They have a small internal resistance (in series) and their output voltage stays constant even when the load changes its resistance (Impedance bridging $R_i << R_L$).

Voltage sources are not short-circuit proof. Batteries should therefore always have an overload fuse protection. Old batteries with a high internal resistance can not provide high currents and loose their capacity rapidly. The connections of batteries underlie the same principles of series and parallel circuits. All connected accumulators must be by the same make and model and have the same capacity and charging level. Replacements should be at least by the same type and have equal nominal values.

13 SOLAR CHARGE CONTROLLER

The charge controller is the central equipment in a PV stand-alone system. The quality of its battery management system (BMS) will have a significant influence on the lifetime of the battery bank. Low budget controllers for smaller PV systems should have at least the following features:

Blocking Diode

Basically a 12V accumulator can be connected directly to a 36 cell panel. Though at night time the PV panel would act like a consuming semiconductor and discharge the battery. A blocking diode built in the circuit can avoid a reverse current. Schottky diodes with small dissipation losses are regularly integrated in charge controllers.

Overcharge Protection

Series controllers have an integrated transistor that disconnects the plus line of the PV generator when the end of charge voltage is reached. The gate of the transistor draws a constant current from the battery which results in a permanent power dissipation. With a totally discharged accumulator the transistor can not receive the necessary gate current to switch on the generator again.

Parallel- or **shunt controllers** do not disconnect the power line but open a bypass line that short circuits the generator. Low cost chargers are usually two point controllers i.e. they work with on-off control. When the battery reaches the terminal voltage level the regulator disconnects the power line to the generator. When the voltage of the battery drops below a minimum level the line will be switched on again.

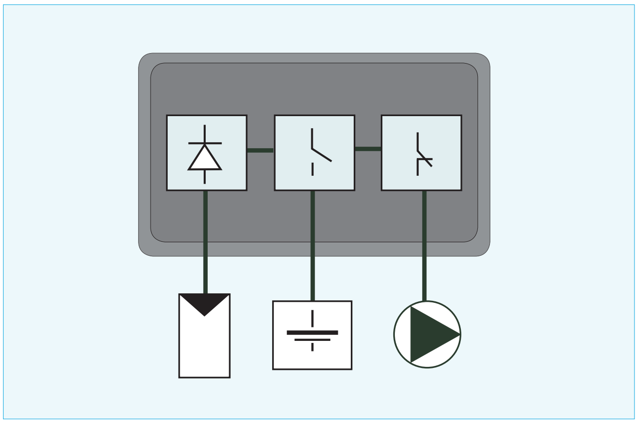


Fig. 100 Mandatory features of a Solar charger

System Voltage

Small panels with 36 to 40 cells are dimensioned for 12V accumulators. Bigger stand-alone systems can be operated with DC currents of 24 or 48 volts to reduce current load.

If a charge controller can be connected with more than one battery voltage level (e.g. 12/24V), the charge regulator should be connected first with the battery and not with the generator in order to detect the correct system voltage. Some regulators can be set to the appropriate system voltage by a switch or in the program setup.

Deep Discharge Protection

When the battery level drops below a critical voltage, the controller must automatically disconnect all consumers to avoid irreversable battery damage. The difference (Hysteresis) between on- and off-point is approx. 1 Volt.

13.1 PWM Controllers

Pulse width modulation (PWM) chargers can decrease the current output by choping up the power signals into a series of modulated on and off cycles. Once a battery reaches full charge, the PWM controller can gradually reduce the charge current.

Once the battery is topped up, the PWM provides a controlled amount of continous power inputs to keep the charge level. Since the PWM acts like a direct switch between the PV panel and battery, the maximum voltage level will always be determined by the momentary voltage of the battery.

13.2 Maximum Power Point Tracker

Since Solar radiation and panel temperature permanently change, maximum power point trackers (MPPT) contain a microprocessor controlled algorithm that continously scans the V/I curve of the PV generator for its maximum power point (P=V×I). By adjusting its internal resistance to the momentary MPP, full PV power can be transferred.

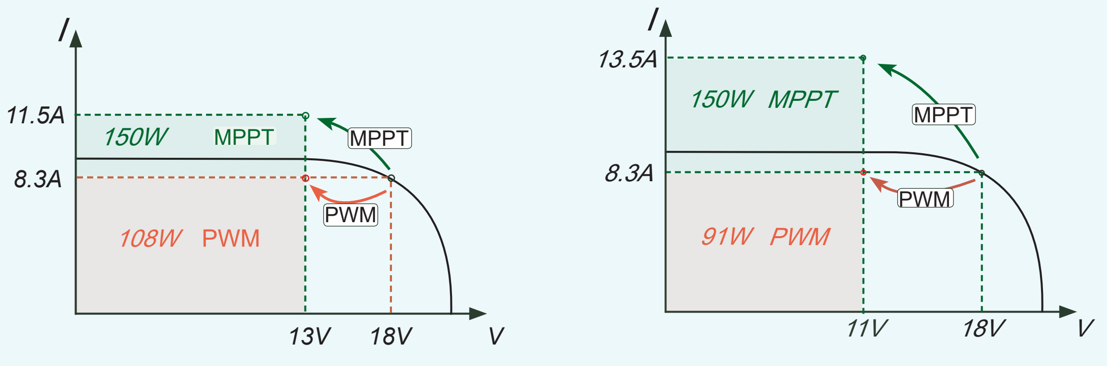
Electronic switching by an inductance (buck-boost converter) adjusts the voltage and current for an optimal charging cycle. Power consumption of MPP trackers is higher than of PWM chargers and MPP tracker do need a certain PV voltage level above battery voltage to initiate their charging cycles.

13.3 PWM vs MPPT

Fig. 101 shows the power loss of a PWM system caused by the draw down of the battery voltage level. The MPP charger will always be able to transfer a maximum of the PV yield by impedance matching.

With a fully charged battery (left) and a relatively small voltage difference (18-15=5V) the PWM charger will loose less than 30% of the available PV power.

But in the case of discharged battery (right) when the demand for power is imminent, mismatching can cause a power loss of almost 60%.



Highly Charged Battery 13V			
Modul	18V	8.3A	150W
PWM	13V	8.3A	108W
Factor		1.38	
MPPT	13V	11.5A	150W

Low Charged Battery 11V			
Modul	18V	8.3A	150W
PWM	11V	8.3A	91W
Factor		1.63	
MPPT	11V	13.5A	150W

Fig. 101 Different PV yields of PWM and MPPT charge controllers

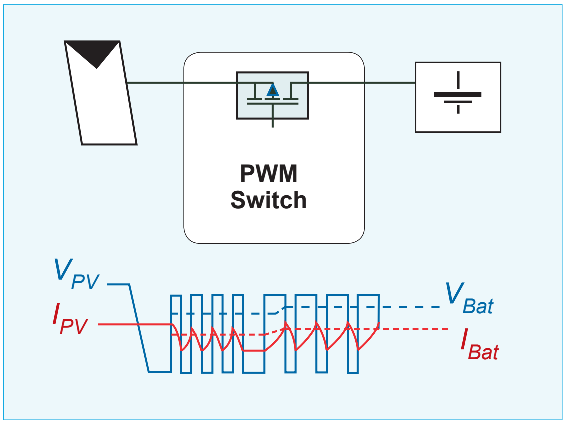


Fig. 102 Pulse width modulation solar charger

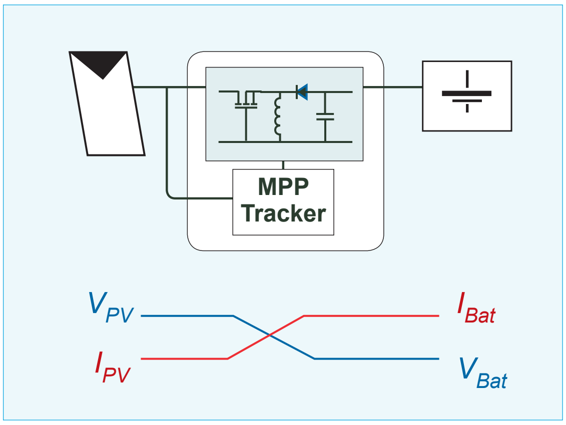


Fig. 103 Maximum power point tracker

13.4 Battery Management System

Advanced charge controllers contain programmable algorithms that can factor in for type, size and age of a battery. Batteries are chemical systems and therefore time dependent. A battery management system (BMS) logs the charging and discharging time spans to calculate state of charge and cycle life of a battery.

Discharge

Low cost charge controller refer to the battery voltage for a load disconnect to protect the battery from a deep discharge. When there is not enough PV yield for a full charge, the capacity of the battery will start to cycle between partially loaded and fully discharged. If this takes place over a longer time period, it can dimish the lifespan or even damage the battery.

Advanced charge controllers with a proprietary battery management system can adapt to this condition by gradually increasing the load disconnect voltage level until the PV yield is high enough to charge the battery as close as possible to a 100%. This procedure can be repeated periodically within a specified time range (e.g. once a week).

13.5 Charging Cycles

Bulk Stage

In this first stage also known as Boost stage, the battery receives a constant current (CC). The amount of charging current should be defined in the battery specs but a safe rule of thumb is a maximum of 10% of the battery capactiy (10A for 100Ah). During the CC phase the battery voltage will continously rise until the maximum voltage is reached. Depending on the type of lead acid battery, this value can go beyond 14V but the gassing voltage should be the terminal upper limit. At the end of the bulk phase, the battery should be charged by 80%.

Absorption Stage

During this phase (also known as topping stage) the voltage is maintained at a constant level (CV) while the current gradually tapers off to approximately 1-2% of the full capacity (1-2A for 100Ah). The absorption stage completes the charging cycle which is finished when the current falls below a mininal threshold (tail current) or when a programmed time is over.

Some solar chargers calculate the length of the absorption stage dependend on the length of the bulk stage. A shorter bulk stage can indicate a rather full battery and therefore the absorption stage with its high voltage level can be shortened as well.

Float Stage

The battery is completely charged and can provide full capacity. Optimal voltage level is reached and the chemical recombination process on the plates has taken place. Any additional current would now be turned into heat and gassing.

Float stage voltage is lower than the constant voltage of the absorption stage but the battery requires a certain amount of voltage input to maintain its full charge and compensate for self discharge. The current level is usually below 1% of the battery capacity. If no discharge of the battery happens, some charge controllers reduce the battery voltage even more from float to a standby mode.

Equalization Mode

Some battery manufacturers recommend occasional equalization stages when batteries remain in a longer standby mode. Equalization is a limited controlled overcharge with a constant current that helps to remove sulphate crystals from plates and prevents stratification (fluid separation) in flooded batteries.

Equalization stages can be programmed by a certain time interval (e.g. once every 180 days) and the current is limited to a certain percentage of the bulk current. Equalization stops when a certain time limit (e.g. 1 hour) or a defined voltage level is reached. Battery specs should indicate if equalization is recommended for the specific accumulator type. It is not required for VRLA (AGM/Gel) batteries.

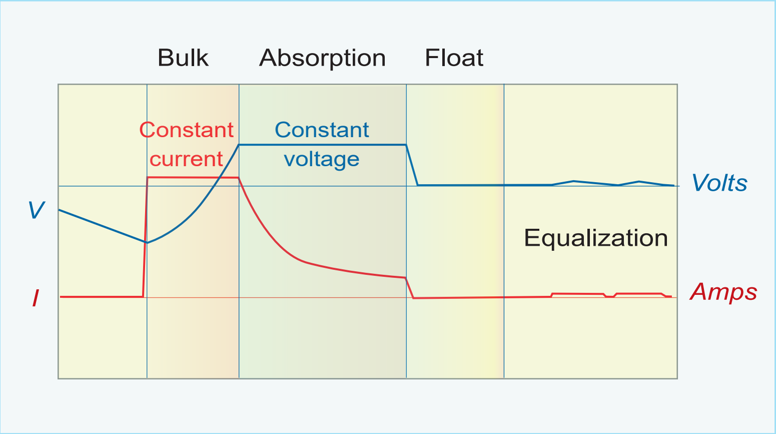


Fig. 104 Three main stages of a battery charging cycle

14 LITHIUM BATTERIES

Lithium (*chem. symbol* Li) is the lightest metal and also the lightest solid element having half the density of water. It has the highest electrochemical potential of all elements, meaning it has a strong tendency to loose its outer electron. Therefore Lithium is a highly reactive and flammable element. The term lithium battery applies to various types of accumulators that use lithium as their active electrode material.

14.1 Lithium Metal

Lithium or lithium metal batteries use lithium in its metalic form as the negative anode. Because of the high reactivity of lithium with water, non-aqueous liquids or solids (e.g. polymers) are used as electrolytes. The cathode contains various types of oxydants like manganese oxide.

With a few exceptions lithium metal batteries are primary (non rechargeable) batteries. During discharge, the metal structure of the lithium anode desintegrates.

Because of their high energy density and long battery life, lithium metal cells are used for medical applications (pace makers), high-end technical, military and small electronic equipment (button cells).

Lithium metal batteries have a cell voltage ranging from 1.5 to 3.7V and their high energy density is also provided in low, subzero temperatures. They have a low self discharge rate and are supposed to have a shelf life up to ten years.

The advantage of lithium is also its biggest downside. The high reactivity of the material and the energy density of the battery poses a potential fire hazard. Lithium batteries underly certain transportation and travel restrictions relating to their lithium content (grams), their capacity (Wh) and form of cell packaging. Additonally they can also develop a decaying phenomen known as dendrites. Small crystaline structures that can grow on the surface of lithium metal electrodes. Their sharp edges can pierce separator layers and cause short circuits.

14.2 Lithium Ion

Lithium ion batteries (Li-Ion or sometimes LIB) contain no free metallic lithium. Instead lithium atoms are present in the molecular structure of a metal oxide that forms the cathode of the cell. An aluminium plate adhered to the metal oxide layer serves as a current collector. The opposite anode side of the battery is made of a graphite layer with a copper plate as current collector.

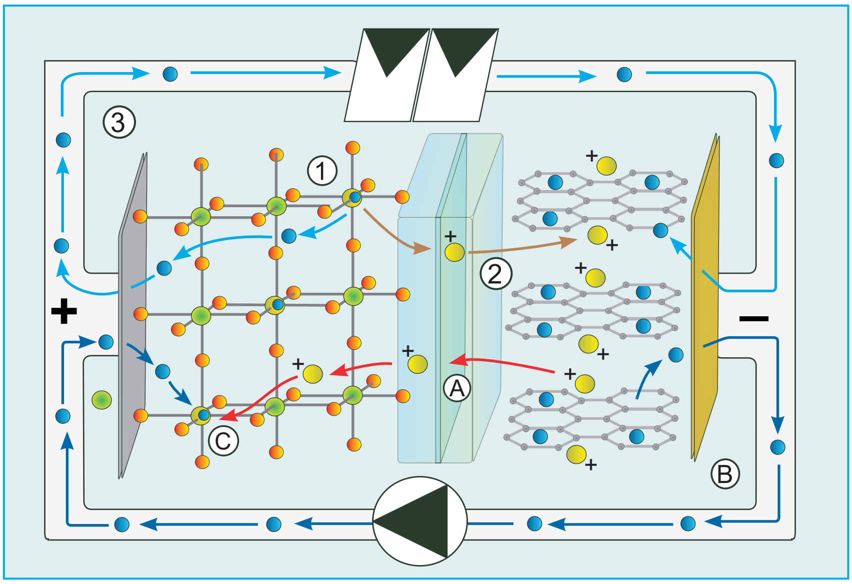


Fig. 105 Charging and discharging process in a Li-Ion battery

When an electrical charge like a PV module is connected to the battery, the lithium atoms in the anode get ionized splitting into positively charged lithium ions and a negatively charged electrons (1). The lithium ions now pass through a non-aqueous electrolyte (2) into the graphite layers.

The electrolyte also serves as a separator. The micro porous layer poses a barrier for the negatively charged electrons. Instead, the electrones are drawn towards the external PV circuit (3) to the anode where they can also intercalate into the graphite layer. When all lithium ions have migrated into the graphite layer, the battery is fully charged.

During discharge the reverse process takes place. The lithium ions are drawn back through the electrolyte (A) while the electrons can pass through the external consumer circuit (B). Both particles reunite in the molecular structure of the lithium metal oxide (C).

Construction

One major cell type are **cylindrical tubular cells**. Electrodes, separator and conductor foils made as thin sheets are rolled up around a hollow core and then placed into a sealed, pressure resistant metal case cylinder. Li-ion cylinder cells have numeric classification code. The very popular 18650 cell has a diameter of 18mm and a height of 650mm. One cell has a nominal voltage of 3.7V with 3,400 mAh. The metalic cylinders can be connected in parallel and seriell battery packs for their required battery capacity. For a 89kWh EV battery 7,104 cells are stacked in a series of16 modules with 74 cells in parallel.

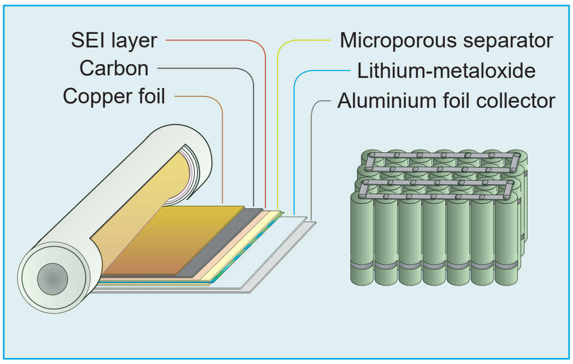


Fig. 106 Li-Ion cylindrical cell and battery stack

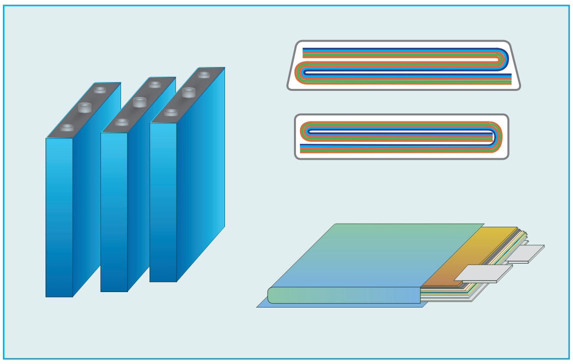


Fig. 107 Prismatic cell and pouch cell forms

Prismatic cells are encased in a solid rectangular enclosure. The sheet foils are thightly packed in a jelly roll or z-folded manner. They can be easily connected as series or parallel battery stacks. Prismatic cells can have a similar size classification as cylindrical cells e.g. a 103450 has a thickness of 10mm, a width of 34mm and a length of 50mm

In the pouche cell (sometimes coffeebag cell), the sheet foils are stacked in alternating layers and sealed into a expandable aluminium foil. The light enclosure improves the energy density (Wh/g) and facilitates heat dissipation. There are no standards for pouche cells and some manufacturers pack the cells in a second enclosure to enhance their rigidity.

14.3 Electrolytes

Liquid electrolytes are composed of a mixture of lithium salts and an organic, non-aqueos solution. Battery cells with liquid electrolytes need a robust, impermeable and seal tight enclosure but the complete immersion and wettability of the electrodes provide a favorable ionic conductivity and they have a reasonbly low cost production.

During the first charging cycles a layer of decomposed solute materials builds up on the graphite and forms a protective layer. Lithium ions can still pass through this solid electrolyte interface (SEI) layer but it protects the electrolyte from further decompostion. In time SEI layers can increase their thickness growth which leads to an increase of internal resistance and a decrease of free lithium ion movement.

Solid state electrolytes (SSE) have no leakage issues and do not need tight sealed enclosures. Therefore they offer a wider range of possible manufacturing designs and a better thermal, mechanical and electrochemical stability. But their production is still difficult and cost intensive plus their ionic conductivity is still much lower than their liquid counterpart, mainly caused by the poorer interfacial contact area between solid materials. SSEs can be made of inorganic materials like ceramic oxides or solid state polymers which consitst of a solvent salt solution in a polymer host material or a mixture of both ceramic and polymer composites.

Lithium polymer batteries (**LIP**)with **gel polymer electrolytes** (**GPE**) can be seen as a kind of hybrid form between SSE and liquid electrolytes with the aim to combine the advantages of both types i.e. , rigidity, stable thermotolerance and good ion conductivity.

Internal Safety Features

The safety and reliability of lithium ion batteries can be problematic if they are not handled appropriately. Besides the general system control of an external BMS (see chapter 14.5), most Li-Ion cells have additional internal safety features. Positive temperature coefficient (PTC) semiconductors can block excessive current flow by raising their internal resistance. Protection circuit boards (PCB) offer short circuit and overcurrent protection. Current Interrupt Device (CID) is a fuse disk that ruptures the circuit when the internal cell pressure or temperature exceeds a safety limit. CIDs interrupt the current flow permanently, while the electronic safety features usually reset themselves automatically.

14.4 Li-ion Cell Types

The type of metal oxide which is used as a carrier material in the cathode usually determines the name of the Li-Ion cell e.g. LMO stands for Lithium Manganese Oxide. Tab.22 shows a comparison of the prevailing lithium ion cell types. Since the momentary world market orientation for LIBs is concentrated on electrical vehicles, energy density (kWh/kg or kWh/l) is a dominant criteria.

This might not be as important for stationary Solar applications where weight and volume are not as crucial as cycle life and charge characteristics. Lithium Iron Phosphate Oxide ($LiFePO_4$) tend to be the number one choice when it comes to stand-alone applications, mostly because of their fast charging and deep discharge capabilities, their long life span and relatively stable chemistry compared to other LIB types.

For the time being recycling of old lithium batteries is not really existant but in some countries there are “second life” programs. Once the lithium batteries have expired their capacity for electric vehicles, they can still be re-used as stationary energy storage units.

Tab.22 Most Common Li-Ion Cell Types

Li ion Type*	Nominal voltage	Energy density Wh/kg	Charge rate to 4.2V	Discharge rate cut off at 2.5V	Cycle life	Thermal runaway
LCO	3.7	180	0.7-1C	1C	500-1,000	150°C
NCA	3.6V	150-260	0.7C	1C (cut off 3V)	500	150°C
NMC	3.7	150-200	0.7-1C	1-2C	1,000-2,000	210°C
LMO	3.7	100-150	0.7-1C	1C (ev.10C)	300-700	250°C
LFP	3.2V	90-125	C/2-4C (3.7V)	1C (ev.300C)	1,000-3,000	270°C

*Lithium Cobalt Oxide (LCO), Nickel Cobalt Aluminium Oxide (NCA), Nickel Manganese Cobalt (NMC) Lithium Manganese Oxide (LMO), Lithium Ferro/Iron Phosphate (LFP)

14.5 BMS for Li-ion Batteries

For a safe and efficient performance, Lithium Ion batteries require an electronic charge and discharge control unit known as battery management system (BMS). In general the algorithm of a BMS uses three measurements inputs, temperature (ΔT) voltage (V) and current (I) to determine the batterie's **state of charge** (**SOC**) and the **state of health** (**SOH**).

Fig. 108 shows the charging regime of a LiFe battery cell. The initial stage is at a constant current (CC) until 80% of the capacity is reached. Then the mode changes to a constant voltage (CV) of 4.2V. This is the upper limit of the charging cycle while the current continously drops until full capacity is reached.

Unlike lead acid, Li-Ion batteries do not require full charging to maintain their optimal capacity. Partial charging actually expand the number of the battery life cycles (Fig. 109). Another advantage of LIBs is that they can be discharged to a hundred percent of their capacity.

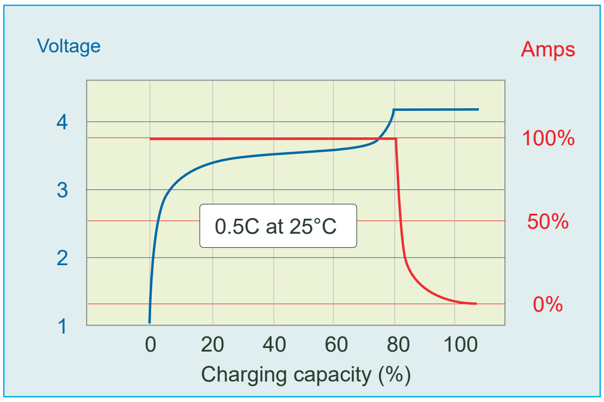


Fig. 108 Charging stages for Li-Ion batteries

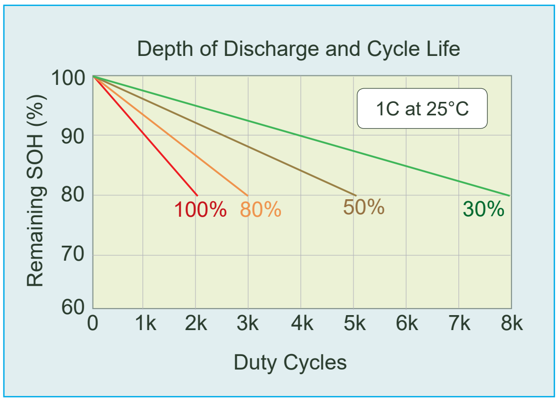


Fig. 109 DoD influence on LIB cycle life

State of Health (SOH) defines how much adversary aging effects (e.g. cell degradation) have affected the batteries abilty to provide energy compared to its nominal (i.e. factory new) condition. Battery management systems can evaluate the momentary SOC and SOH of a battery by logging the total amount of discharged and charged electrical current over time (Ah) also known as Coulomb counting.

Due to variances in the manufacturing process or different life cycle degradation, individual cells of the same battery type can have different voltage levels. Battery packs connected in series with imbalanced cells can loose overall efficiency and a cell with a lower than average voltage level could go into deep discharge during a regular load cycle. Cells with a higher charge could be damaged by overcharging or even go into thermal runaway because they would exceed their maximum voltage limit before the overall charging process is terminated. Battery packs can be balanced by connecting them in a parallel charging cycle. Larger battery banks should have a BMS (Fig. 110) that can monitor and eventually equalize such cell assymetries by passive (load shedding) or active (load shifting) balancing.

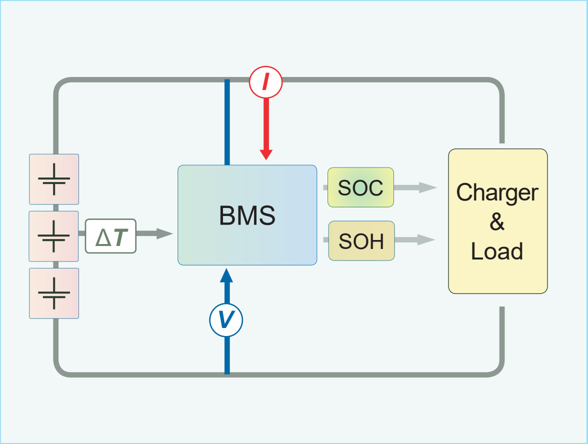


Fig. 110 Battery management system topology

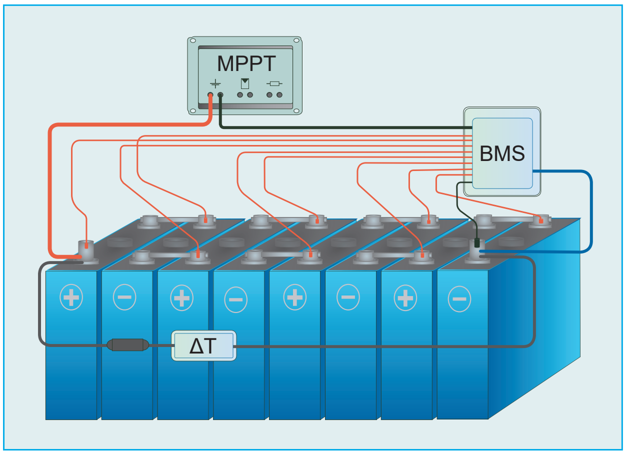


Fig. 111 BMS with individual cell balancing

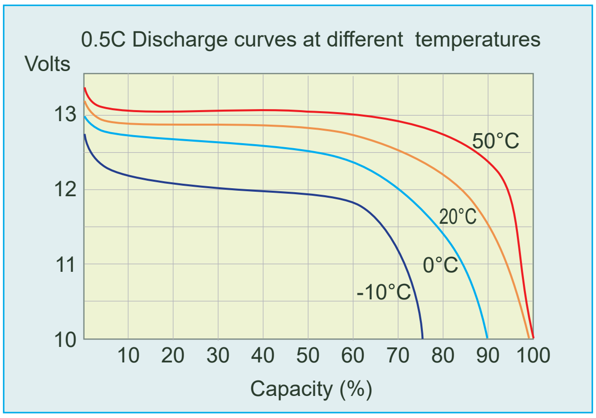


Fig. 112 Temperature influence on LIB capacity

Temperature

LiFe batteries have a broad nominal performance temperature range. Low temperatures increase battery impedance and reduce capacity. Due to a better ion conductivity, LiFe batteries can even increase their capacity output when operating at higher temperatures but exceeding temperature limits especially during charging can lead to battery degradation and reduced battery life. Fast charging above the nominal C-rate contributes to this negative effect.

14.6 Comparison Lead Acid and Li-Ion

Tab.23 shows a final overview comparsion between LFO and lead acid batteries with their main advantages and disadvantages. Technically Li-Ion seem to be clearly ahead though they are more sensitve to extreme temperatures which is one main reason why LIBs always need a functioning BMS for operation. Total cost calculated per power and energy yield show that lead acid are still the more economical solution.

Tab.23 Comparison of Lithium Iron Phosphate with Lead Acid Batteries

	Lithium Ion		Lead acid	
	Pros	**Cons**	**Pros**	**Cons**
Capacity	80%			30-50%
Cost (2019)		8$/Ah 100$/year	1.5$/Ah 70$/year	
Weight	Lighter			Heavy
Cycle life (DoD)	2,700 (80%)			1,700 (50%)
DoD	100%			50%
Full charging	not required			required
Self discharge per month	1%			3%
Battery Management System		Mandatory	Optional	
Temperature range		0 to 45°C	-20 to 50°C	
Recycling		20%	90%	

15 SORPTION COOLING

15.1 Absorption Chillers

Similar to vapor compression, absorption cooling also uses two separate chambers for condensation and evaporation. Water from the condenser pressure (80mbar) is sprayed through an expansion valve onto a hot heat exchanger pipe in the low pressure (8mbar) evaporator chamber. By the sudden pressure drop (close to vacuum) the water evaporates and this phase change draws heat energy from the evaporator pipe and cools the internal medium e.g. chilled water which is the cooling output of this unit.

Instead of a mechnical compressor, the necessary suction is created by a highly hydroscopic (water attracting) concentrated lithium bromide (LiBr) salt solution (64%) which is sprayed into the adjacent part of the low pressure tank and literally sucks in (absorbs) the water vapor. Mixed with the water the concentrated solution now becomes a weaker (less concentrated) solution (59%) and sets as a LiBr-water mixture on the bottom of the tank. This weak solution is pumped up into the high pressure/temperature tank part called the generator.

The task of the generator is to separate the refrigerant (water) from the absorber (LiBr) again. An external heat source brings up the mixture to boiling and will make the water evaporate (desorption). The water vapor can recondensate in the collector side of the condenser while the LiBr will stay at the bottom of the generator as a fresh concentrated absorber solution. Both fluids then separately re-enter the cooling cycle.

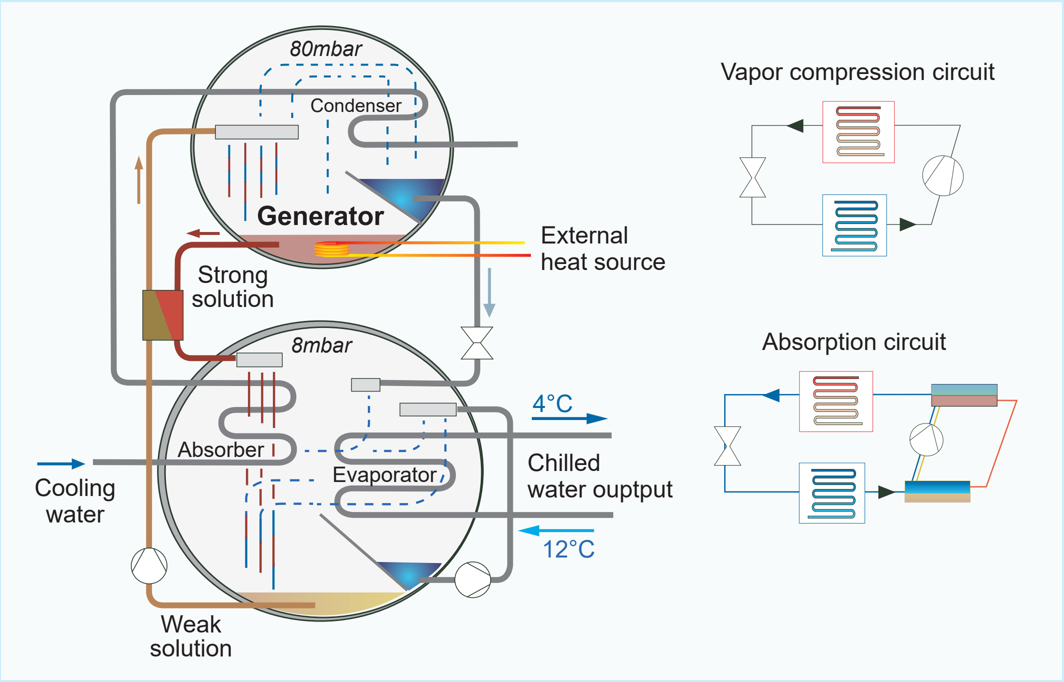


Fig. 113 Absorption cooling circuit

Circuit Pumps

One of the main advantages of sorption chillers is that they do not require a large amount of electrical power for any circuit or compression mechanisms. One centrifugal pump with a low suction height is required to pump the LiBr-water mixture up to the pressure chamber. A second pump recirculates the water that has not evaporated and sprays it back onto the evaporator coil. Smaller absorption chillers (for camping and hotel rooms) can even completely omit any mechanical units by using air lift pumps for circulation.

Heat Exchangers

To improve the thermodynamic efficiency, absorption circuits can incorporate additional heat exchangers. The thermal energy which is constantly drawn from the cooling pipe heats up the low pressure chamber and can therefore be diverted by an additional cooling circuit. This cooling circuit is also used to provide the required cooling in the condenser chamber. A separate heat exchanger draws excessive heat from the concentrated LiBr solution and preheats the LiBr-water mixture before it enters the boiling chamber of the generator.

Absorption systems that use water as a refrigerant reach cooling temperatures down to 6°C. Main applications of these chillers are in the HVAC sector. Temperatures far below freezing can be achieved in absorption systems that use ammonia as refrigerant together with hydrogen as an inert gas and sodium chromate as an inhibitor (against corrosion). Water is used as a solvent.

Ammonia absorption chillers are most commonly used in camping and RV applications. They only require a heat source temperature of 70-120°C which can be supplied by a gas burner (LPG), car battery or grid power.

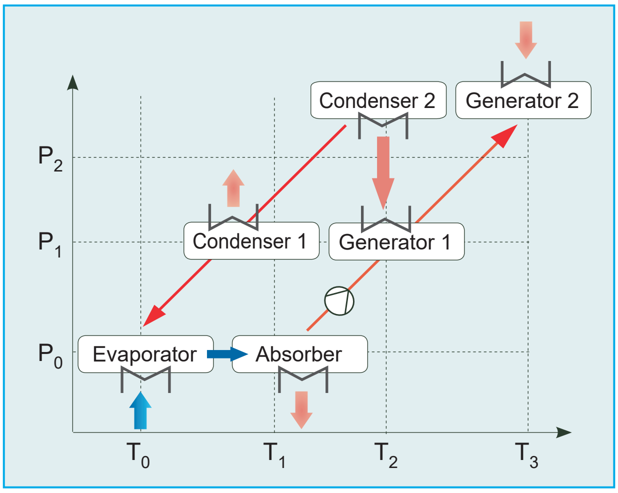


Fig. 114 Multistage absorption circuits

Tab.24 Energy Efficiency Ratio of Sorption Chillers

EER ζ =	Useful cooling output [kW] / Thermal input [kW]
EER Example: Heat input 20kW useful cooling 15kW. EER is 0.75	
Note: Comparsion of Compression COP and EER of sorption chillers is misleading since compression chillers use high exergy and sorption often uses waste heat	

Single stage absorbtion chillers use generator temperatures of 70-90°C with an energy efficiency ratio of 0.7. Double stage absorption systems employ two generator stages where the heat energy from the water vapor in the first stage is used to heat the second stage. High temperature heat sources (110-190°C) can be used more efficiently (EER >1.0) and it also lowers cooling requirements.

15.2 Adsorption Cooling

The main distinction to absorption systems is that **adsorption** chiller use solid sorption materials. The refrigerant is also not drawn into the medium (absorbed) but it **adheres** to the outer surface of the sorbent.

In relation to their volume solid sorbent materials like zeolith or silica gel have a very large, porous structure. The refrigerant water is injected via an expansion valve into the low pressure evaporator chamber. The suction pressure from the zeolith in the adsorber chamber causes the water to evaporate, drawing the required heat energy for the phase change from the cooling coil. The cooling coil provides the chilled water output. Since the zeolith and the water need to be separated again to repeat the cycle, adsorption machines consist of two similar chambers that are both filled with zeolith. While the cooled dry sorbent from chamber A creates the suction that evaporates the water over the cooling coil, chamber B uses an external heat source for the drying (resorbtion) process.

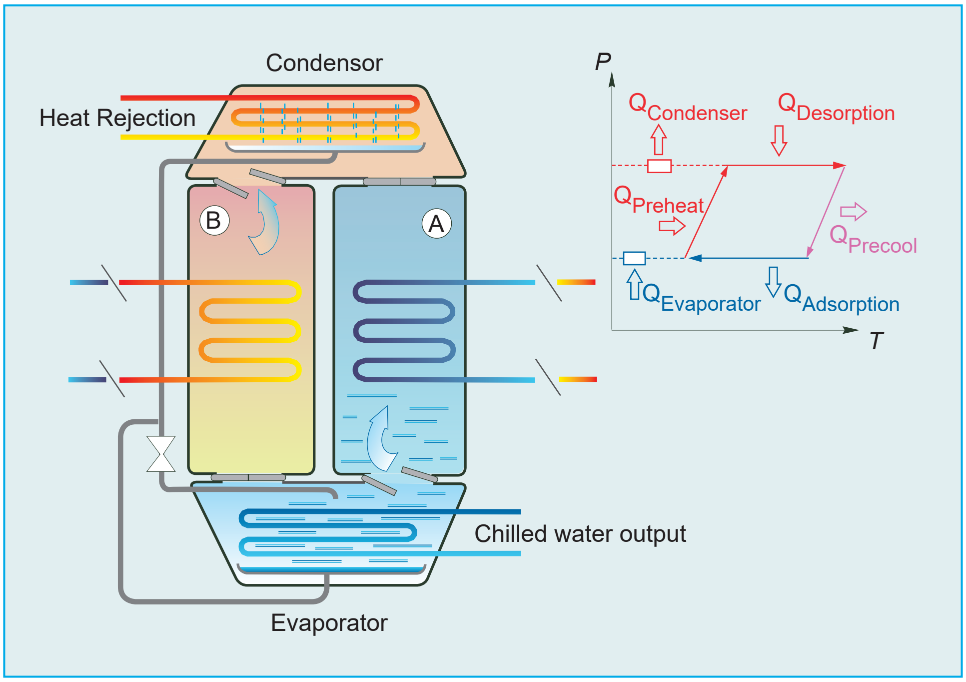


Fig. 115 Alternating adsorption chambers for adsorption and resorption (drying)

The heat causes the water to leave the surface of the sorbent material as steam. The water steam rises up into the condenser chamber were it recondensates on the condenser coil. The liquid water is then directed back towards the expansion valve for the next adsorption.

The flow of refrigerant as steam and liquid is controlled by automated hydraulic valves and flaps between the chambers. The heat exchanger coils in both adsorption chambers can either supply heat or cooling in an alternating cycle. Absortion chillers can already work efficiently with heat supply temperatures of 55°C which makes them suitable for a combination with Solar thermal heat. Another economical area of application for adsorption machines in HVAC is the use of surplus heat (industrial cooling water).

Tab.25	Small mobile absorption chiller	Single stage absorption chiller	Multi stage absorption chiller	Adsorption machine
Refrigerant	Ammonia	Water	Water	Water
Sorbent	Water	Lithium Bromid	Lithium Bromid	Zeolithe, Silica Gel
Cooling Temp	0-10°C	>5°C	>5°C	>3°C
Generator Temp	35°C	75-130°C	110-190°C	55-90°C
Generator Pressure	30mbar	95mbar	3-11bar	60mbar
EER ζ	0.65	0.75	1.32	0.5-0.7
Size	40-80W	15-30,000kW	50-30,000kW	11-12,000kW

16 THERMOELECTRIC COOLING

The charged particles of various conductive materials possess different energy levels (valence). Peltier elements use two different types of semiconductors (Bi_2Te_3 or SiGe). One type is doped with free negative electrons (n-doted) and has a low energy level, while the positively doped (p-doted) type of semiconductor has a higher energy level.

When a voltage is applied, the electrons in the n-doted semiconductor will draw energy, the positively doted holes in the p-doted semiconductors will eject energy (thermocouple with energetic balancing). Both energy transfers happen in the form of heat exchange. The n-doted semiconductor generates a cooling effect while p-doted one will emit heat. Since the maximum appliable voltage for one thermocouple is 0.12V, a number of semiconductors are connected in series (Fig. 116).

The copper contacts on both sides of the Peltier element are covered with ceramic plates to improve the heat transfer. According to the first law of thermodynamics, the ejected heat Q_H is the sum of the heat drawn (Q_L) and the added electrical energy P_{EL}. ($COP=Q_L/P_{EL}$). The detrimental paradox of Peltier elements is that an increase of P_{EL} also increases heat procuced by the electrical current (Q_{EL}). The maximum temperature difference of Peltier elements is 70K. A Peltier cooler under partial load (COP ~ 30%) can reach a temperature difference of 23K, hence a Peltier cooler can reach freezing temperatures.

Peltier elements are used in smaller cooling applications like camping and mobile cooler boxes. An attached ventilator can improve heat dissipation by forced convection. The main advantage of a Peltier system is that the cooling circuit does not require any mechanical parts or fluid mediums. This allows cooling application in very small applications like laser cooling or sensor technologies.

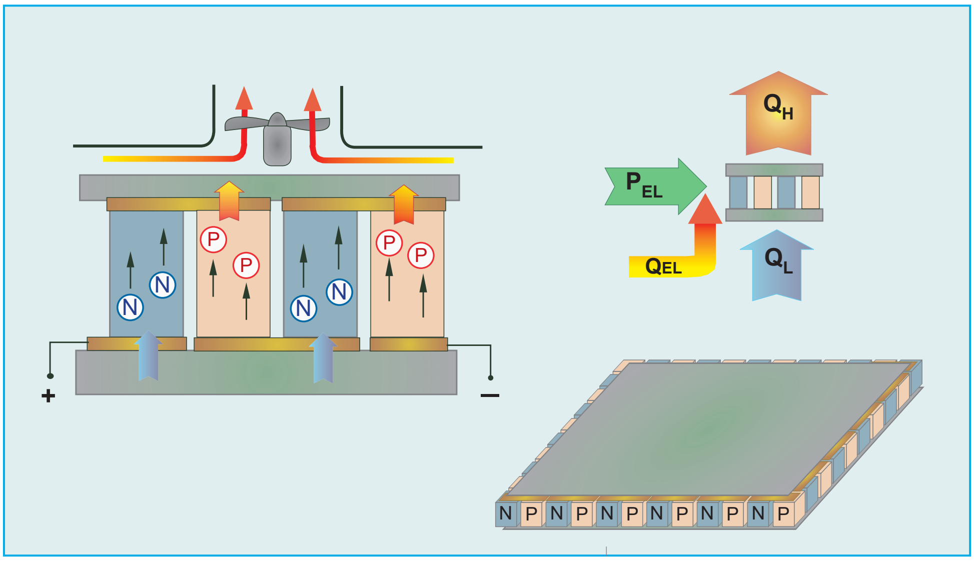


Fig. 116 Peltier elements can generate a cooling effect

17 APPLIED SOLAR COOLING

Battery Charging and Cooling

Battery recharging and product cooling can take place at the same time imposing a double load on the PV battery system (Fig. 117). At early morning hours a fresh batch of product e.g. milk with 28°C is added to the cooling unit. At the same time the PV generator will start to deliver power but the electrical current will be diverted between battery charging and power demand to run the cooling compressor. If the system is well designed both tasks will be accomplished by the Solar charger. The battery will reach full charge around midday and the milk containers will be cooled down to the required temperature (4°C). In the evening hours the cooled milk will be replaced by a second batch of fresh milk. The whole power for the cooling load must now be provided by the battery.

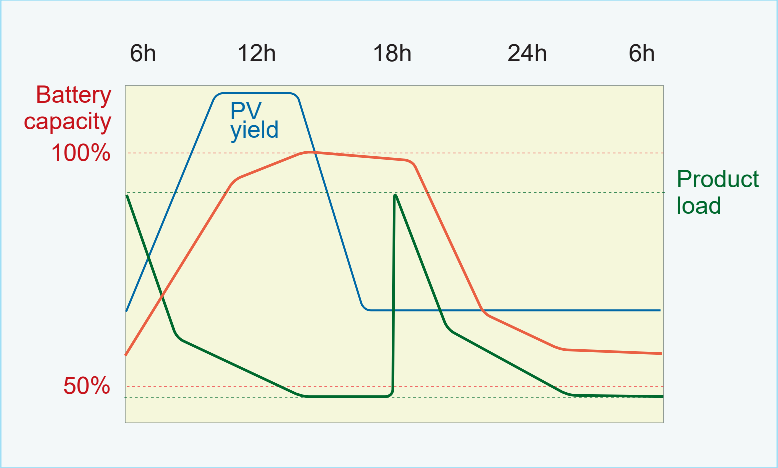


Fig. 117 Simultaneous cooling and recharging times

Bulk mode

The load current for product cooling has to be deducted from the current that is provided by the charge controller. If 50% of the available Solar power are diverted to cool down the product, the bulk charging time can take twice as long.

Absorption mode

If the Solar charger can hold up the constant voltage level for the absorption stage, the required charging current for the battery will go down to a tail current leaving the majority of the PV current for the cooling load. If the cooling load exceeds the capacity of the Solar charger and the charging voltage drops below absorption voltage for a predetermined time length, the charger might jump back into bulk mode.

Float Stage

The charger will show the same behaviour as in absorption mode. It will try to keep the battery at the float set point voltage. But with an exceeding power load, the battery voltage might drop below the set point (float voltage) for a certain amount of time. A new charge cycle could be triggered and the charger could also return to bulk charging mode.

Tab.26 Cooling Load and Battery Charging Log

Time (hh:mm)						
PV						
Voltage						
Current						
Battery						
Voltage						
Current						
State						
SOC (%)						
Cooling Load						
Current						
RPM						
Temp (°C)						

17.1 Cooling Unit Battery Management

Similar to a charger controller, the cooling unit measures the battery voltage to define the RPM settings of the compressor. When the temperature measurement of T_2 (product temperature) is still above the target temperature, the cooling unit will run at its maximum capacity with a compressor speed of 3,500 rpm as long as the battery voltage stays above 12.7V. Between 12.7 and 12.2 Volts the ACU will adapt the compressor speed to the cooling demand. The Adaptive Control Unit will turn off the compressor power and only supply the controlling units when the charge level of the battery drops below 11.7V.

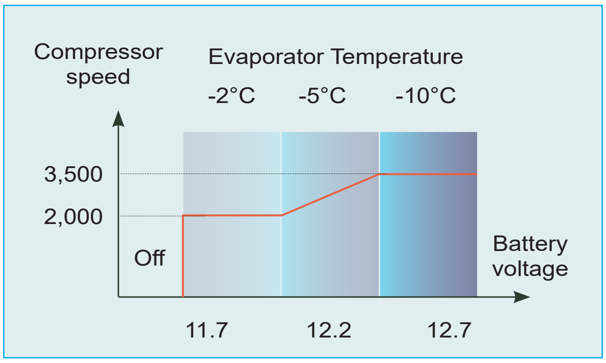


Fig. 118 Battery voltage determines compressor speed

17.2 Cold Rooms

Larger facilities for the storage of perishable food products will start at a size that they can be accessed by a regular door opening. Cold room walls usually consist of prefabricated XPS foam board modules. With a thickness ranging from 60 to 200mm, the polysterene foam is housed between two corrugated sheet metals and can be cut and assembled to the required wall length.

Enthalpy removal from the interior is usually done by a heat exchanger.The product items release their thermal energy to the colder room air. The integrated fan of the heat exchanger forces the warm air over a finned tube coil.

The refrigerant medium which flows through the coil takes up the enthalpy and transfers it to the outside where the heat energy is released by a second heat exchanger. PV powered cold rooms can use the PV generator as an additional shading protection from direct sun radiation. In this case the average ambient outside temperature can be taken for all ΔT calculations.

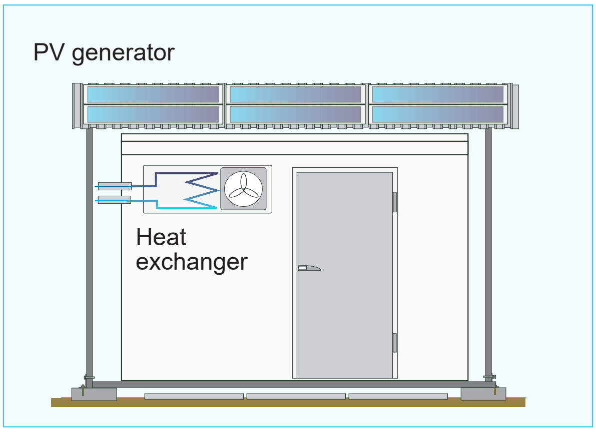


Fig. 119 PV shaded cold room

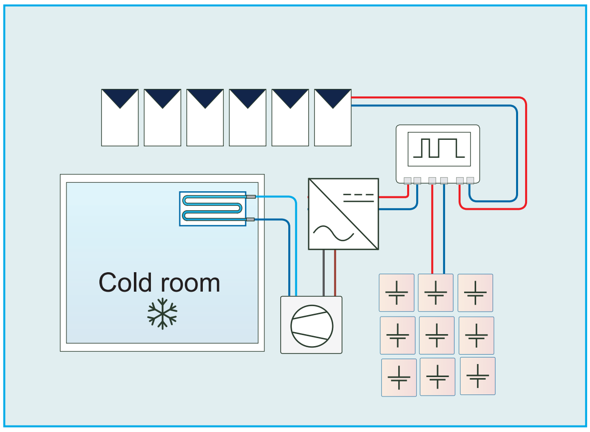


Fig. 120 Conventional PV powered cold room

17.3 Solar PV for Cold Rooms

Fig. 120 shows the topology of a Solar PV powered cooling unit for a small size cold room (20m^3). In this case it is a stand-alone system where the solar power will be the only available energy source. In the late morning hours the solar radiation will reach its peak and the system must now supply enough power for the cooling compressor and at the same time deliver the maximum amount of current to the battery bank for the bulk phase of the charging cycle. Around midday the batteries should be close to their full recharge level. In good weather conditions the sun radiation will still be at peak values for a few more hours. But since the cooling compressor will now also start to decrease its power demand gradually, the rest of the Solar yield for this day will be lost as unusable surplus.

The energy demand even for smaller cold rooms can easily reach into the kilowatt range. Low cost charge controllers and 12V lead acid batteries might not have enough capacity for this power demand. The installation of a large scale inverter to power a 240V compressor (with surge currents) and a stationary 2V battery bank might be necessary. This increases the initial investment costs and also adds up to the long term operational costs.

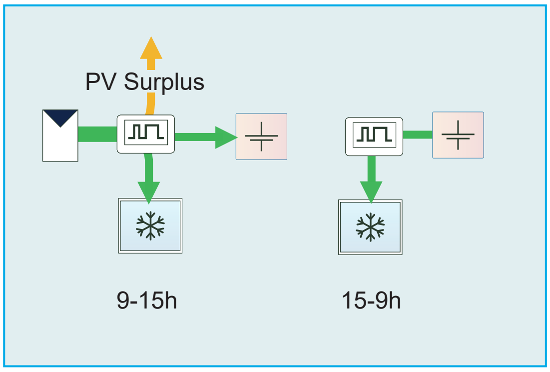


Fig. 121 Current flow of PV yield

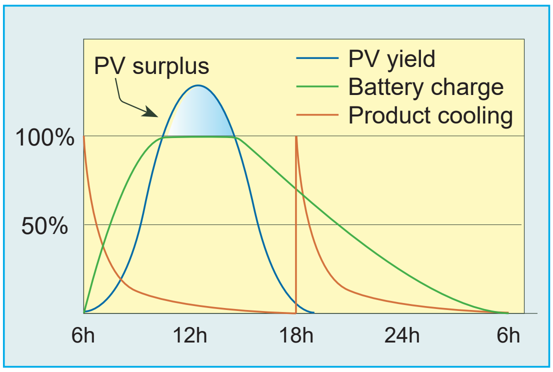


Fig. 122 Unused PV yield during peak hours

17.4 Fusion Enthalpy Energy Storage

An effective and economical solution to fully harvest the daily PV surplus at peak hours is the integration of an additional energy storage method into the cooling system. Water is an excellent heat storage medium and the enthalpy of fusion from a liquid to solid ice has been used a cooling method for centuries.

Fig. 123 shows a DIY construction of an insulated water tank that consists of an intermediate bulk container (IBC) with galvanized steel tubes that serve as a structural holding frame. A box of EPS insulation foam board is filled out with watertight EPDM pond foil.

Such a water tank can hold around 800l of water. Six evaporator plates are completely submerged and provide an extended cooling surface. Since the R600a refrigerant evaporates below the freezing point of water (approx. -10°C) ice will form around the evaporator plates. The liquid water in the tank will also have a temperature near freezing point. Cooling for the cold room is provided by an impeller pump that pumps the cold tank water via a flexible hose to the heat exchanger unit in the cold room.

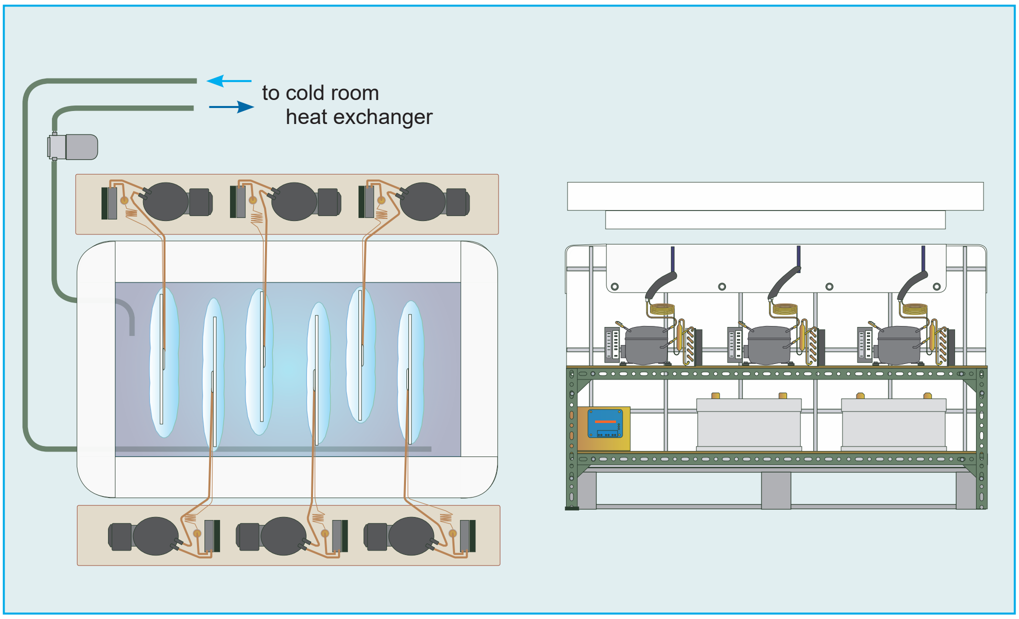


Fig. 123 Ice making water chiller with condenser units and battery bank

Fig. 125 shows the charging topology of the water chiller. During the peak midday hours the maximum bulk current is flowing into the battery bank as well as to power the compressor units of the water chiller. When the main charging of the batteries is completed, the remaining PV yield can flow into the cooling units where the compressors are running at full load producing a maximum possible amount of ice. The enthalpy of fusion stores enough cooling energy to cool the cold room over the night hours. One 70W cooling unit can produce around 25kg of ice per day (approx. 9hrs run time) which equals around 8,000kJ of enthalpy storage.

Another way to understand the efficiency of the system is to see the ice maker as an intermediate enthalpy storage. If the whole PV surplus during the midday peak hours was transfered into cold room the temperature would drop below target temperature. Large day to night temperature fluctuation would be the consequence which could even lead to chilling damage of certain product items. With ice maker the PV surplus can be stored outside of the cold room as enthalpy of fusion over night and probably even longer (reserve days). The electronic control can keep a stable temperature of the stored products by always removing the right amount of enthalpy from the cold room.

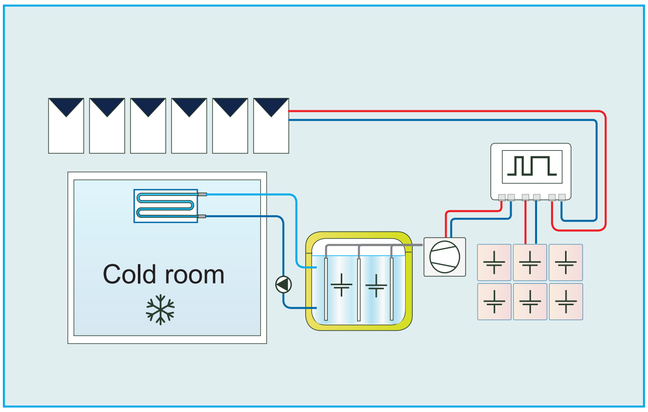


Fig. 124 Integration of ice maker in the cooling unit

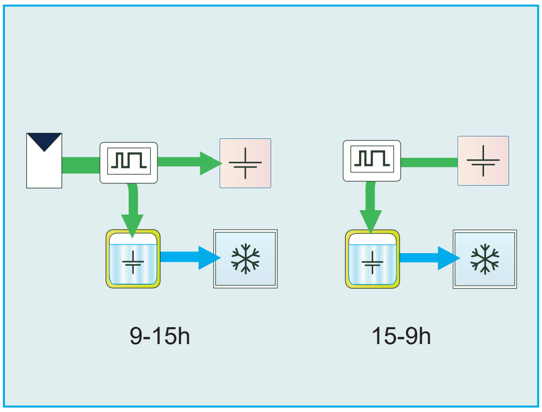


Fig. 125 Energy flow of the fusion ice maker

17.5 Monitoring and Control Unit

The main components and the data flow of the remote monitoring and control unit are shown in Fig. 126 and Fig. 127. The periodical measurements from all temperature sensors are collected by the **thermostat**. The collected data and its connected algorithm results are transfered to the core unit of the logging system, the **Process Control System** (PCS).

The proprietary algorithm of the thermostat unit can calculate enthalpy values and setpoint adjustments can be done for the temperature hysteresis and the target temperatures. After the initial installation all sensors must be calibrated for their correct output.

The PCS can also receive data from the charge controllers if they have proprietary data monitoring features. The Modbus connection from the PCS to the ACU of the condensing units is a two way communication line since the ACU also controls the power output of the compressor pumps.

The third unit in the topology is the GSM modem. Via a SIM card or local network all collected data can be sent to a monitoring platform. The modem can also receive commands for parameter changes like running mode and target temperatures. Power supply for the main control unit comes directly from one of the batteries. The thermostat is supplied via a 5V line from PCS.

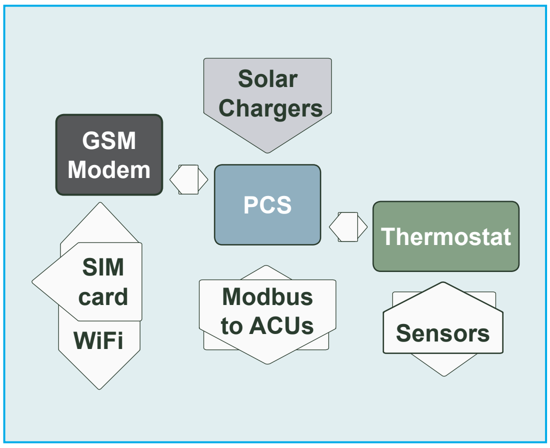


Fig. 126 Data network topology of cooling unit

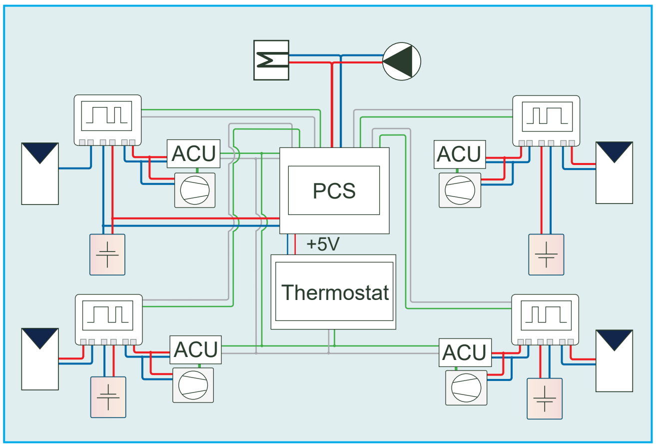


Fig. 127 Power and data connections to the PCS

17.6 Sensor Units

The position of the sensor probes for the cold room unit are summarized in Fig. 128. Enthalpy removal by the heat exchanger can be calculated by the PCS by measuring the flow rate and the temperature difference of the cold water supply ($Q = m \times \Delta T \times c$). Power consumption of the chilled water pump and the heat exchanger fan are measured by an electrical current metering. The door switch can send out an alarm message if the cold room was unintentionally left open beyond a certain defined set time. For an effective and swift control of the food product quality, temperature and humidity sensors are located inside the cold room.

The ambient outside temperature serves as a parameter to determine the cooling load. Together with the temperature of the evaporator plates and the product (target) temperature the required power input for the cooling unit can be determined.

To select the right target temperatures and the appropriate cooling program (Energy saving, efficiency, max. power mode), the ACU measures the battery supply voltage and determines the electrical current demand of the compressor.

If the Solar charge controller has a proprietary data monitoring feature, the PCS can also retrieve important information about the state of charge (SOC) of the battery bank and the daily PV yield. These parameters are essential to provide an up to date and comprehensive picture of the whole cooling unit. Preferably all data loggings should be compiled on a common monitoring plattform to provide a single sight overview.

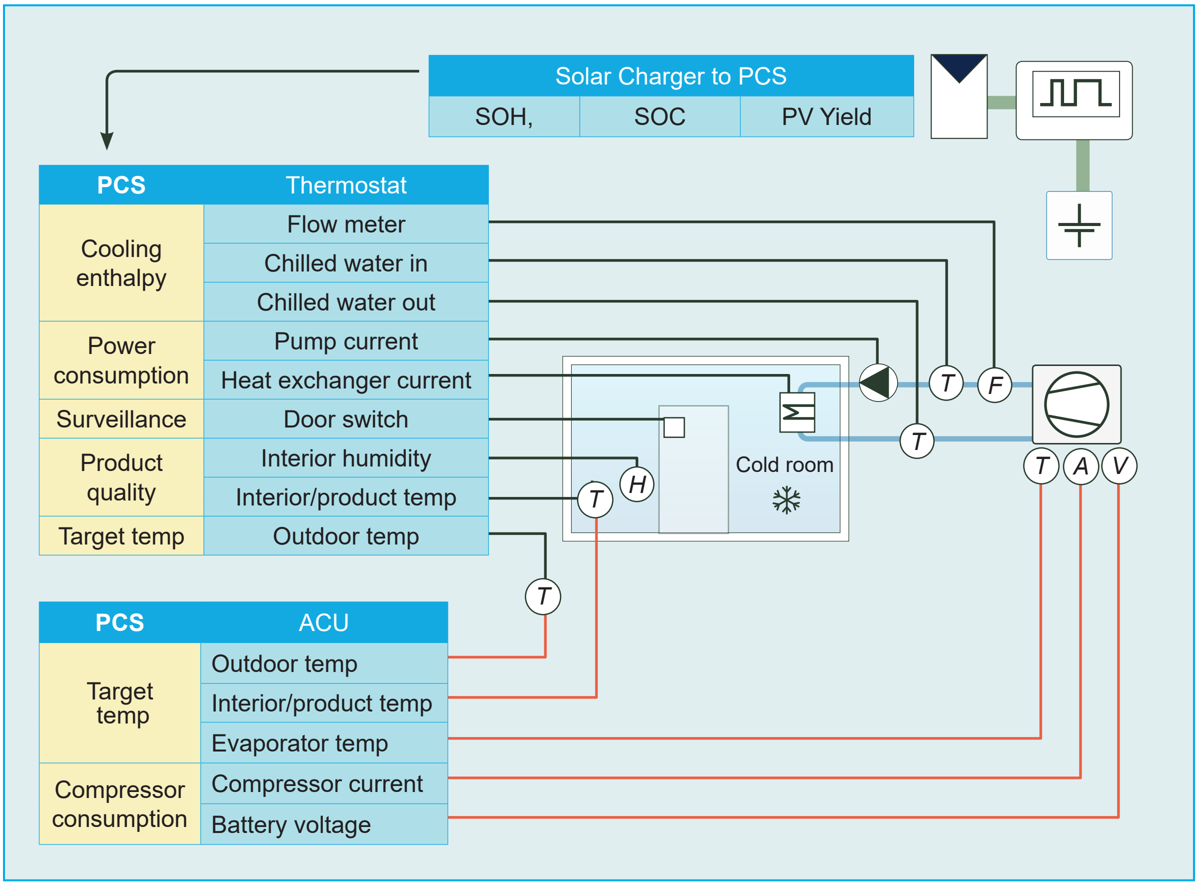


Fig. 128 Sensor units and their connection to the central control units

17.7 Milk Cooling

Conventional milk cooling usually consists of a stationary compressor and an insulated stainless steel tank. The refrigerant flows directly through evaporator coil which is situated at the bottom of the tank (Fig. 129).

With a similar PV supply (2kWp/ 600Ah) the same latent water chiller arrangement (6 cooling units) can be used to operate a 560l mobile steel tank for milk cooling (Fig. 130). The higher energy density (compared to a 20m^3 cold room) will help to bring down the fresh dairy to the required temperature within the necessary time frame (4°C in less than 3hrs).

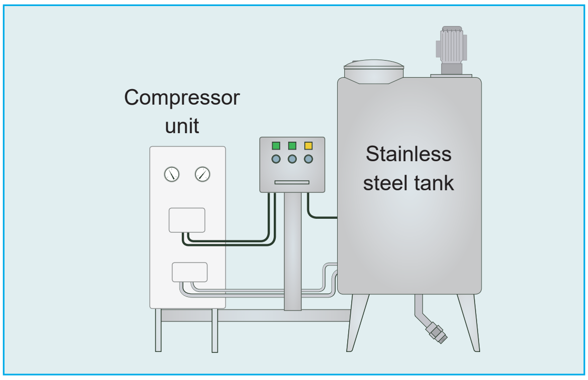


Fig. 129 Stationary compressor cooling of a milk tank

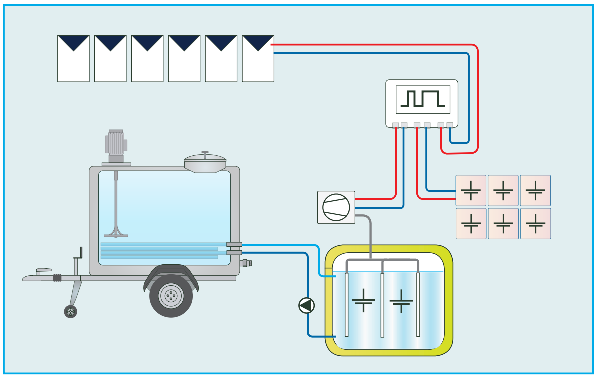


Fig. 130 Mobile milk tank with latent cooling unit

17.8 Block Ice Production

The cooling effect of ice is based on the large amount of enthalpy removal required to change the state of a substance from liquid to solid. It is the removal of internal energy from the molecules so that they change from a free floating to a relatively calm state and arrange in a crystalline structure (see Fig. 18).

Sodium chloride (NaCl) is an ionic compound commonly known as table salt. It is the major dissolved component of seawater. When sodium chloride is dissolved into water, the salt molecules break up into their ions Na^+ and Cl^-. Due to their different charges, the ions can dock on the bipolar water molecules.

More enthalpy removal is now necessary for the water molecules to break free from these bonds and to transform into ice crystalls. This is why saltwater has a lower freezing point than freshwater.

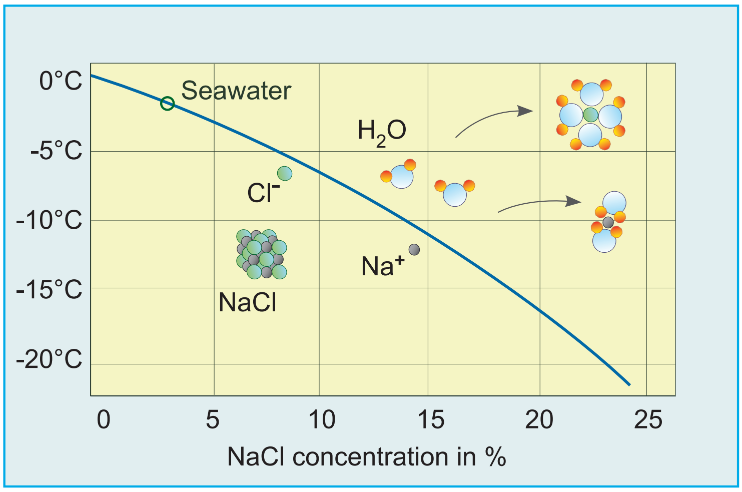


Fig. 131 Freezing point depression of saltwater

For Solar water chillers this phenomenon provides an additional advantage. Filling the water tank with a saltwater solution, the tank temperature can be brought below 0°C and the fluid medium will still be in a liquid state. To produce ice, metal compartments filled with fresh water are submerged into the tank.

The water chiller tank has a smaller size than the one being used for cold rooms and milk cooling. A 400l tank is cooled by 4 cooling units. That leads to an increased energy density and with a target temperature of -7°C around 50kg of fresh ice can be produced per day.

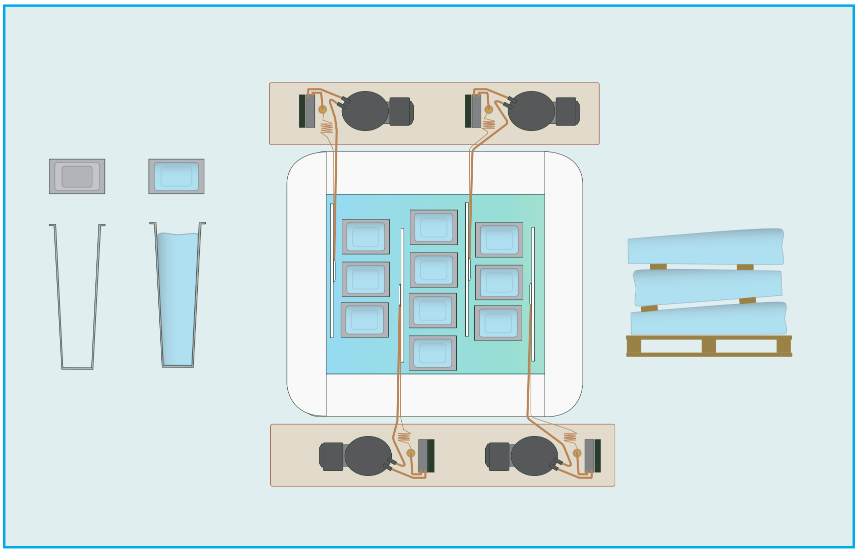


Fig. 132 Saline water tank with fresh water freezers

17.9 Block Ice Applications

Solid ice blocks as a cooling medium provide a decentralized application of Solar Cooling in remote areas. A good example for an application of block ice cooling is small boat fisheries.

Sample A in Fig. 133 explains a very common practice of fresh fish distribution. After the catch, the fish is stored on the logboat in an EPS cooling box but usually without any form of cooling support.

It might take a whole day until the catch is brought ashore where a part of it is sold and the rest ends up in a local domestic freezer where the power supply might come from an instable utility grid. Product losses up to 40% with this form of distribution are not uncommon.

Sample B is based on the same scenario but in this case the EPS cooler box on the logboat already contains a few ice block as a cooling medium. Fresh catch immediately gets cooled as soon as it gets into the boat. When brought ashore the fish should be transferred directly to a cooling truck and brought to its further distribution.

This provides an uninterrupted cooling chain and the ice blocks could be provided by a locally based Solar Cooling system. The unit could be operated and managed by the local community or the Beach Management Units (BMU). The purchase of ice blocks should be cost neutral for the fishermen since they are immediately compensated by minimizing their catch losses.

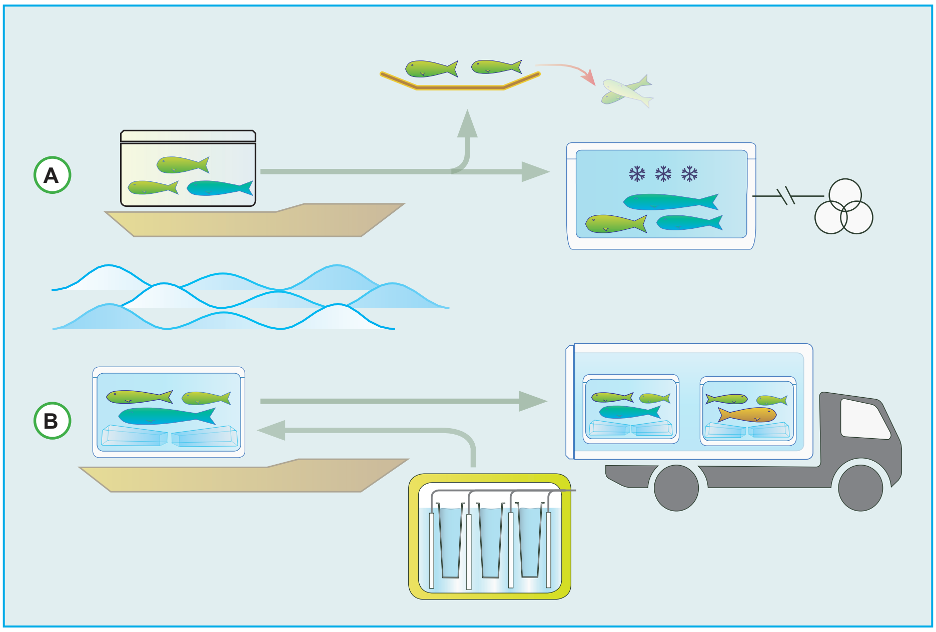


Fig. 133 Block ice production for fresh fish cooling chain