



Solar Cold Rooms

Technical Handbook



2024
Edition

Foreword to the 2024 Edition

Sustainable cooling solutions have become very relevant in recent years. At the same time, it has become increasingly difficult to maintain an overview of the various technologies available on the market and to keep abreast of the issues that are relevant to the engineering behind them.

In the case of walk-in cold rooms, many topics have been covered in great detail in the wealth of technical literature available. However, for those readers who are new to the subject, the available literature is neither easily manageable nor readable in the time available. This is where the Solar Cold Rooms Technical Handbook comes in. It is structured in such a way that it is easily accessible even to those readers who are new to each technical aspect. The most important topics relevant to the engineering behind solar cold rooms have been compiled in a compact and easily understandable form. The handbook is accompanied by Excel-based design toolboxes to guide the reader through the first design steps.

The basic content of the handbook is based on the course transcript developed by **Strathmore Energy Research Centre**, the Institute of Agricultural Engineering of the **University of Hohenheim** and **Solar Cooling Engineering** in 2022, which was supported by the Green People's Energy for Africa initiative of the **Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)**.

The current 2024 edition has been extensively improved and expanded to include all existing cold room technologies available. This work was supported by the **Efficiency for Access Research and Development Fund**. The Efficiency for Access Research and Development Fund is funded by **UK aid**, via the **Transforming Energy Access platform** and the **IKEA Foundation**.

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Your notes:

1 HEAT AND TEMPERATURE

1.1 Temperature Scales

In the 18th century heat was believed to be an invisible, massless fluid that could penetrate all objects and that determined 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 volume of the bulb reservoir is larger than the increment tube. When temperature decreases, the **kinetic energy** of the substance decreases.

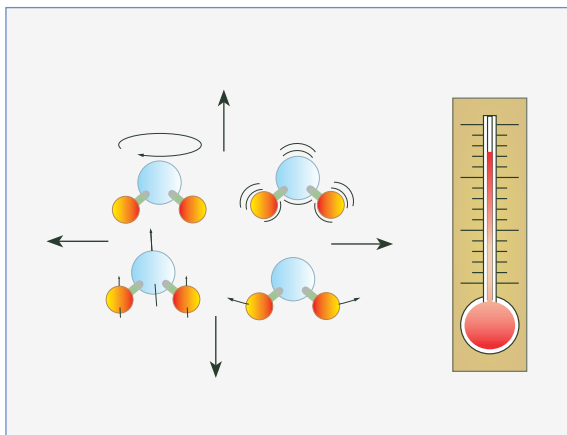


Fig. 1 Atomic movement leads to expansion

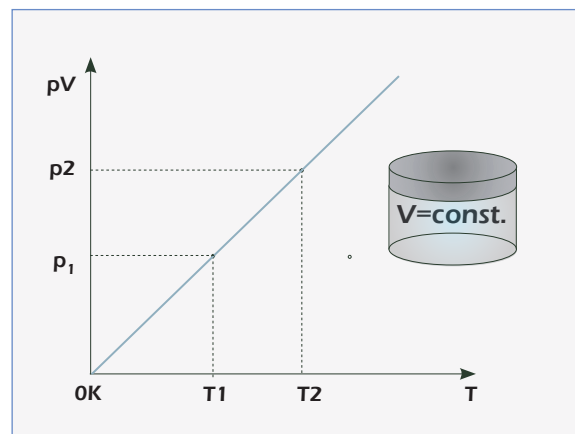


Fig. 2 Pressure temperature correlation of a gas

An ideal gas thermometer consists of a diluted gas in a closed containment with a constant volume (Fig. 2). 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 correlate with 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. 1)

Tab. 1 Use of Temperature Scales Kelvin and Celsius			
Temperature Points [°Celsius]		Temperature difference [Kelvin]	
T _{ambient}	25°C	25°C - 5°C = 20K	ΔT
T _{water}	5°C		

1.2 Heat Transfer

The molecules of the ambient air contain a certain amount of kinetic energy. They are moving around randomly and whenever an air molecule hits an object, it transfers a certain amount of kinetic energy. The impacted particles of the object will 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**.

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 by a cooling fan improves the heat exchange and can shorten 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 emit 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.

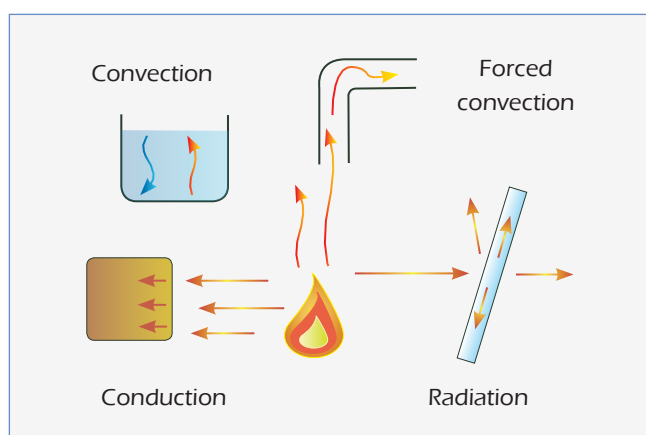


Fig.3 Different methods of heat transfer

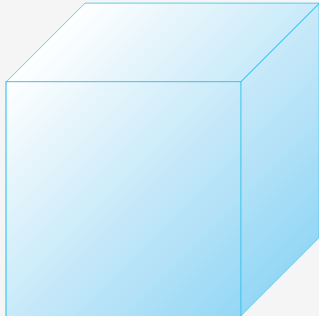
2 HEAT ENERGY AND MATTER

On a sunny morning air will warm up much faster than water (e.g. a pool or a lake). While air will thermally equalize with the ambient temperature in a few minutes, water will keep its low temperature for a much longer time. In the evening when the outside air will cool down rapidly, the ambient water will still keep its daytime temperature for a while. Water is therefore an excellent medium for thermal energy storage.

Temperature difference (Δt) and mass (m) are 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. 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 laws of physics determine the lowest temperature point as zero Kelvin or **absolute zero** (- 273.16°C) Every matter above zero Kelvin has a kinetic (motional) 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.

Tab.2 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	20	0.07	1.5
Water	4.175	20	0.07	6.15
Note: 3,600kJ are equal to 1kWh				



1 kg of air



1 kg of water

2.1 Matter and States

Gaseous Phase

Air is a mixture of various gases like nitrogen, oxygen, 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 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. 2).

The air in our troposphere 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.

2.2 Psychrometric Charts

Psychrometric (*ψυχρὸν* 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). In general, 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. 4 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 H₂O (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%.

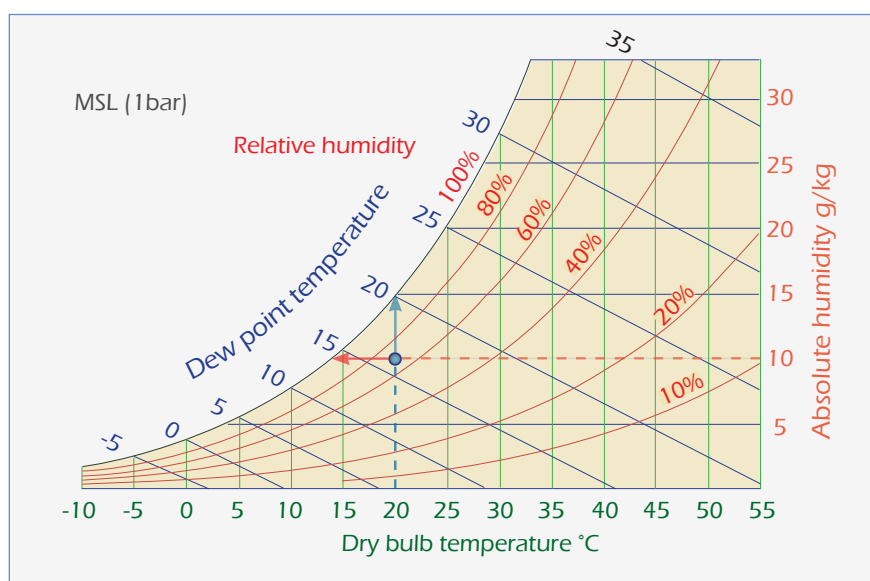


Fig. 4 Psychrometric charts determine the water content of air

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).

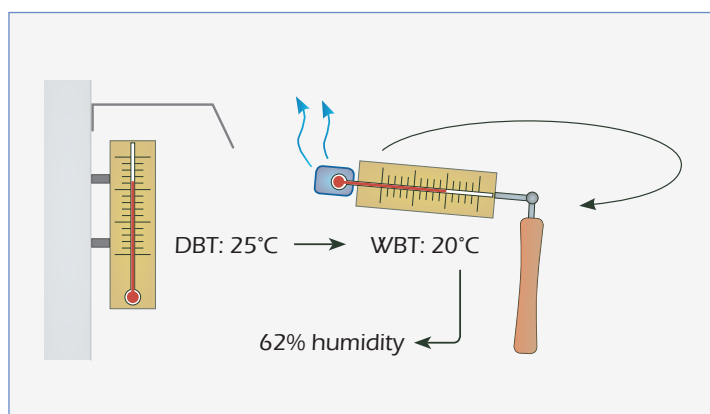


Fig. 5 Sling thermometer to measure wet bulb temperature

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 indispensable utility and it is predicted that by 2060 the worldwide energy demand for cooling will outrun the one for heating.

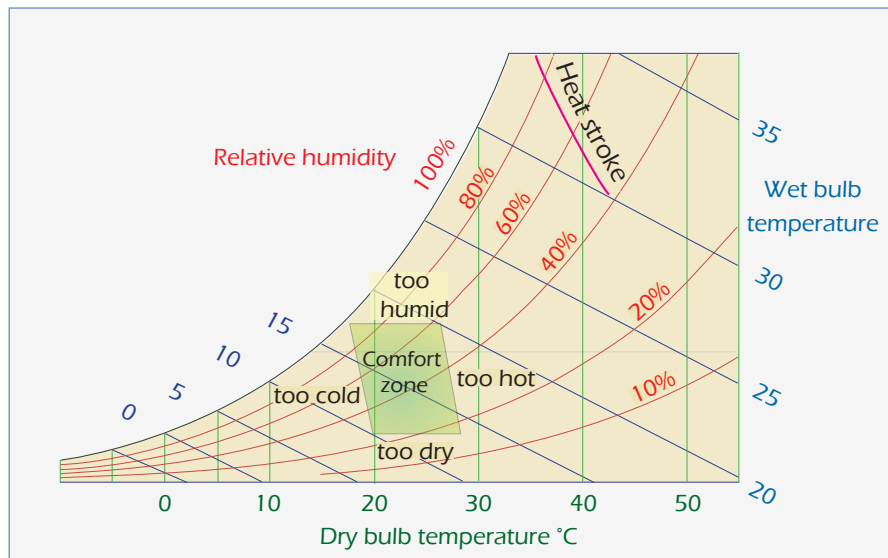


Fig. 6 Psychrometric charts and the comfort zone for the human body

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.

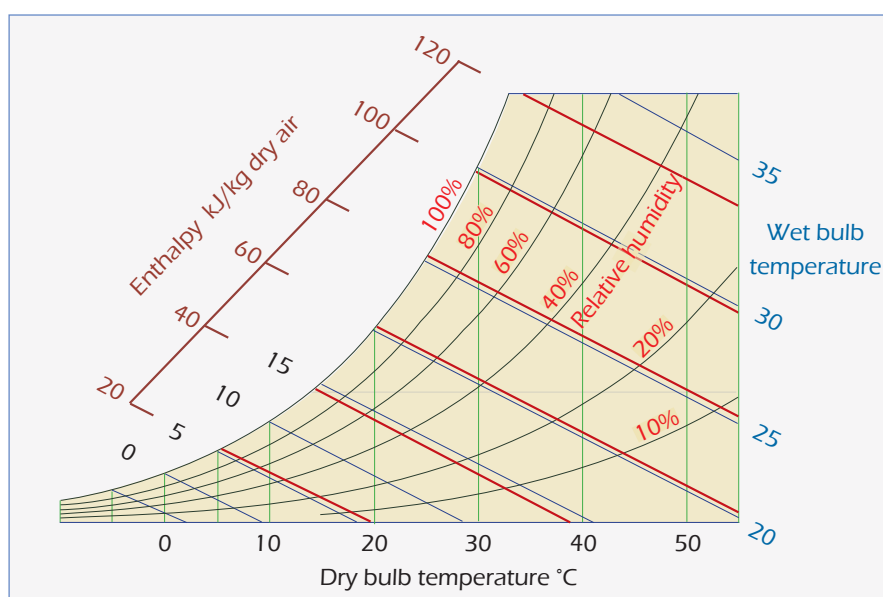


Fig. 7 Enthalpy lines on a psychrometric chart

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. 8) 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. Water is also the only substance on earth that can be found in nature in all three states (frozen, liquid, gaseous). At 4°C the water bonds condense to small plates (Fig. 9). At this temperature water has its highest density. Even solid frozen water has a lower density. This is the reason why ice floats on the top of water bodies.

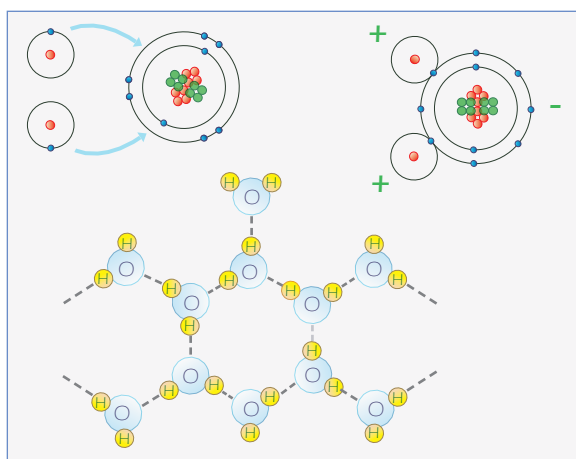


Fig. 8 Hydrogen bonds of water

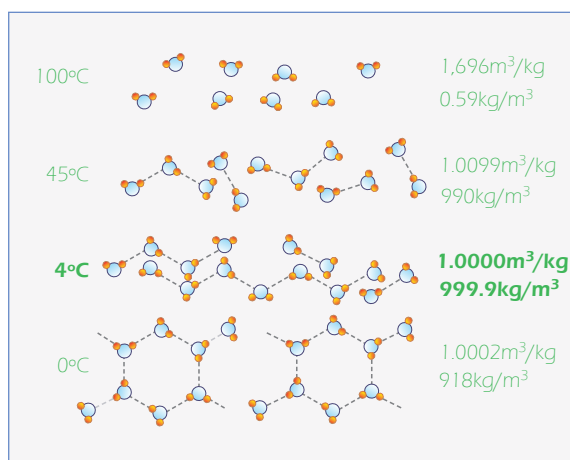


Fig. 9 Thermodynamic properties of water

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 (amorphous 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 ($\Delta h_{\text{Evap}} = 2,257 \text{ kJ/kg}$) 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 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. 11).

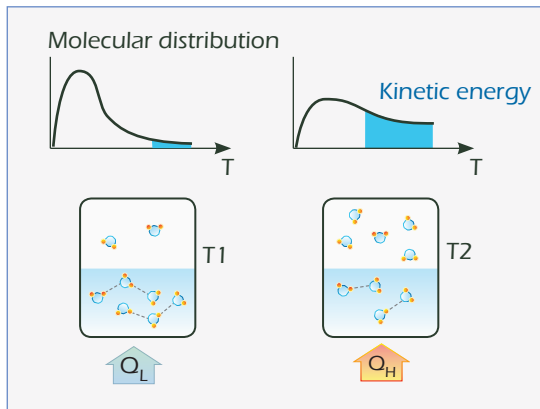


Fig. 10 Kinetic energy increases evaporation

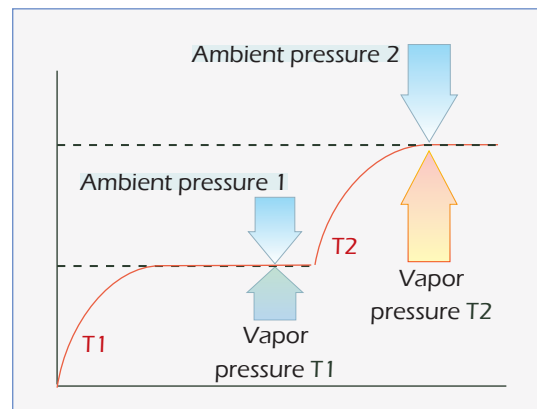


Fig. 11 Liquid vapor equilibrium

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.

3 LATENT AND SENSIBLE HEAT

In Fig. 12, 100ml water with a temperature of 2°C are poured into a glass filled 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 crystals and melt the ice was taken from the warm water resulting in a significant cooling effect of 17K.

Fig. 13 shows the temperature-enthalpy (T_h) diagram for water. **Enthalpy** is the measurement for the internal (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.

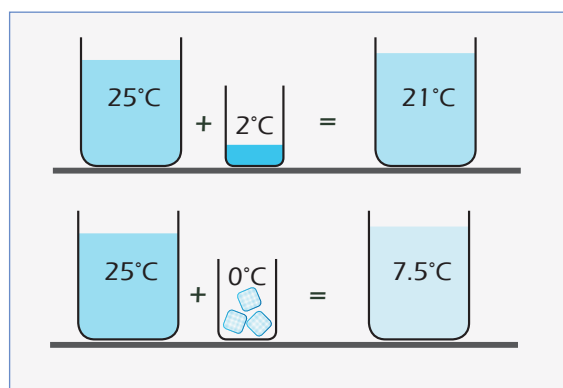


Fig. 12 Latent heat effect of ice

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**.

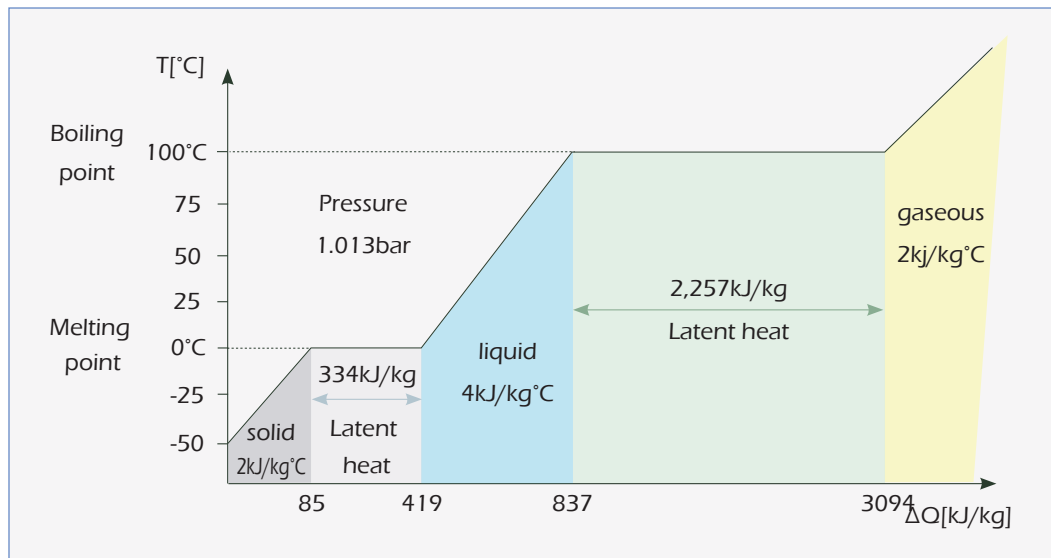


Fig. 13 Th diagram of water with phase change enthalpy

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 1 bar) would make the gas particles re-condensate 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 (2,257kJ/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.

4 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.

4.1 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**

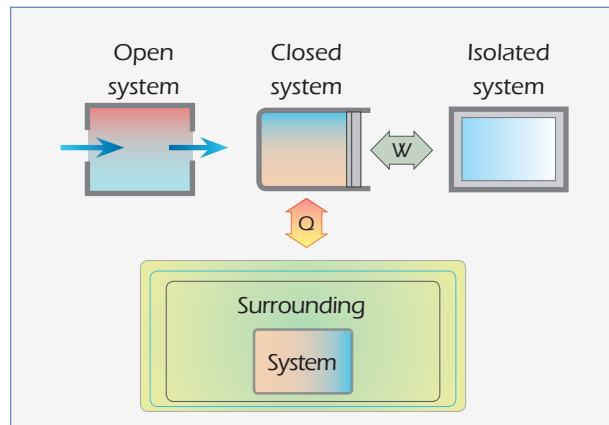


Fig. 14 Thermodynamic systems

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.

Thermal Reservoirs

A **heat engine** can convert thermal energy into mechanical work (W). 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 without any change in temperature.

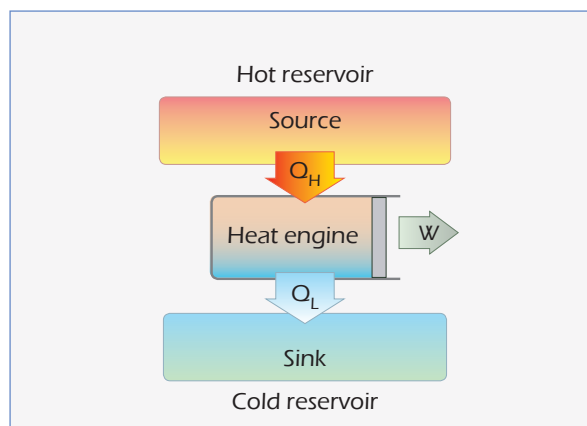


Fig. 15 Thermal reservoirs and heat engine

4.2 First Law of Thermodynamics

The first law could be described as the thermodynamic law of strict bookkeeping. Every system 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.

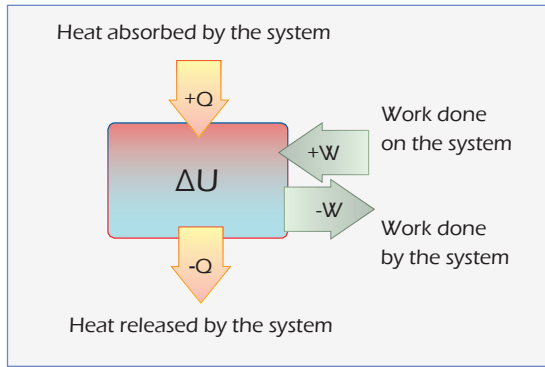


Fig. 16 First law of thermodynamics

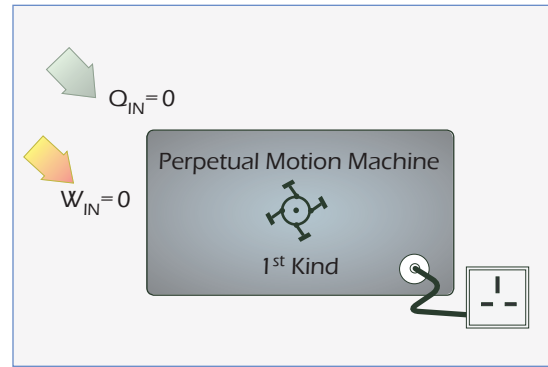


Fig. 17 Perpetual motion machine 1st kind

4.3 Second Law of Thermodynamics

A bowl of mixed 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. 18). 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.

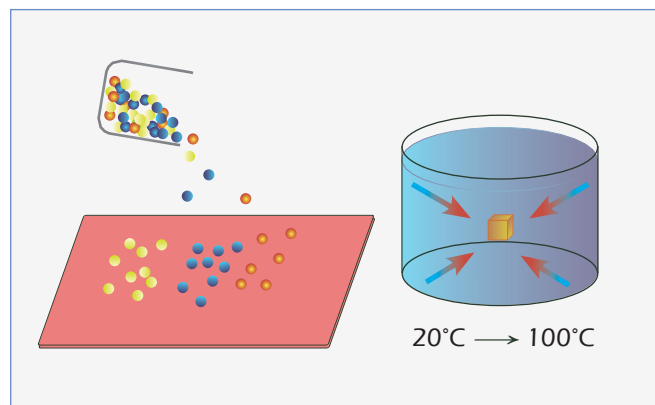


Fig. 18 Events that do not contradict 1st law of TD

4.4 Carnot Engine

In 1824 French engineer Sadi Carnot came up with the generic model for 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 a heat engine's efficiency. Fig. 19 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.

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 step 1.

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.

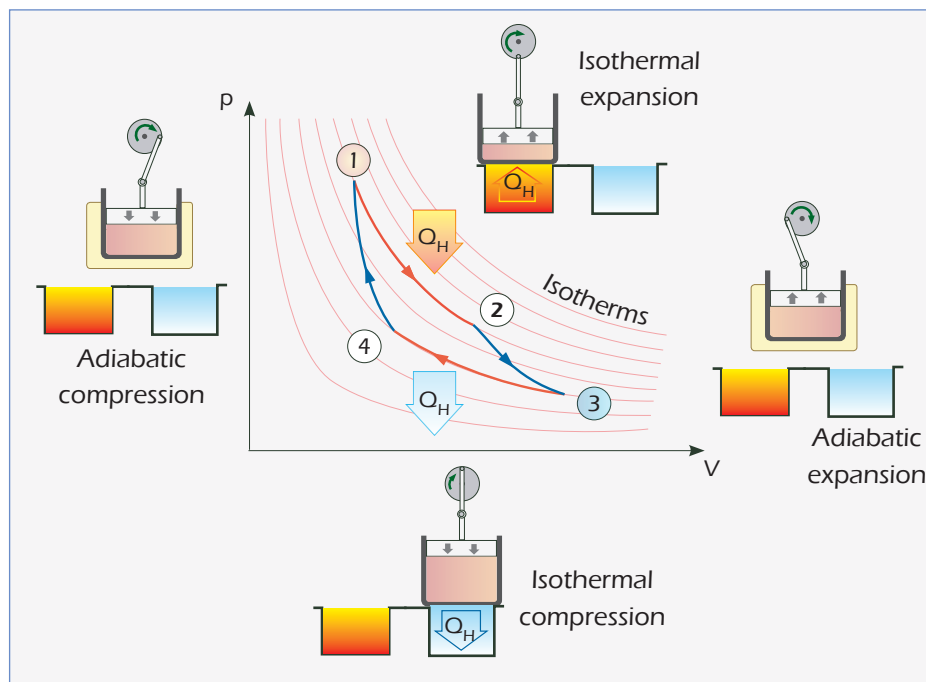


Fig. 19 The carnot cycle represents the theoretical max. efficiency of a heat engine

- There is no device whose only effect is the conversion of heat completely into work -

Second Law of Thermodynamics (Kelvin, Planck statement)

- 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)

4.5 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%.

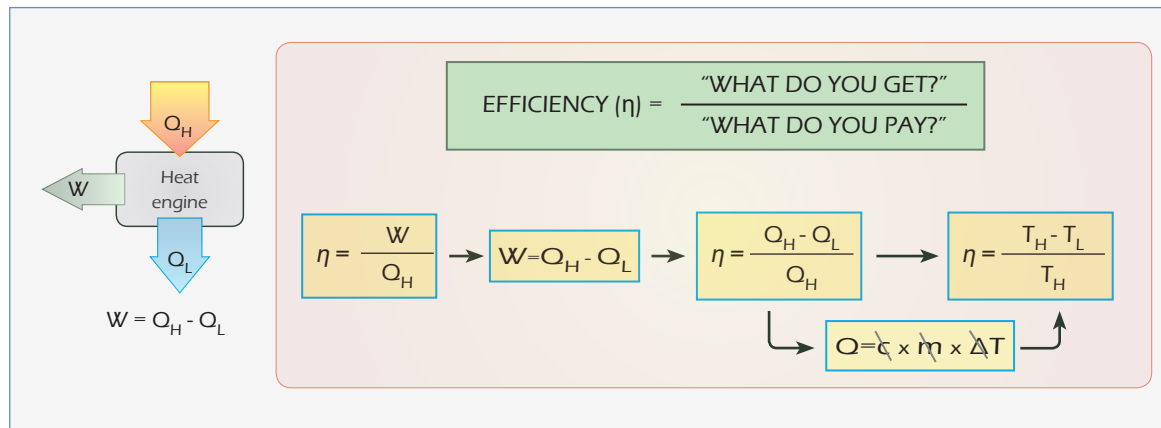


Fig. 20 Carnot theorem of the theoretical maximum heat engine efficiency

4.6 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.

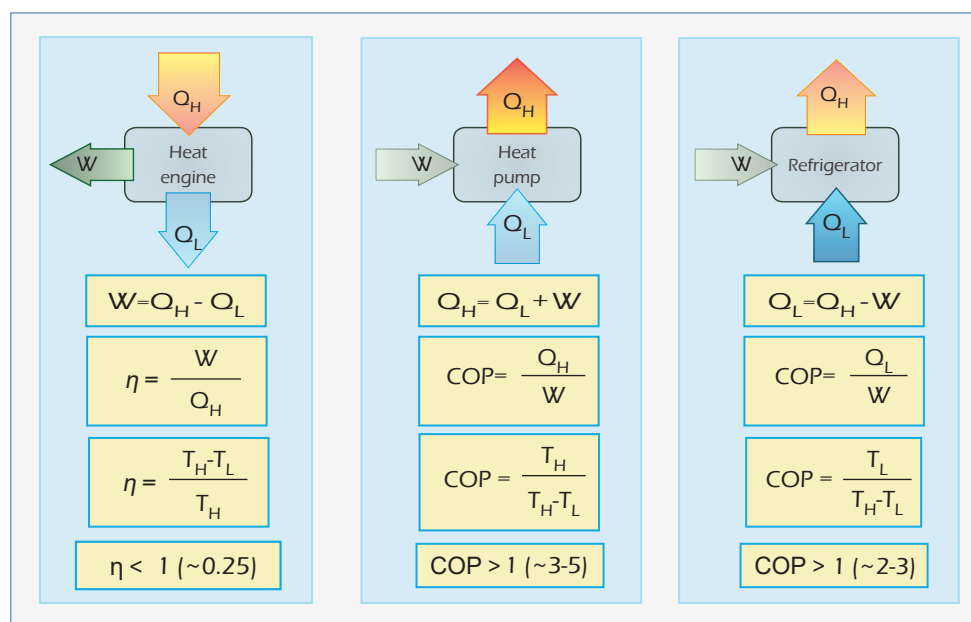


Fig. 21 Comparison of efficiency factors for heat engines

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 (e.g. building) to provide 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.

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.

4.7 Theoretical COP, Ideality Factor and Real COP

The ideal COP is based on theoretical assumption of ideal circumstances. In reality ideal technical parameters might not be practicable (see 4.4 Carnot Engine). For a realistic performance estimate of a refrigeration system, an ideality factor (or true factor) of approximately 25% must be added to the calculation

T_{LOW} (evaporator temperature) and T_{HIGH} (condenser temperature) must always be converted into Kelvin before a COP formula can be applied.

Celsius/Kelvin	Theoretical or Ideal COP	Realistic COP
$T_H: 35^{\circ}\text{C} + 273.15 = 308\text{K}$ $T_C: -1^{\circ}\text{C} + 273.15 = 272\text{K}$ $T_H - T_C: 308\text{K} - 272\text{K} = 36\text{K}$	$\text{COP} = \frac{T_L}{T_H - T_L}$ $\text{COP} = \frac{272\text{K}}{36\text{K}} = 7.5$	$\text{COP}_{\text{IDEAL}} \times \text{True factor } \alpha = \text{COP}_{\text{REAL}}$ $7.5 \times 25\% = 1.875$

Fig. 22 Theoretical COP multiplied by the true factor (25%) gives a realistic number for a refrigeration system

5 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 into the environment (Fig. 23).

All previous scenarios of latent heat exchange referred to water as a transfer medium. Due to its hydrogen bonds, water has excellent heat storage capabilities and is used as a distribution medium in larger HVAC systems (air-ports) and as a cooling medium in a wide range of industrial applications e.g. heat engines, power generation.. But because of its relatively high boiling point (100°C at 1bar), water is generally not suitable as a phase change refrigerant to generate ambient cooling. Volatile liquids have the advantage that they already evaporate under ambient pressure at cooling temperatures (4°C to -20°C) and they re-condensate when the pressure is raised by a few bars.

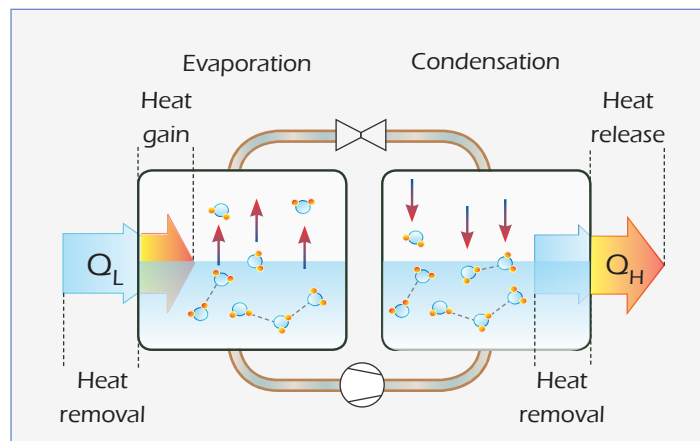


Fig. 23 Heat transfer by phase change

5.1 Enthalpy Diagrams

One of the most helpful tools to understand the cycle process of heat transfer for refrigeration is a pressure-enthalpy (pH) diagram. Fig. 24 shows the **pH-diagram** for **isobutane (R600a)**. 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.

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.

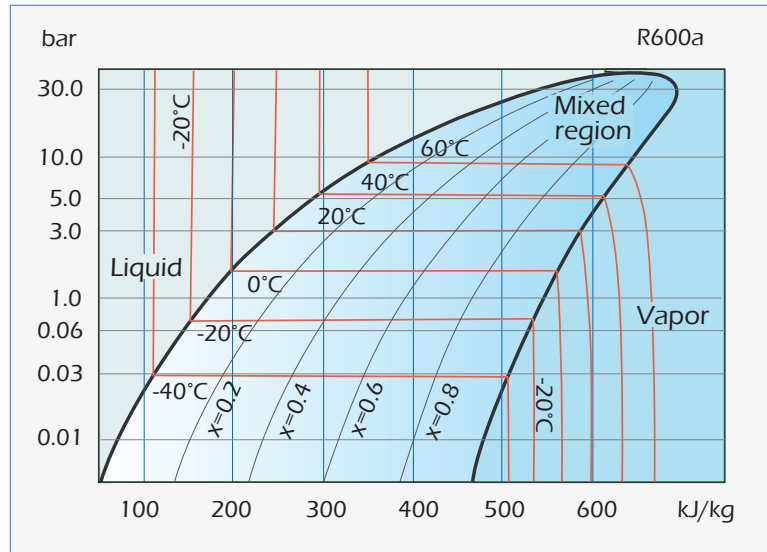


Fig. 24 Ph-diagram of Isobutane (R600a) with vapor dome

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**.

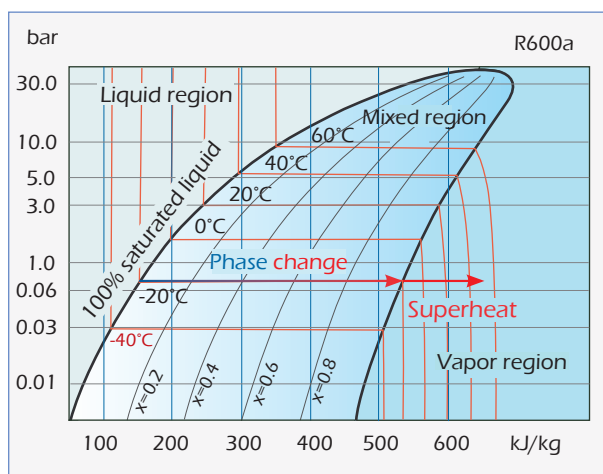


Fig. 25 Phase change-saturation-superheat

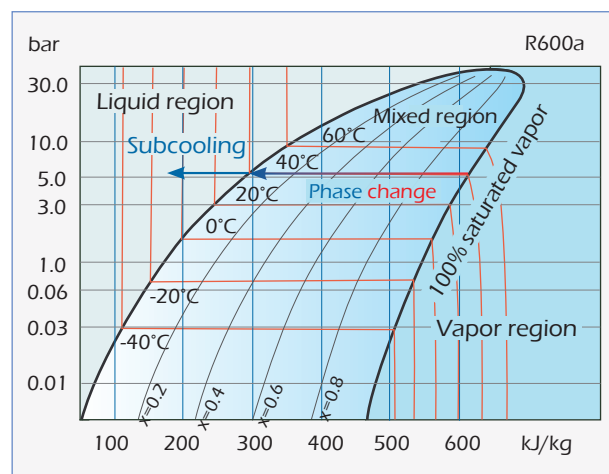


Fig. 26 Phase change-saturation-subcooling

Fig. 27 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 insulated 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.

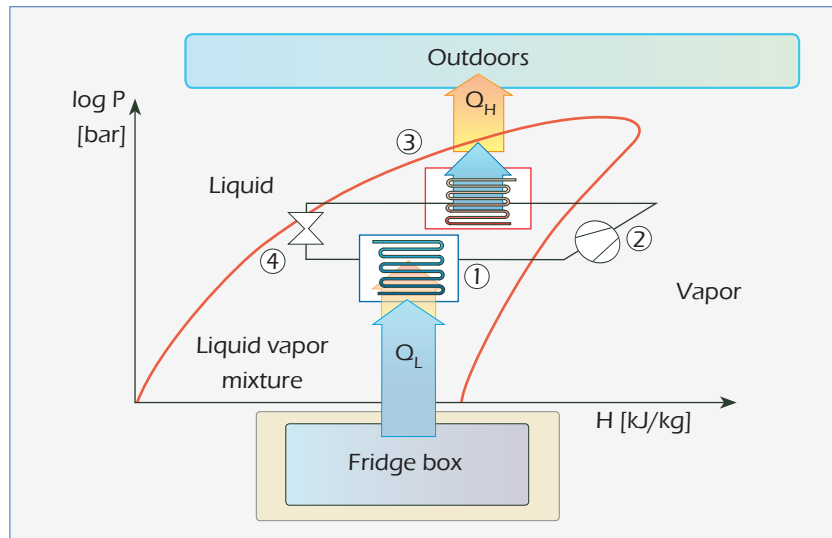


Fig. 27 R600a refrigeration circuit on a pH-diagram

5.2 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** (Fig. 28) 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. 29) are becoming more present in the HVAC market but for small commercial and domestic refrigeration systems reciprocating piston pumps are still the dominant type for vapor compression.

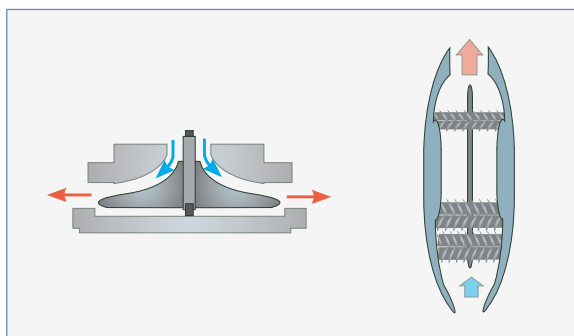


Fig. 28 Axial and radial flow compression

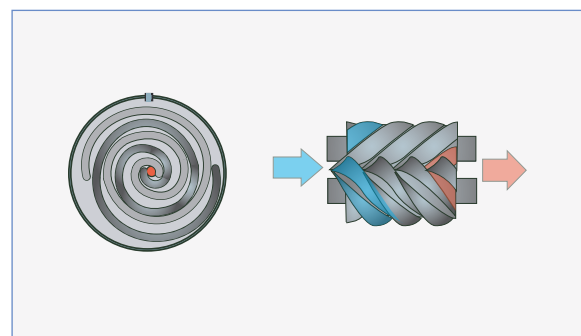


Fig. 29 Scroll and screw compressor

5.3 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 facilitates 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.

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 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 eccentric 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.

The mechanical moving parts of the compressor require lubrication. Polyester (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 acidic. Therefore correct purging and air evacuation (humidity) of the cooling circuit before charging with refrigerant is important.

Flooding the compressor with liquid refrigerant can dilute the oil and obstruct sufficient lubrication. Since liquids are not compressible, ingestion 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 subcooling 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 $+5^{\circ}\text{C}$).

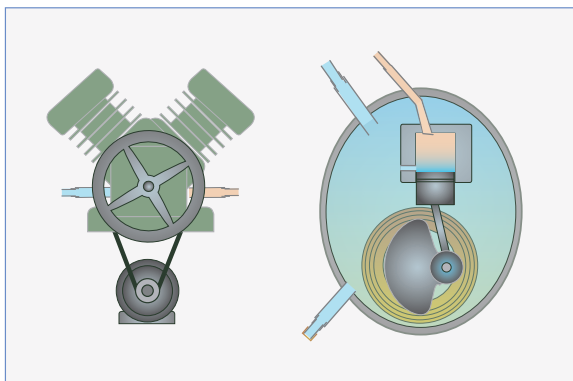


Fig. 30 Open and hermetic piston compressor

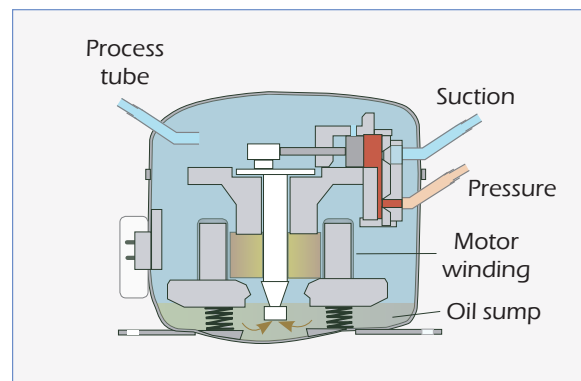


Fig. 31 Hermetic compressor cross section

5.4 Single Phase AC Compressors

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

Resistance Start Induction Running (RSIR) has an auxiliary starting winding made of thinner wire with fewer turns. 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. Similar to the RSIR, the **Capacitor Start Induction Run (CSIR)** 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.. **Capacitor Start and Run (CSR)** or CSCR motors have a capacitor in the starting circuit and in the running circuit. After the run-up is reached, the starting capacitor must be turned off by a switch or a relay. They have a high starting torque (HST) and are used for larger refrigerators and air conditioning systems (3.5kW). In **Permanent Split Capacitor (PSC)** motors the capacitor and the starter winding stay after run-up in the circuit for normal operation. PSC motors are used in larger applications and air conditioning systems (3-5kW). No starter relay or switch is needed and it can be used in systems with capillary tubes or automatic regulator valves (TXVs).

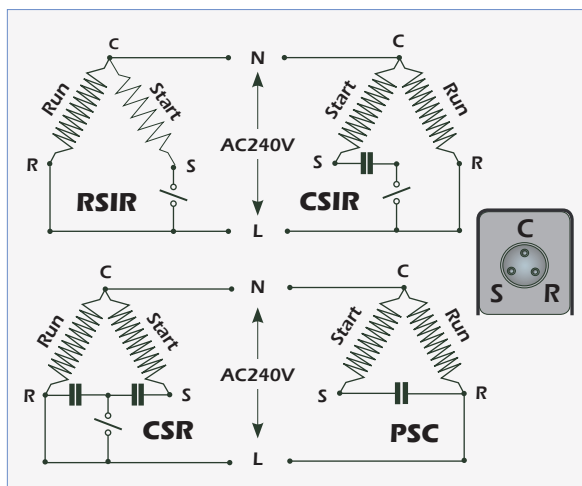


Fig. 32 Single phase compressor modes

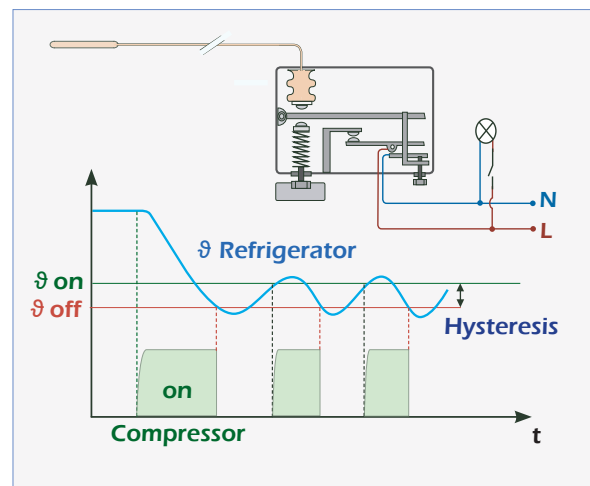


Fig. 33 Thermostat switch to control cooling circuit

5.5 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. 56). 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 refrigerator starts to run.

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. $+2^{\circ}\text{C}$), the thermostat will start the compressor cycle again.

Different cooling ranges (e.g. -6°C to $+2^{\circ}\text{C}$ 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 separate 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.

5.6 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.

Smaller cooling units with a relatively stable temperature range use **capillary tubes** as an expansion device. Copper tubing with a length of 2-4 meters and a few millimeters 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) and low side (evaporator) equalize in pressure when the refrigerator is not running. This facilitates the start of the compressor and allows a motor start with low starting torque. The pressure equalization also leads to accumulation of liquid refrigerant at the bottom of the evaporator. Since the long thin tubing 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.

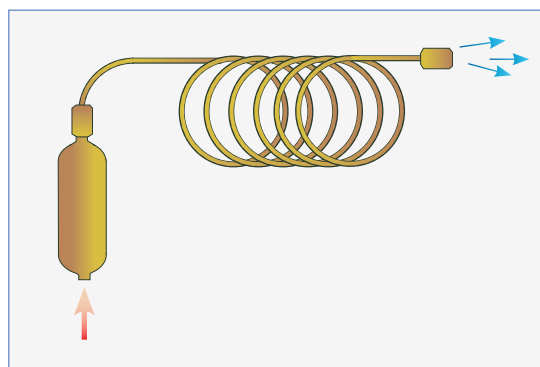


Fig. 34 Capillary tube with filter drier

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 minimizes 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. 36).

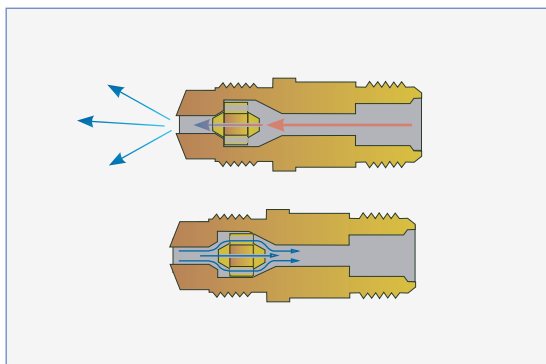


Fig. 36 Fixed orifice in reverse flow (below)

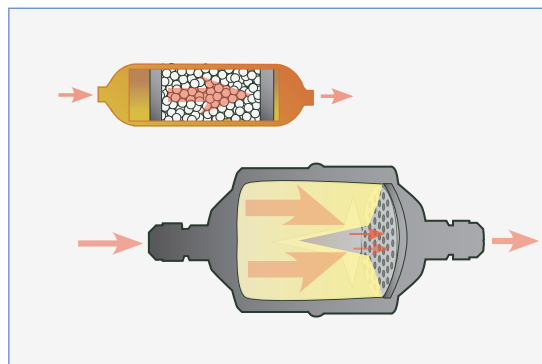


Fig.35 Copper spun and welded steel filter driers

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 hygroscopic, 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 Aluminum oxide beads. These materials have extremely small pores ($3 \times 10^{-7} \text{mm}$). 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 disintegrate polymer fittings. Other solid contaminants like oxidated 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. Larger systems use welded steel shell design filter driers. 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.

5.7 Thermostatic Expansion Device

Larger refrigeration units, especially those with larger heat load fluctuations like HVAC, 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.

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 diaphragm. The attached injector piston drops down and widens the refrigerant valve. More refrigerant can enter the evaporator coil and the superheat will decrease again.

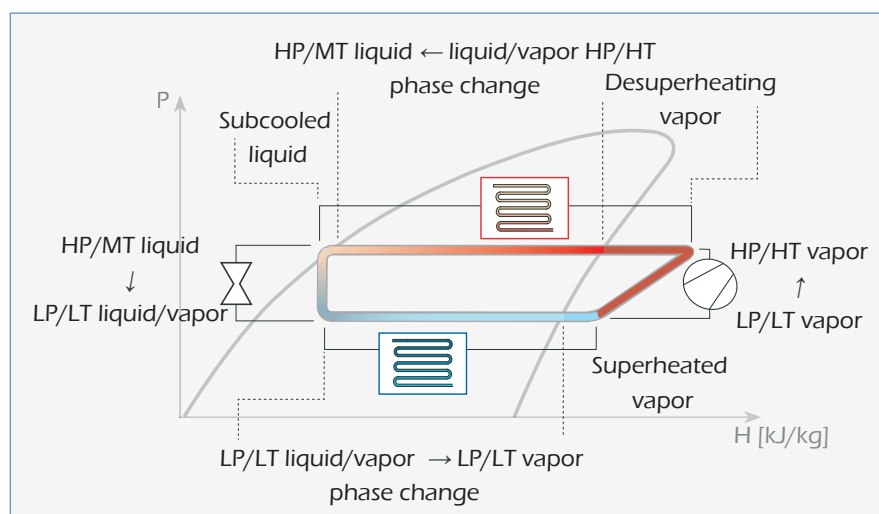


Fig. 37 Refrigerant phase changes in the cooling circuit

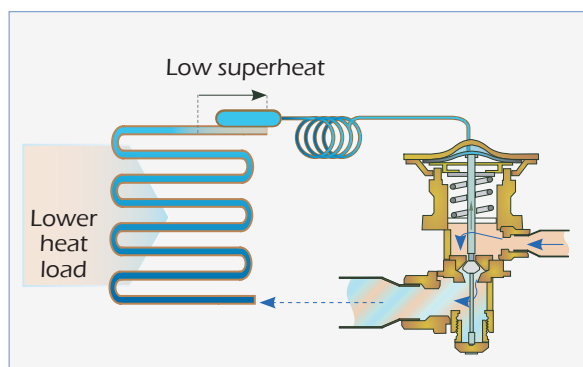


Fig. 39 Low superheat requires less refrigerant flow

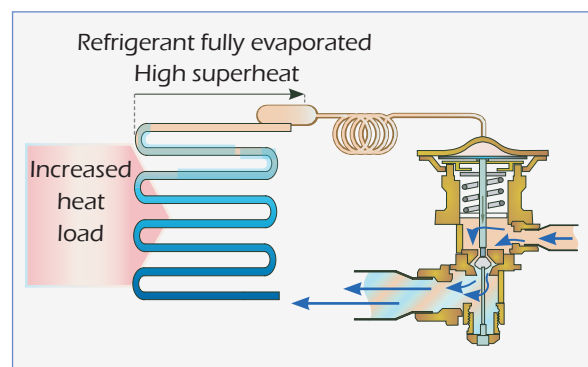


Fig. 38 More refrigerant flow decreases superheat

5.8 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 aluminum) 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 coefficient significantly.

In domestic and small business applications the most prevailing type is the roll bond evaporator. A special coating (weld stop) in the form of the refrigerant serpentine pattern is applied between two aluminum 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 welded 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.

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.3).

Empirically the evaporator capacity can also be measured and calculated by the enthalpy removal times mass flow (see chapter 4). 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 .

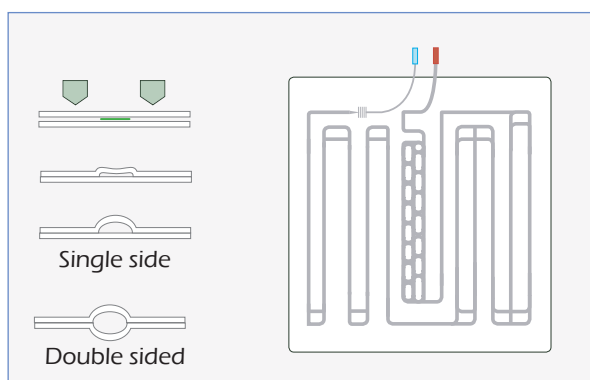


Fig. 40 Manufacturing of roll bond evaporator

Tab.3 Evaporator Capacity			
$Q_{\text{Evap}} = A \times \Delta T \times k$			
Evaporator capacity	Q_{Evap}		W
Evaporator surface area	A		m ²
Temperature difference	ΔT		K
Heat transfer coefficient	k		W/m ² K

5.9 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.

First, the refrigerant enters the condenser at constant pressure as a superheated gas. It then undergoes a phase change where it releases the bulk amount of enthalpy and finally 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 a sufficient 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 metal 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. Aluminum fins brazed to the 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 calculated with the total amount of heat (cooling plus compressor power) compared to the total capacity of air flow.

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 flood-back 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 sufficient 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.

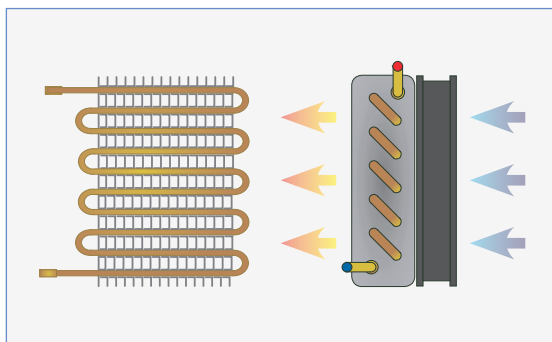


Fig. 41 Face area (left) of a forced air flow

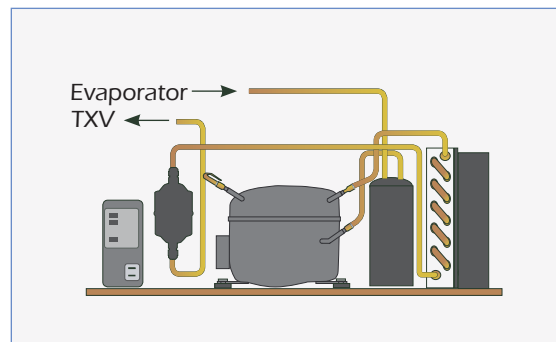


Fig. 42 Condensing unit with accumulator

6 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 sulfur 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.

6.1 Fluorinated 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 fluorine. **Chloroflourocarbons** (CFCs) and partially derived **hydrochloroflourocarbons** (HCFCs) were non toxic, non flammable, non corrosive and highly efficient.

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 aggressively with the O_3 molecules of the ozone layer, the protective shield that bounces off the sun's cytotoxic 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.

Ozone depletion potential (ODP) and **Global Warming potential (GWP)** are the main environmental threats caused by refrigerants (Tab.4). 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 retain in the market for the foreseeable future. In the moment they are the most dominant category of refrigerants in the global market (e.g. R134a). HFCs can also be mixed with hydrofluoroolefins (HFOs). Hydrofluoroolefins are unsaturated organic refrigerants with low GWP, zero ODP and are considered the fourth generation of refrigerants.

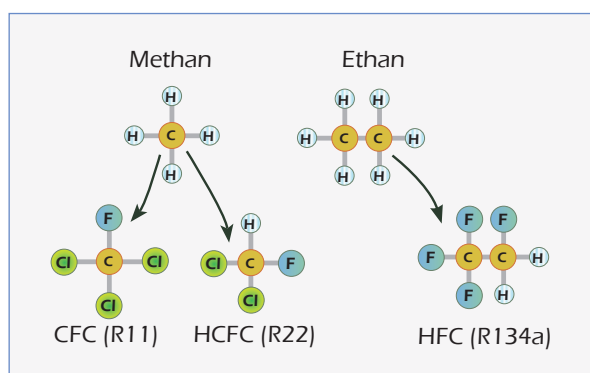


Fig. 43 Halogenation of hydrocarbons

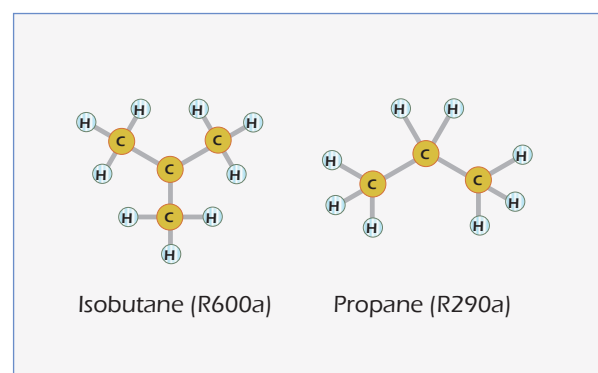


Fig. 44 Natural hydrocarbon refrigerants

6.2 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 p-h diagram (temperature glide). **Near azeotropes** are blends with different bubble and dew points but in a closer range.

6.3 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/m³).

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.4 General Quality Requirements for Refrigerants	
Efficiency	Environmental
Chemical stability under the occurring pressure and temperatures in the refrigeration cycle	Non persistent and biodegradable
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

Tab.5 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		-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 ₂ O	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 CO₂

7 COOLING LOADS

The total amount of thermal energy that has to be removed from the interior of a refrigeration unit 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.

Transmission Load

Transmission load is the heat ingress 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 cooling room for which the compressor has to compensate with additional cooling.

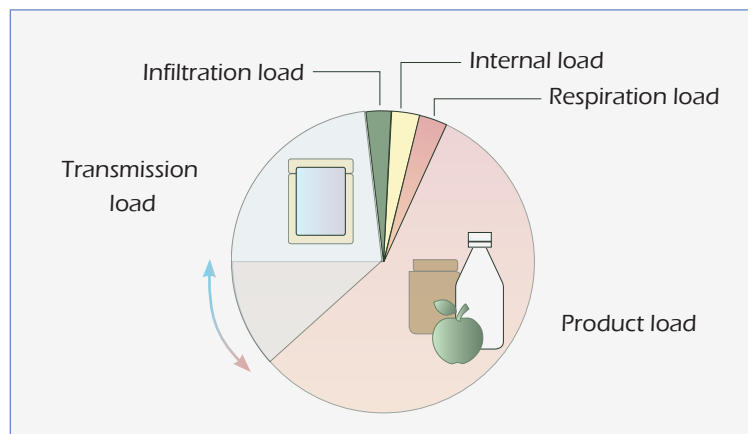


Fig. 45 Specific components of the total cooling load

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 (furnaces, machineries) can help to decrease the amount of transmission load.

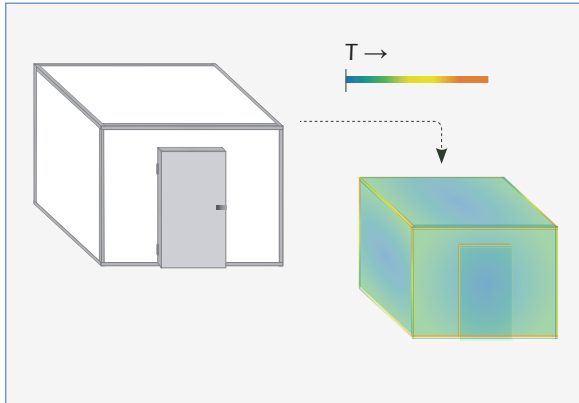


Fig.47 Heat ingress by thermal bridges

Tab.7 Transmission Load

$\frac{A \times \Delta T}{R} = Q_T$			
Total surface area	A	30	m ²
Temp difference	ΔT	26	K
Thermal resistance	R	2.86	m ² K/W
Transmission load	Q_T	273	W

Thermal Resistance

The thermal insulation material for cold rooms is made of **extruded (XPS)** or **expanded (EPS) polystyrene** foam boards. Widely used as an insulation material in the construction sector, polystyrene is lightweight, easy to cut and moisture resistant. Its biggest disadvantage is its non-biodegradability. Polystyrene foam consists of 95% air, encapsulated in tiny polymer beads which makes it a material of extremely low thermal conductivity (see Fig. 46).

Tab.6 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. The **total transmission load (Q_T)** is the outside area (A) of a cold room 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**).

R-Value of Multiple Materials

Insulated walls are sometimes constructed of different 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.

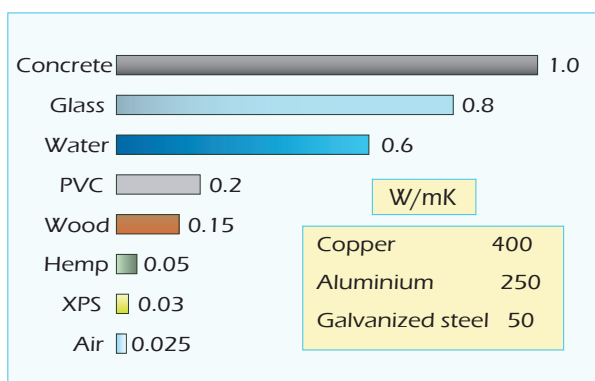
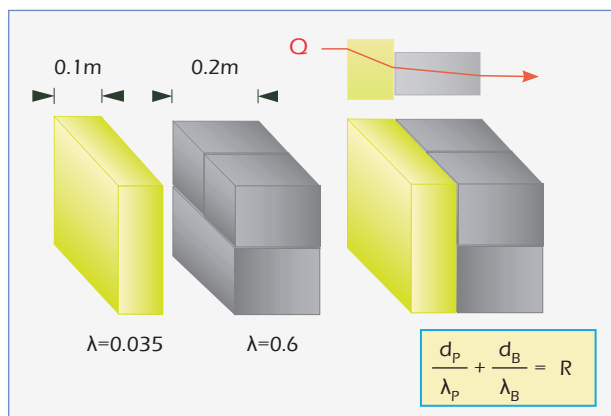


Fig.46 Thermal conductivity of building materials

Tab.6 Thermal Resistance of XPS Foam Board

$\frac{d}{\lambda} = R$			
Material thickness	d	0.1	m
Thermal conductivity	λ	0.035	W/mK
Thermal resistance	R	2.86	m ² K/W



Tab.8 Total Transmission Load of different insulation materials

Material	d [W/mK]	λ-value [m]	U-value [m ² K/W]
Polysterene	0.1	0.035	2.86
Concrete blocks	0.2	0.6	0.3
Total R-value			2.91

Fig.48 Insulation materials with different R-values

7.1 Cold Room Assembly

Sandwich panels with 100mm extruded polystyrene foam between two galvanized sheet metals (0.7mm) are the base modules used to build a custom sized cold room. Aluminum U-profiles are cut into the planned rectangle shape (e.g. 3x3 meters) and fixed to the prospective base foundation. The first sandwich panels are placed in upright position into the U-frame starting with the rear side.

Mortice and tenon joints are used to connect two panels together while corner joints are structurally supported by aluminum L-profiles. The top end of the sandwich panels are also stabilized by a rectangular aluminum frame and all joints are sealed with spray polyurethane foam. Once all sandwich panels are in place, the door frame can be fitted into the cut out opening on the front side.

In areas with occasional floodings, the floor level of the cold room should be at a height well above the flood water level. Rectangular steel tube is used to weld a firm foundation grid. In areas with sub zero winter temperatures, concrete foundation blocks should have additional steel reinforcement. Exposed steel tubes should be primed with anti corrosion paint.

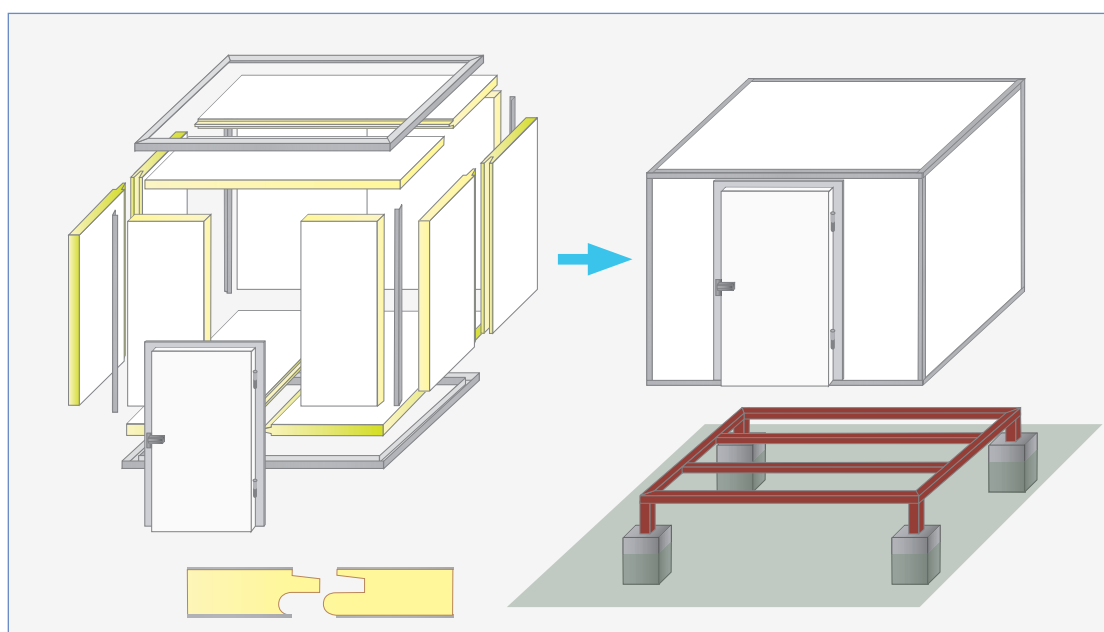


Fig.49 Cold room assembly with sandwich modules and concrete foundation with steel frames

7.2 Net Zero Cold Rooms

The use of natural resources like straw as the prime insulation material, does not only offer an environmental friendly alternative but also significantly reduces initial costs of a cold room project. 3x2" timber is used to construct the wooden framework, the outer walls are made of recycled eco-boards. The interior is stuffed out firmly with straw, joints can be sealed with natural rubber silicone. A simple but robust foundation is made of 50x100mm timber beams on stone or concrete blocks. Long term experience has shown that the persistence of straw module cold rooms mainly depend on a well functioning outside **vapor barrier** especially in a hotter more humid environment. Interior humidity does not play such a crucial role since the bulk share of vapor will condensate at the condenser plate.

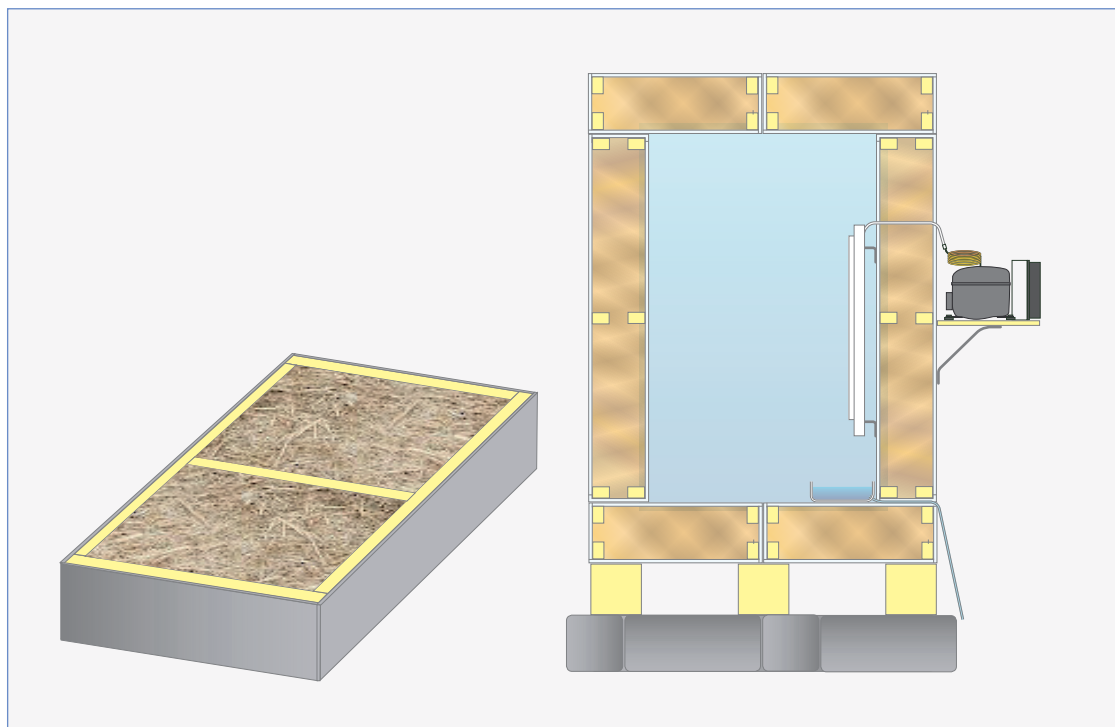


Fig. 50 Net zero cold room with straw as main insulation material

7.3 Transmission Load

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.9).

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.

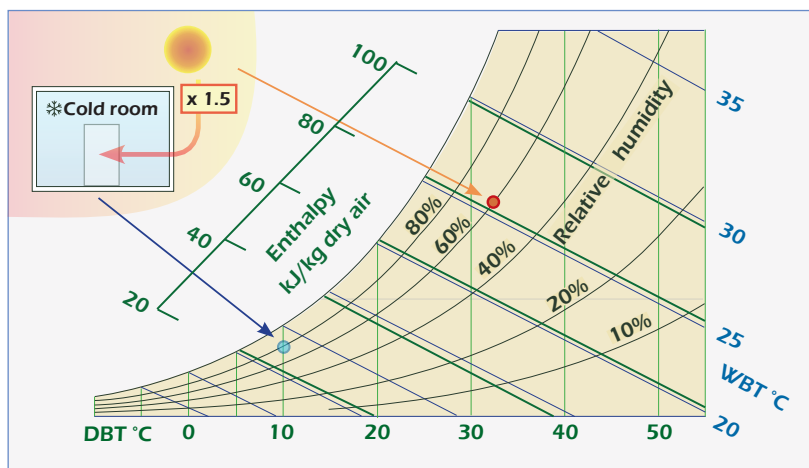


Fig.52 Psychrometric chart for enthalpy calculation

Tab.9 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	5.73	19.41	Wh/m ³
Additional enthalpy per day*		369	Wh
*Cold room with 18m ³ and an air mass exchange of 1.5 per day			

7.4 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.51 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 ($\Delta T=20K$). The whole amount is then replaced by a new batch. The cooling load remains the same.

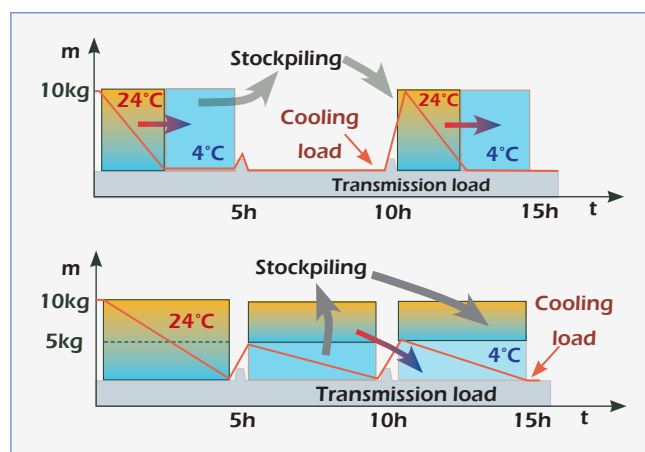


Fig.51 Stockpiling determines cooling load

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.

Tab.10 Product load above freezing			
$QT = C \times m \times \Delta T$			
Specific heat (Bananas)	C	3.35	kJ/kgK
Mass	m	10	kg
Temp difference	Δt	21	K
Heat load	Q	703.5	kJ

7.5 Freezing Product Load

Moisture content determines the freezing characteristics of organic products. 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. 53 calculates the enthalpy change of three stages and adds them together. The sensible heat (chilling) load above freezing, 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.

The **enthalpy method** (Fig. 54) takes the usual chilling load Q_C for temperatures above 0°C and for subzero temperatures the enthalpy difference ($T_{0^\circ\text{C}} - T_S$) 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.

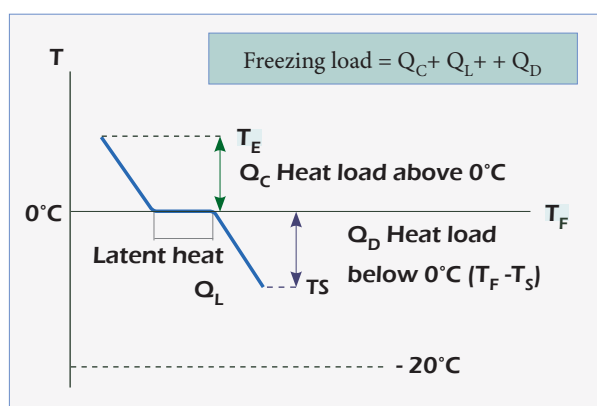


Fig. 53 Conventional freezing load method

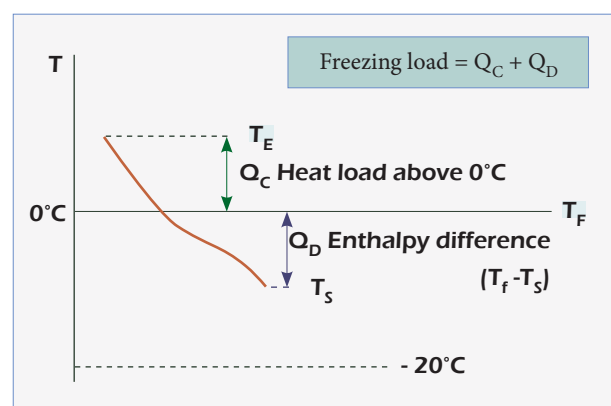


Fig. 54 Enthalpy method to calculate freezing load

7.6 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. 55 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.

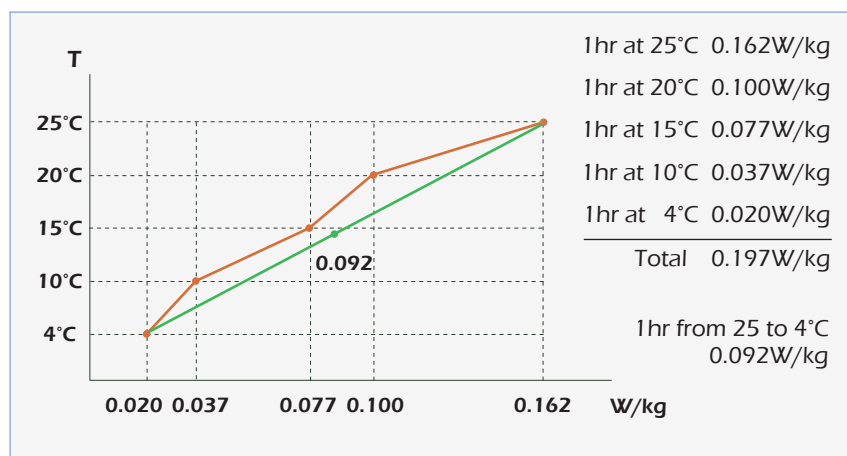


Fig. 55 Respiration load of bananas at different temperatures

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 pallets, 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.

7.7 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. 56). 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 $\times$ 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.

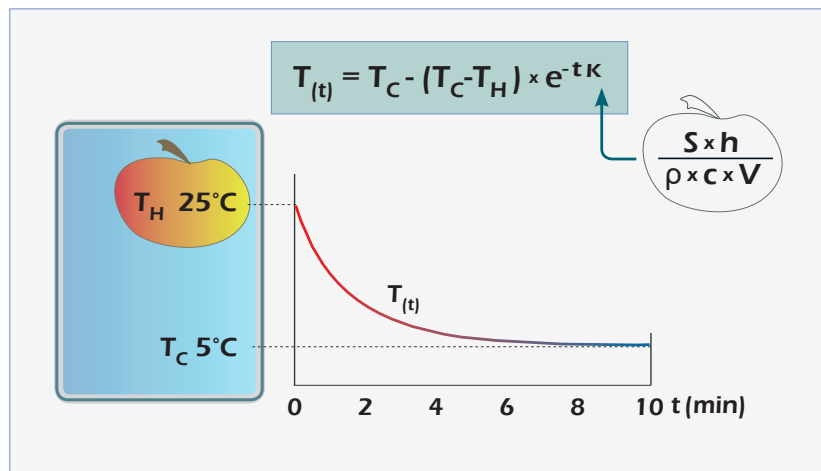


Fig. 56 Cooling time curve and influencing factors

8 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 definitely 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 7.6).

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 decelerates 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. 55). Besides lower quality, a five percent moisture loss equals five percent weight loss (salable mass).

Lowering the temperature below 4°C decelerates micro-organic 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 intended (dry aging of meat or ripening of cheese).

8.1 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.

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 humidity 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. 57 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.

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 have a sharp point but a zone of freezing that starts with the initial point of freezing, T_f .

The cells of animal and vegetable tissue are surrounded by an extracellular fluid which has a different concentration than the fluid inside of a cell, the protoplasm. 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.

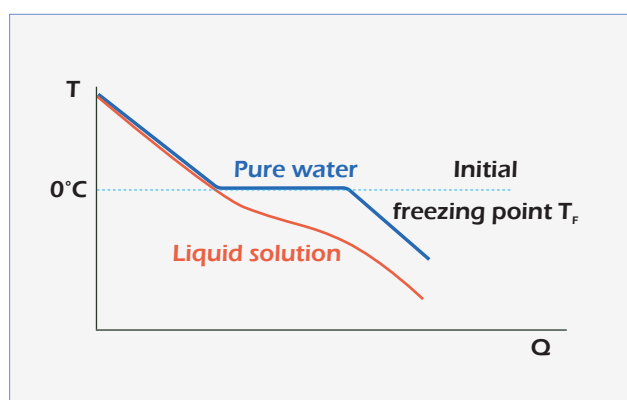


Fig. 57 Freezing of pure H_2O and water content

During freezing the extracellular fluid becomes more concentrated. The drop in osmotic pressure also causes a drop in turgor and the protoplasm 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 crystals. 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 hygienic advantages but their use is mostly limited to flat food products like fish fillets or leafy vegetables.

Cryogenic 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 sluice between cold storage and the outside.

8.2 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



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).

Tab.11 Refrigeration Temperature Applications	
Normal room temperature	>15°C
Cold tempered 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

Physical stress like cuts and crushes increase the respiration. Unlike most edible plants, some commodities, particularly 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 anaerobic 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.13).

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, fillets) 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.12).

Poultry can be stored for a week when cooled at -2°C. Long term storage 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 susceptible to bacterial contamination like salmonella and liquid refrigeration methods can require disinfection 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.

Tab.12 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	

Dairy products

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 hygienic conditions during milking and a warm climate can accelerate these negative effects (e.g. mastitis).

To ensure safe conditions for further use, raw milk requires special designed cooling equipment which can rapidly cool the product down to 4°C within 3 hours after milking. Cold rooms are therefore not initially intended for the storage of dairy products.

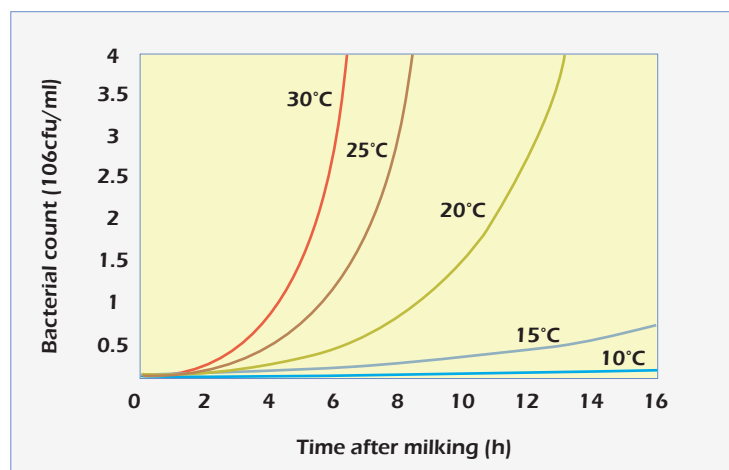


Fig. 58 Bacterial growth in fresh milk

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 melt water 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 seawater can be used but both should come from relatively clean sources. Seawater ice has the advantage that its melting point is around -2°C (depending on its salinity) so the latent 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 pickling or smoking.

Tab.13 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

9 PHOTOVOLTAICS

When sunlight hits a Solar cell, the doted semiconducting layers create an electrical charge separation of approximately of approximately 0.6 to 0.65 volts known as the **open circuit voltage** (V_{OC}). When connected to an electrical circuit, **photovoltaic cells** react in the typical curve manner of **semiconductors**. Once the internal resistance of the consumer matches the V/I of the Solar cell the optimal power transfer (**impedance matching**) or **maximum power point (MPP)** is reached. The MPP voltage of a PV cell lies around 0.55V. When a Solar cell is cut in half, both cell cuts will still have the same voltage output.

PV manufacturers connect PV cells in series to raise the voltage output to a useable level. The electrical current of a Solar cell is mainly determined by its size. Two half cells in series will therefore have double voltage but the same power output as the original full cell.

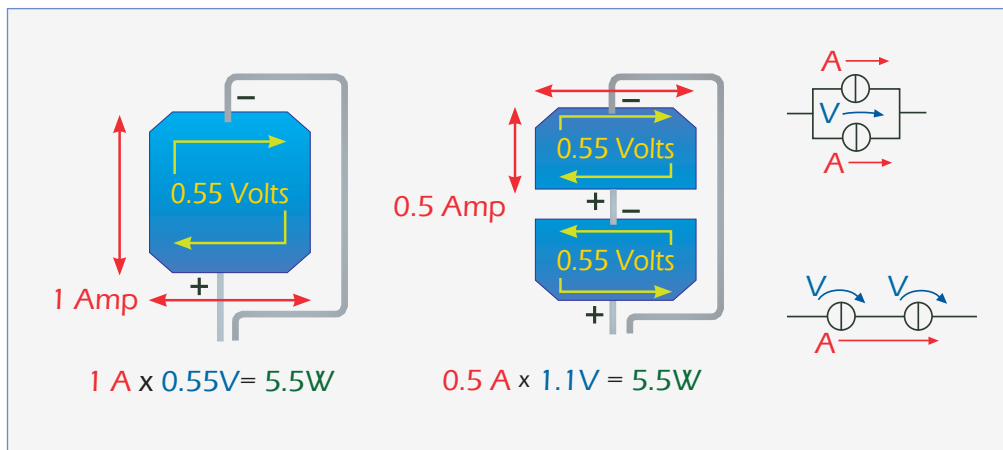


Fig. 60 Voltage current (V/I) values of PV cells

To provide sufficient mechanical resistance against environmental conditions, PV cells are embedded in an aluminum square tube frame. A front toughened, low reflective glass cover plus an additional number of sealing polymer layers provide a maximum ingress protection (IP68).

Crystalline cells are the most dominant PV type on the world market. **Monocrystalline cells** can be identified by their dark unichrome surface. They have a better power yield (and higher price) as **polycrystalline cells** with their blue ice crystal like surface. **Thin film cells** in some way are a second technology with a world market share (5-10%) but they are mainly used for building integrated photovoltaics (BIPV) and small indoor applications (e.g. calculators).

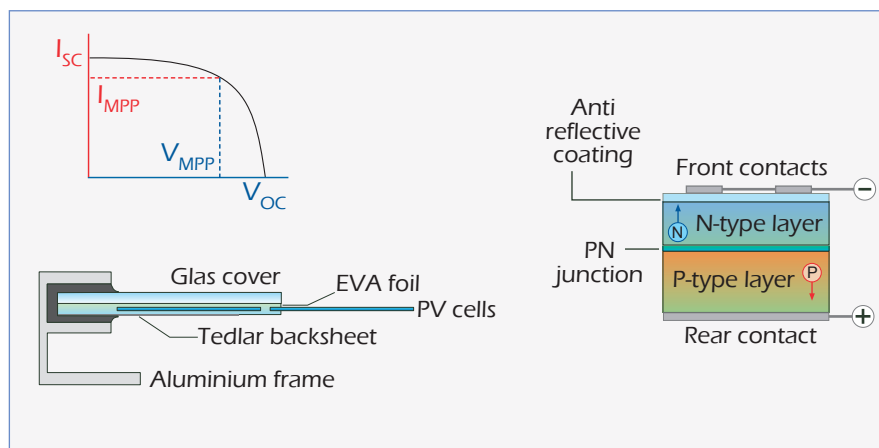


Fig. 59 Cross section of a PV cell and PV panel

Fig.61 shows the typical cell arrangements for various PV panels. The left graph depicts a 200Wp panel where 60 full cells are connected in series to generate an output voltage of 33V. The downside of a **serial connection** is that only one malfunctioning or completely shaded cell could block the whole electrical circuit. **Bypass diodes** divide the power circuit into three separate strings (3x20cells). If one string gets blocked the current flow of the remaining two strings ($6.1A \times 22V = 134Wp$) can still detour via the bypass diode of the shaded string.

12 cells of the same type can be cut in thirds and then be connected in a series of 36 cells to provide a nominal voltage of 19.8V. Such a PV panel can be used to charge a small stand-alone system with common 12 volt car batteries.

Half type Solar panels can even provide a better protection against partial **shading**. When part A is shaded, the parallel part B can still contribute to the power output together with the remaining strings CD and EF. The lower string current reduces the internal resistance (less heat generation) and increases the overall efficiency. Some manufacturers also use the increased space between the cell cuts to harvest an additional amount of deflected sun rays by applying an additional **PERC layer** on the rear side of the PV cell.

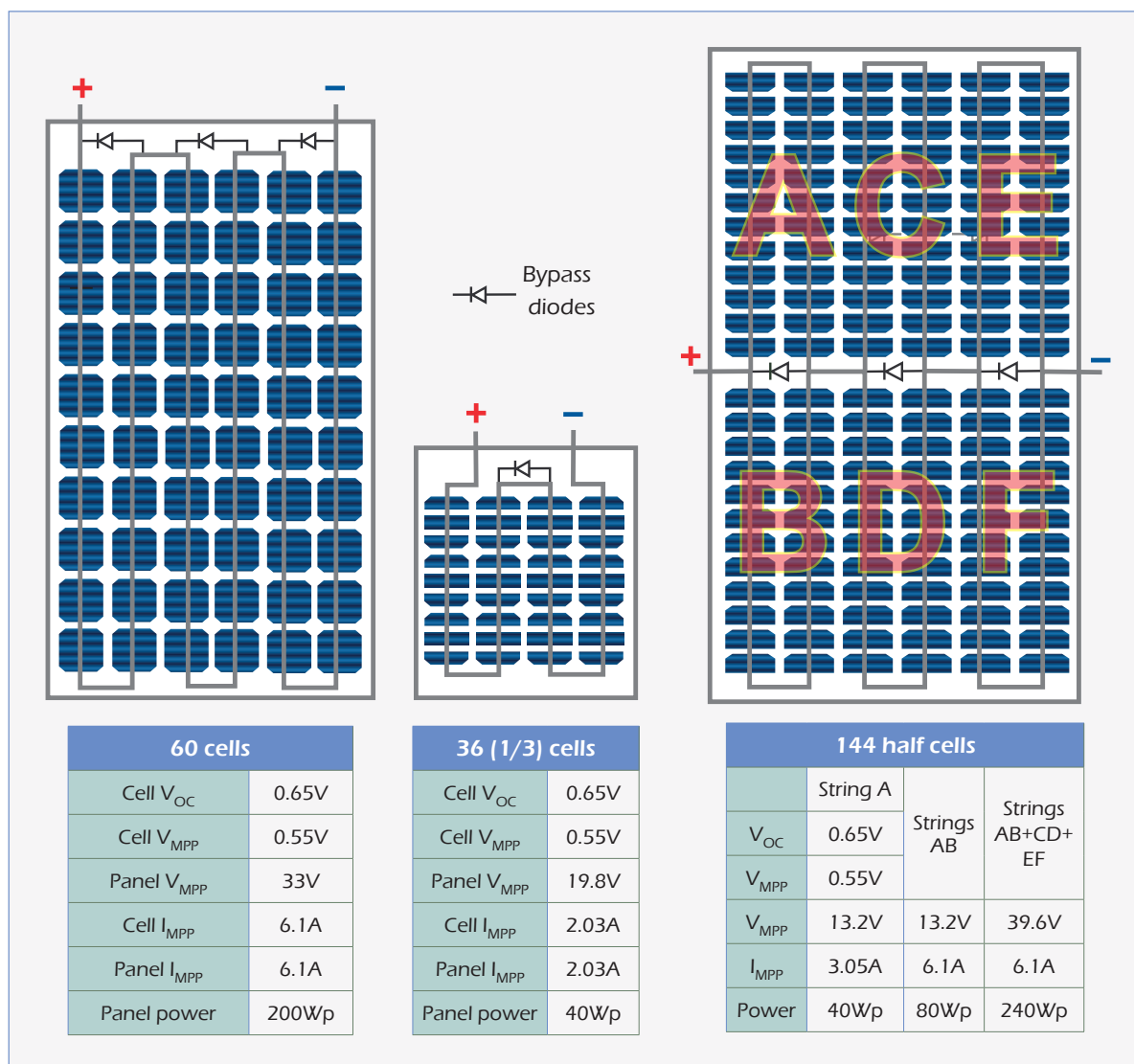


Fig.61 Cell arrangements for full cell (left) and half cell (right) PV panels

Datasheets of manufactures will always state the nominal (maximal) power output of their PV panels under **Standard Test Conditions (STC)** conditions i.e. a vertical radiation of $1,000\text{W}$ on a surface of 1m^2 at 25°C with a sun angle of 42° (**Air mass** or **AM1.5**). Variation of Solar insolation has the biggest influence on PV yield. Therefore in reality PV generators will perform most of their time under partial load. The influence of temperature variations (Fig. 63) are usually indicated on specs sheet by a **temperature coefficient** (e.g. $-0.3\%/^\circ\text{C}$)

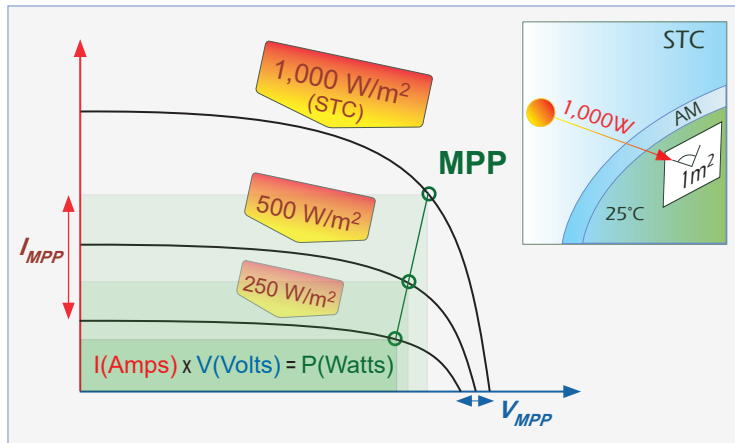


Fig. 62 Solar radiation impact on cell performance

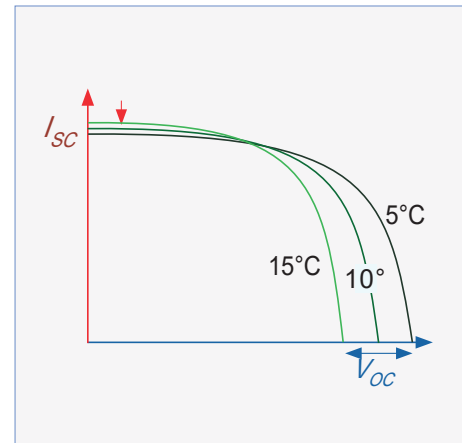


Fig. 63 Δt influence on cell voltage

PV Orientation

Fig. 64 shows how the annual sun paths are defined by the **geographic latitude**. In countries beyond the tropic latitudes, PV panels will generally be orientated towards the month with the least insolation e.g. in Capetown (RSA) a PV generator should be orientated towards the north with a 30° angle. In the sunbelt countries (between 23.5°N and 23.5°S) panel orientation does not play a crucial role. Months with lesser energy yield are more dependent on seasonal factors (dry and rainy seasons).

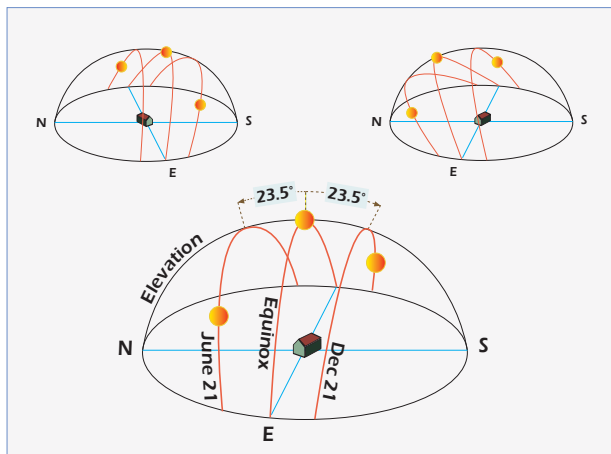


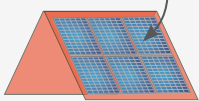
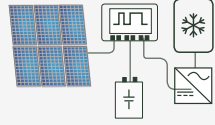
Fig. 64 Geographic latitude defines annual sun paths

Tab. 14 Calculation of the Sun Elevation

Sun altitude = $90^\circ - \text{Geo latitude} \pm \text{declination}$

Declination: (at midday)	Khartoum 16°N	Nairobi 1°S	Capetown 34°S
23° (Dez 21)	51°	68°N	79°
0° (Mar 21/Sep 21)	74°	89°	56°
23° (Jun 21)	97°	66°S	33°

Another important aspect for lesser energy yield can be panel staining. In countries with frequent rainfall throughout the year, PV panels which are installed with a steeper tilt angle ($>25^\circ$) will be prone to a **self cleaning effect** by rain wash-off. Panels with a lower tilt angle and in areas with less rainfall, occasional manual cleaning of the PV generator might be necessary to avoid a significant energy loss. Water hose spray cleaning should be conducted during the morning hours to induce less heat stress on the panel structure.

Tab.15 Nomenclature of Photovoltaic Components		
PV cell	the smallest photovoltaic unit with an electrical charge separation when exposed to sun light	
PV panel	PV cells in series in an enclosed weatherproof frame	
PV generator	The total number of connected PV panels at an outdoor location e.g. roof installation	
PV system	The complete system with all technical components to provide electrical energy	

Connector Cables

Larger PV panels come with pre-installed 4mm² double insulated connector cables. Certain connector types require special crimping tools for their plugs (MC4). Some types can be fixated with regular electrical hand tools (Weidmueller). Fig. 65 shows how PV strings can be connected in loop type and leap frog manner.

Roof installation of PV panels do not increase the risk of direct lightning strikes but as a preventive measure against indirect lightning surges, the loose parts of the connector cables should always be secured tightly along the center line with cable binders to avoid surge currents by indirect induced lightning strikes

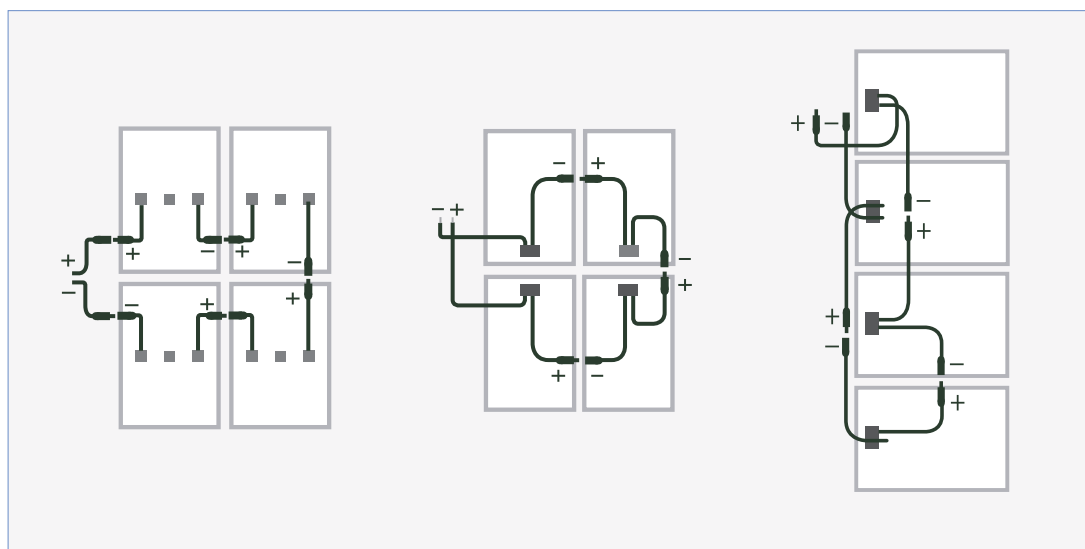


Fig. 65 Loop wiring and leapfrog (right) connection of PV panels

Panel Mounting

Most common fastening systems for PV panels consist of aluminum profile rails which can be installed directly on a load bearing steel frame of the cold room roof structure. If a corrugated sheet metal is used as roofing, the rails can be fixed via adjustable stainless steel clamps. Middle clamps between panels and end clamps can be slid into position with counterbolts that fit into the rail profile. According to manufacturers, these mounting systems are generally designed to withstand wind gusts up to 100km/h (30m/s) or more.

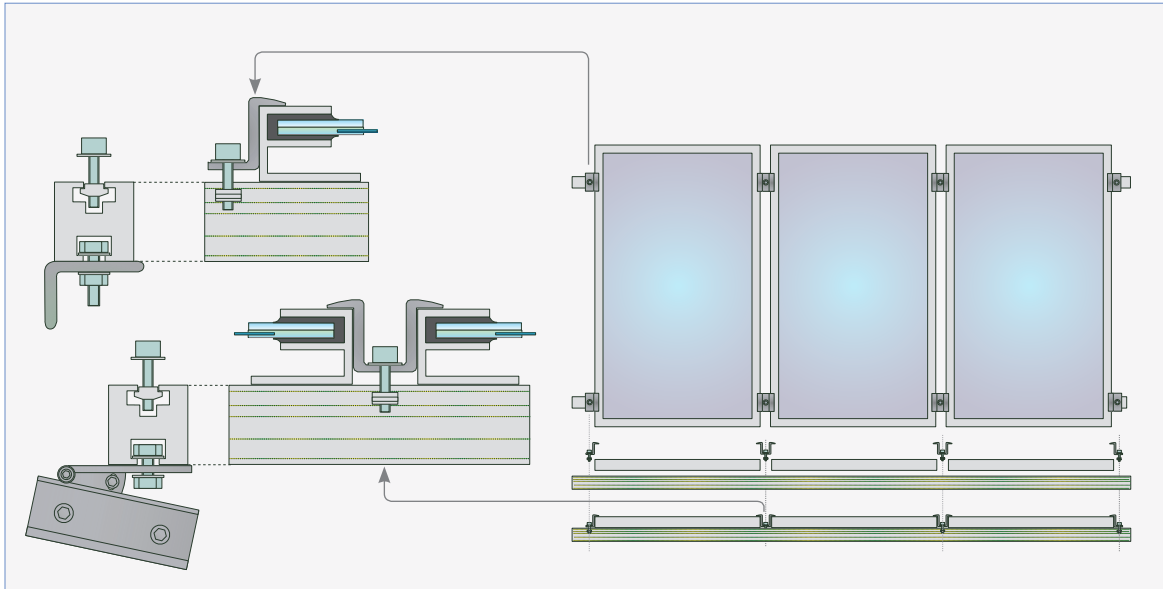


Fig. 68 PV racks with aluminium profile rails and panel clamps in horizontal position

9.1 Generator Junction Box

Due to their high internal resistance, PV panels are short circuit proof. But a PV panel exposed to sun light should never be disconnected manually since the opening gap between the two cable poles can lead to an **arc flash** similar to the light arc used in electric welding. The dashed red line in Fig. 66 shows that such an arc incident can already be created by one 415Wp panel. To safely disconnect a PV generator from its controlling unit at any time, larger PV systems must be installed with a **generator junction box (GJB)**.

Fig. 67 shows the central DC switch which is capable to safely disconnect loads up to 1,000V. A GJB should also contain a surge protecting device. Surge currents induced by indirect lightning can be diverted towards earth via the yellow/green grounding cable. The three pole surge protectors for PV cold rooms should have a maximum current diversion of 40kA. A visual status indicator shows a color change (green to red) when the surge protector is no longer functional and needs to be replaced.

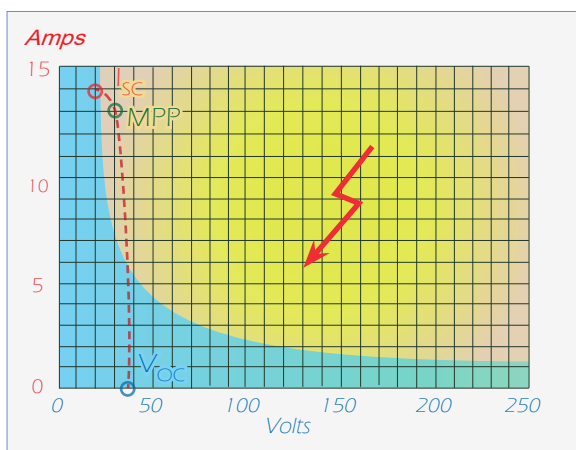


Fig. 66 Accidental arc flash generation

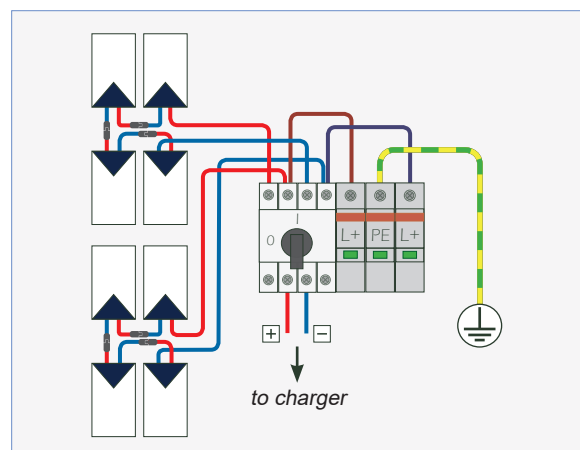


Fig. 67 Cable wiring in a generator junction box

10 ENERGY STORAGE

The possibility to consume Solar energy throughout the whole day and night requires some sort of electrical energy storage. At the moment lead acid accumulators and Lithium-Ion batteries are the prevailing technologies of the energy market. Electrochemical accumulators (lat. accumulare: to heap) can store energy in a chemical form and release it as electrical energy. To raise capacity and voltage output, cells are stacked up in series, hence the name batteries.

10.1 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 flooded with an electrolyte, a mixture of distilled water and sulfuric acid (H_2SO_4). 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. 69)

Putting a higher voltage potential on the outside terminals recharges the battery. The charging and discharging of a battery is called a **duty cycle**. Manufacturers recommend a maximum **depth of discharge (DOD)** of 50%. According to Fig. 70 a battery with such a DOD has around 500 duty cycles. A smaller depth of discharge would prolong the lifetime of the battery. Usually the life span of a battery is reached when it can 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.

Battery Capacity 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.

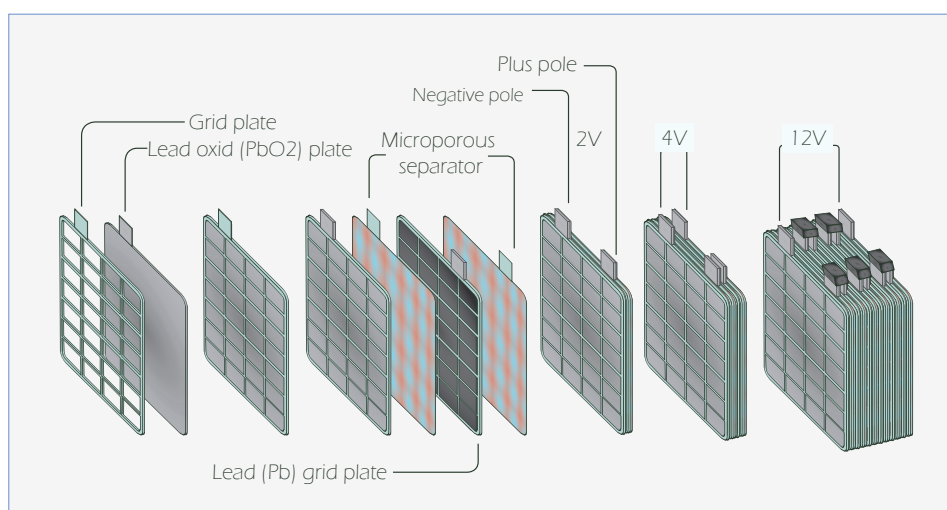


Fig. 69 Alternating lead oxide and lead plates form a rechargeable lead acid battery

Fig. 71 shows the real (usable) 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.

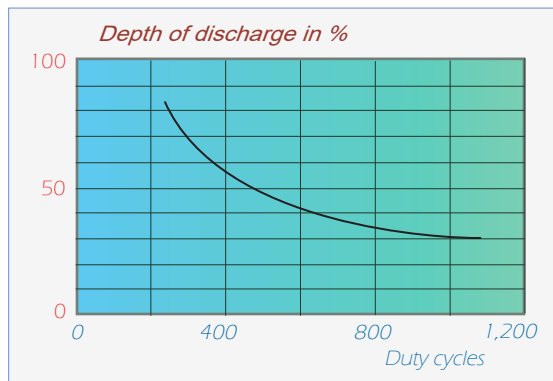


Fig. 70 Depth of discharge and battery life

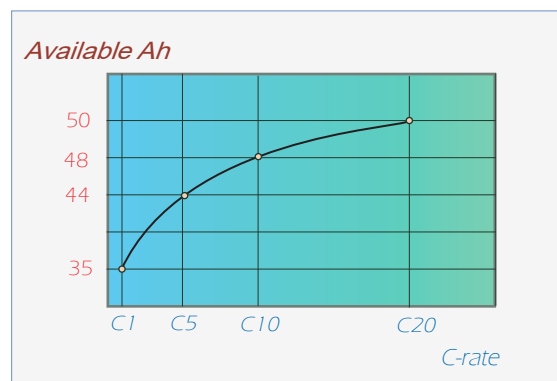


Fig. 71 Usable capacity of a 100Ah battery

Battery data sheets should provide the information about available capacity at various C-ratings. Eventual discharge load spikes are of course always possible. C relates to the average discharge rate.

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.

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.

A lead acid battery that will not be charged for a longer time can lead to self discharge. Starter batteries are more prone to be damaged by this effect. Lead acid batteries for Solar applications 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.

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 division slash is omitted and C/20 is written as C-20 or C20 or stated as a factor (0.05).				

Lead 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 $R_i \ll R_L$). Voltage sources are not short-circuit proof. Batteries should therefore always have an overload **fuse protection**. Encapsulated ceramic fuses with a visual inspection cover can be mounted at the battery clamp and have a current rating between 50-300A.

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.

10.2 Solar Charge Controllers

Maximum power point trackers (MPPT) contain a microprocessor controlled algorithm that continuously scans the V/I curve of the PV generator for its **maximum power point** ($P=V \times I$). By adjusting its internal resistance to the momentary MPP, the maximum available PV power can be yielded at all times.

MPP charge controllers with a separate load terminal (see A1 in Fig. 72) contain an integrated transistor that acts as a deep discharge protection (**DDP**). It disconnects the load with a MOSFET switch when a critical minimum voltage level of the battery is reached. When the charge voltage drops below a minimum level the consumer loads will be reconnected again. MPP trackers with no load terminal need an extra DDP battery protection between battery and the DC loads respectively the AC inverter (see B1 in Fig. 72). Like PV cells battery blocks can connected in series to raise their system voltage (e.g. 24, 48 Volts). The DDP device must be chosen according to the battery voltage and the expected load and peak currents.

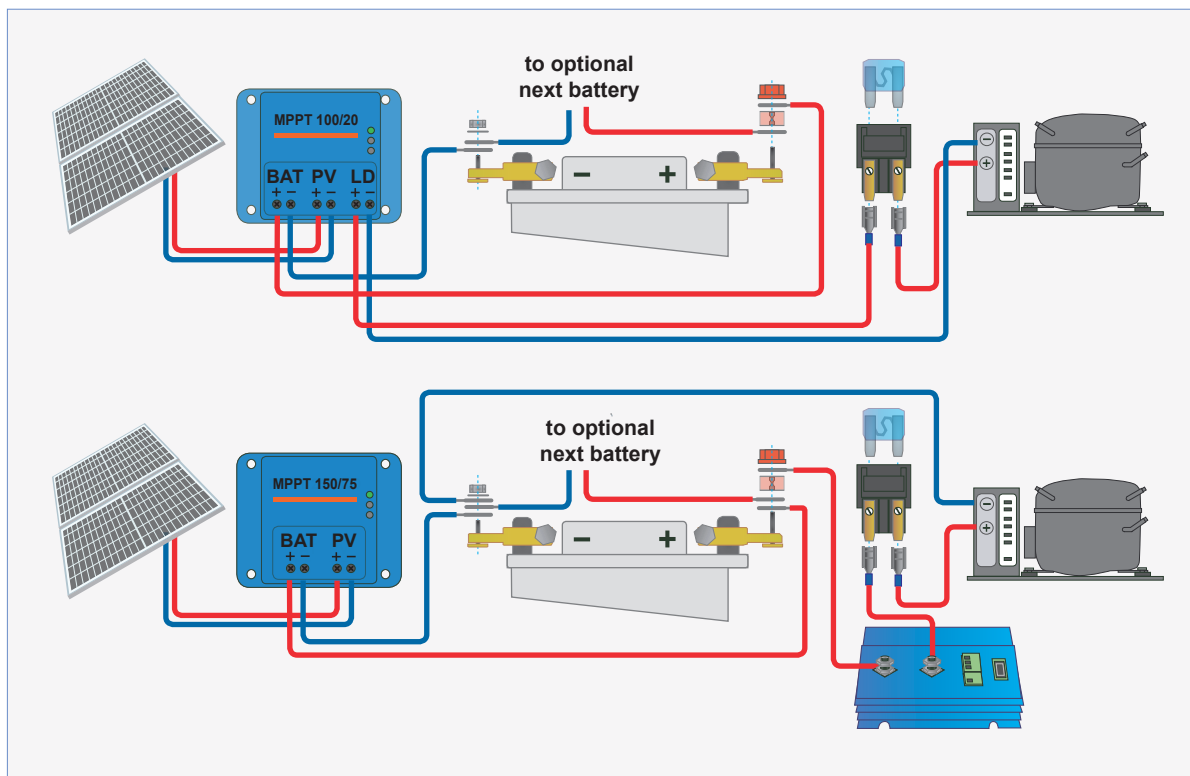


Fig. 72 DDP of charge controllers with short circuit and overload protection (NTS)

10.3 DC Safety Features

Electrical batteries are voltage sources, short-circuiting leads to immediate overheating (thermal runaway) which can lead to fire or even explosion of the battery. Direct short circuiting of the battery poles can be avoided by using PVC pole covers. Short-circuiting from the consumer side should be avoided by interconnecting a thermal fuse in the load circuit. Ceramic fuses can be placed on the mounting thread of a battery clamp. Their enclosure offers spark protection and a transparent side cover offers visual inspection of the melting element. Fig. 73 shows the exponential curve of a fuse with a nominal rating of 50A for a maximum voltage of 58VDC (1).

At 100A ($I/I_N=2$) the fuse will melt after 10 seconds ($t=10^1$ s). Beyond the critical value of 300A the fuse will blow immediately (10ms). To protect the electrical circuit and its consumer against over currents, automotive blade fuses are used. With a nominal voltage of 32V one fuse for each cooling unit is rated at 15A, which can be seen by its color coding (light blue). All circuit fuses can be mounted in a single connector box with a transparent PVC cover at a position where they can be easily inspected and replaced.

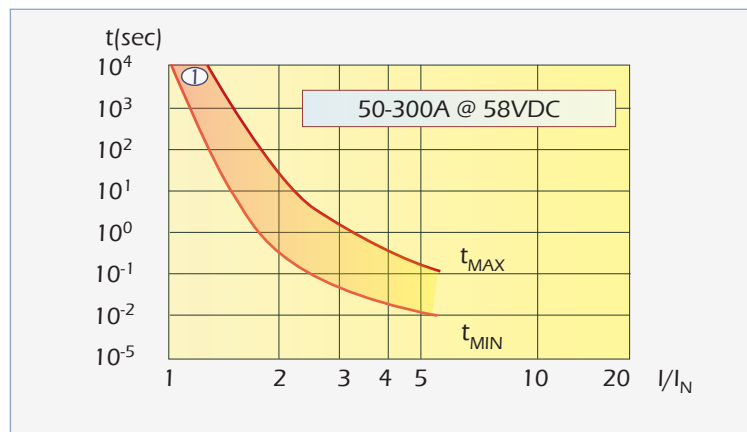


Fig. 73 I/t characteristics of a battery fuse

Lead Battery Charging

Besides the basic protection against deep discharge, reverse polarity and overloading, MPP trackers should also provide more advanced features to optimize Solar yield and prolong battery life. A whole battery charging cycle is usually divided into separate different stages.

The first stage is known as **boost** or **bulk 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 capacity (e.g. 10A for 100Ah battery).

During the CC phase the battery voltage will continuously rise until the maximum voltage is reached. At the end of the bulk phase, the battery should be charged by 80%.

Absorption stage or 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 minimal threshold (tail current) or when a programmed time span is over.

Some solar chargers calculate the length of the absorption stage dependent 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.

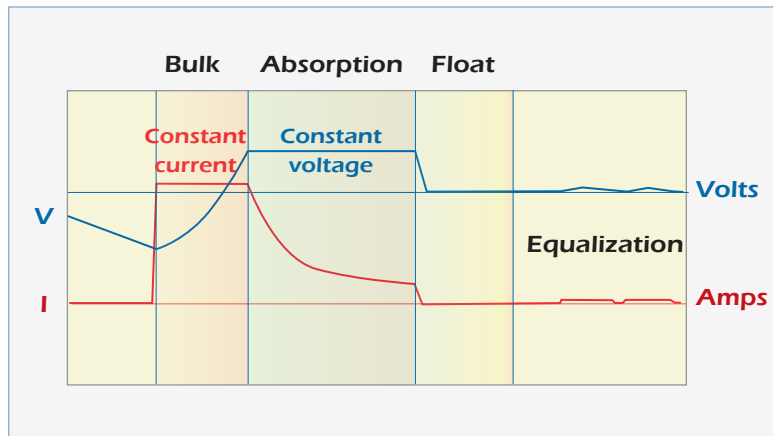


Fig. 74 Three main stages of a battery charging cycle

When the **float stage** is reached, 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.

Some battery manufacturers recommend an occasional **equalization stage** when battery remains 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. To observe and eventually change the settings of these charging stages an MPP tracker should have data logging and monitoring capabilities.

10.4 Lithium Batteries

Lithium (chem. symbol Li) is the lightest metal and has the highest electrochemical potential of all elements. Lithium metal batteries have a cell voltage around 3.7V. 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.

With a few exceptions, **Lithium metal batteries** are non rechargeable batteries. During discharge, the metal structure of the lithium anode disintegrates. 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 ion batteries (Li-Ion or sometimes LIB) contain no free metallic Lithium but are present in the molecular structure of a 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 or LFP for Lithium Iron Phosphate.

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.

Lithium battery cells with liquid electrolytes need a robust, impermeable and seal tight enclosure but the complete immersion of the electrodes provide a favorable ionic conductivity and they have a reasonably low cost production. Solid state electrolytes (SSE) have no leakage issues and do not need tight sealed enclosures but their production is still more 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. 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 thermo-tolerance and good ion conductivity.

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 battery's **state of charge (SOC)** and the **state of health (SOH)**.

Fig. 76 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 continuously 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. 75). Another advantage of LIBs is that they can be discharged to a hundred percent of their capacity.

State of Health (SOH) defines how much adversary aging effects (e.g. cell degradation) have affected the batteries ability to provide energy compared to its nominal (i.e. factory new) condition. **Battery management systems (BMS)** 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.

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.

Besides the general system control of an external BMS, 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 over-current 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.

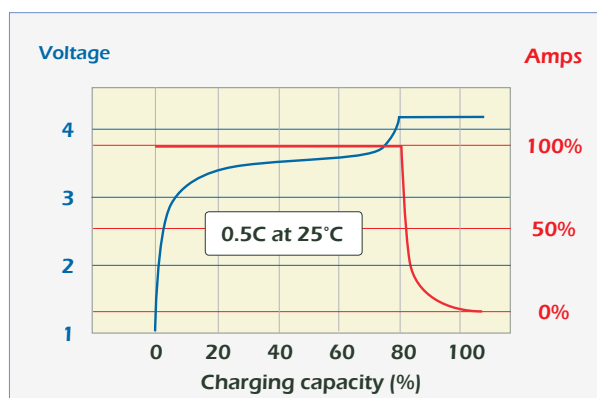


Fig. 76 Charging stages for Li-Ion batteries

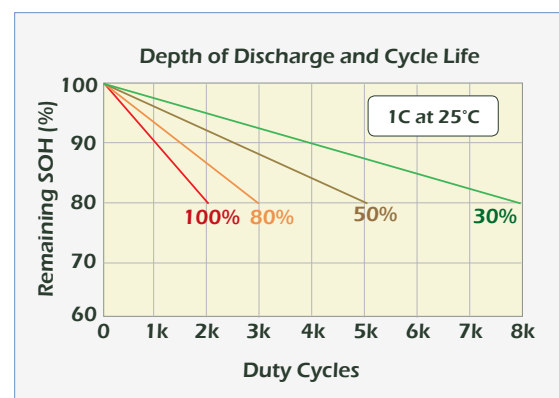


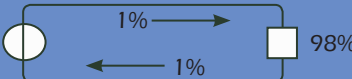
Fig. 75 DoD influence on LIB cycle life

10.5 Cable Dimensions

One of the main parameters to provide efficient power transfer in an electrical system are sufficient cable dimensions. Tab.16 shows the relevant factors to calculate the minimum required cable dimension in mm^2 (A_L) when the voltage drop (and hence the power loss) should be kept below a tolerable 2% (Dissipation loss D). Cable length (L) and power (P) can be found on top part (numerator) of the fraction, the larger these values the thicker the cable diameter needs to be. Large values in the lower part (denominator) will help to decrease the necessary cable diameter. Besides dissipation losses (max. 2%) and the material conductivity, the most important parameter is the system voltage (V^2). Especially in low voltage PV systems the components like PV generator, MPP charger and the battery bank should always be located together as close as possible.

The low voltage (24VDC) system in Tab.16 shows that a 10mm^2 cable is required to provide a sufficient power transfer. The second example shows that if the system voltage is raised to 230VAC a significant amount of more power (2000W) can be transmitted through a much smaller cable dimension (1.5mm^2).

Insufficient cable diameters do not only lead to power loss but can also pose a potential fire hazard caused by overheating and melting of the PVC cable insulation.

$A_L = \frac{L \times P}{V^2 \times K \times D}$ 						
	Length L feeder & return line	Power P	Conductivity K aluminium 36 copper 56	Dissipation losses D	System voltage V	Required cable dimension A_L
MPPT to DC battery	6	680	36	2%	24 (VDC)	10mm^2
Inverter to AC consumer	24	2000	36	2%	230 (VAC)	1.5mm^2

11 AC CIRCUITS

AC or alternating current is mainly used for electrical power transmission because of its easy ability to change the voltage level by transformers into the preferred voltage level (induction). The electrical generator of a utility grid power station will usually have a voltage output level of a few kilovolts (kV). To minimise losses for cross country transmission the utility provider can transform the electrical power via transformer stations to high voltage level (110kV) and then down again to mid voltage level (10kV) and once the distribution lines reach domestic consumers, the voltage level will be transformed further to the final low voltage level of 230V with a 50Hz frequency (50 cycles or full up and down amplitude movements per second).

For a lot of application units it is quite common to convert the AC voltage back to direct current (e.g. IT units). Small transformer units (e.g. housed in electrical plugs) convert the voltage level down to a few volts and a rectifier then straightens out the current back to a straight DC line.

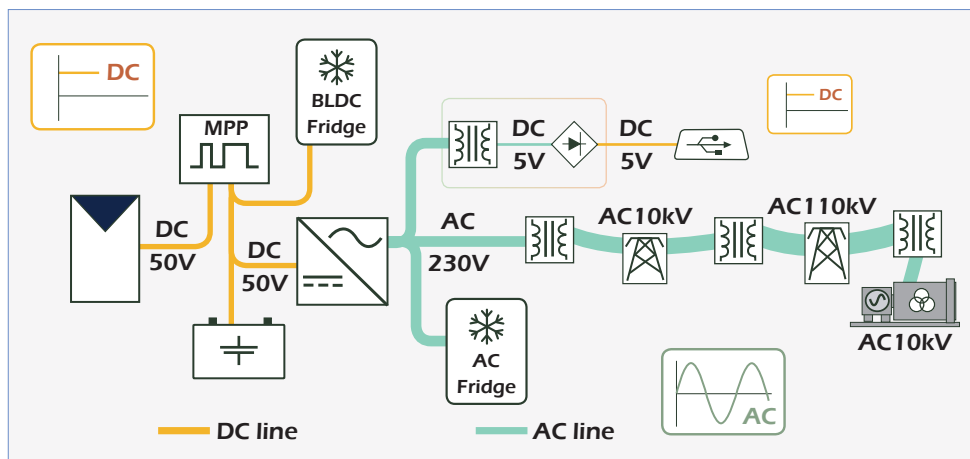


Fig. 77 DC Solar system with inverter tied AC utility grid

11.1 PV Inverter

PV battery systems can supply DC consumers directly like a BLDC refrigeration compressor. For AC units like induction motors or larger ohmic consumers (heating), Solar systems use DC/AC inverters. They basically work on the same principle. The direct current is chopped up into an alternating 50Hz frequency and then converted to the regular voltage level which is usually around 220-240V per phase in a three phase system though some countries also use a 110V/60Hz system

About ten years ago. Solar inverters could be divided into two main groups. **Grid inverters** that were synchronized (aligned) with the utility grid frequency and that supplied their whole energy into the grid (renumeration system). On the other side off grid or **island inverters** that were able to supply a separate small utility grid with power. Larger island systems (mini grids) usually also include a diesel generator as an alternative power backup (**hybrid system**). A combination of both functions (off grid/on grid) in one system required the additional installation of a contactor switch box.

Due to the technical developments of the last years especially advanced data logging and monitoring capabilities and plus an increased global electrical power demand (e.g. electrical mobility) PV inverters are becoming a central one-in-all unit that can distribute power omnidirectional and in a custom preset manner (Fig. 78).

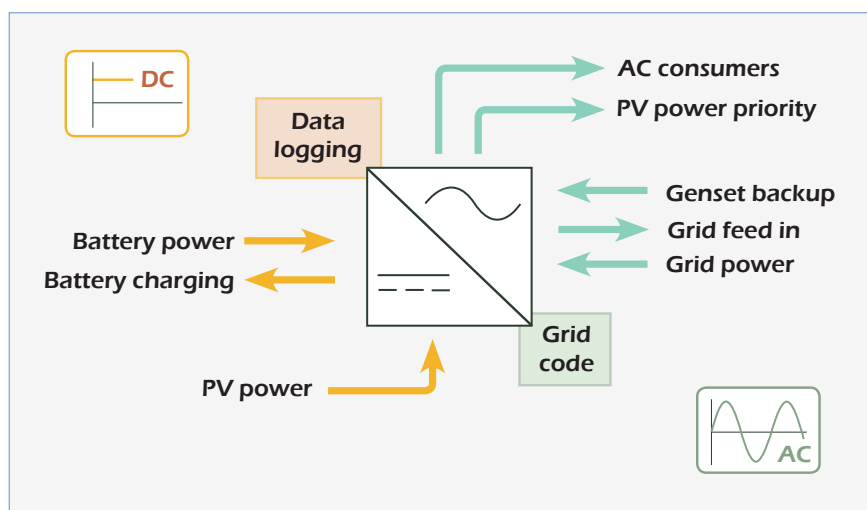


Fig. 78 Hybrid inverter with omnidirectional power distribution

11.2 AC Safety

Since electricity is generally hazardous to the human body, sufficient safety features must be in place to avoid a direct contact with voltage carrying equipment. **Basic protection** can be provided by insulation (wiring), enclosures (plugs), physical barriers (power station fences) or distance (overhead lines). **Fault protection** are additional safety features that prevent contact with equipment that carries electrical voltage by fault or by accident. This can be done by reinforced or double insulation, a lower voltage level (below AC50V/DC120V) or galvanic insulation (voltage transformers).

The public utility grid supply with its AC230V voltage level is built as an **earthing system**. The electric circuit consists of one (220-240V) or three phases (380-415V) and a neutral (blue) line which originates at the star point of the power source (Fig. 79).

Every earthing system must include a separate **protective earth** line which starts at the earliest possible connection with neutral (**PEN**) and must be securely connected to all exposed metallic parts (e.g. motor casings, metallic water piping) which could carry an electric voltage in case of a fault.

Residual current devices (**RCD**) can prevent an electrical accident if a person touches such a fault current carrying device. An interconnected RCD contains a high sensitive magnetic coil that senses the incoming (phase) and outgoing (neutral) current. Under proper conditions phase (I_{OUT}) and neutral (I_{IN}) cancel each other out ($I_{IN} - I_{OUT} = 0$) and the induction into the coil is zero. If a faulty current flows from the metallic casing over the protective earth line back to the star point, the current imbalance induces coil voltage which will trigger a magnetic switch to immediately disconnect the supply circuit. The time/current tripping characteristics of an RCD must be within maximum safe limits that protection is always provided even if a person is already in contact with a faulty conducting device (e.g. bathtub).

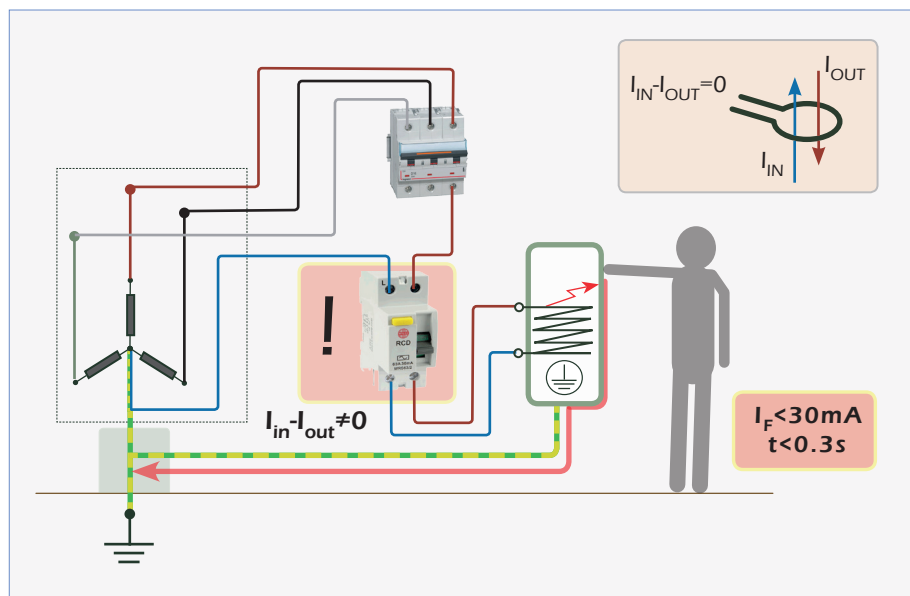


Fig. 79 Personal protection from electrical fault current by an RCD

Miniature circuit breakers (MCB) are automated safety devices to protect cable installations and electrical units. A magnetic jumper provides protection from an instantaneous excessive over-current (e.g. short circuit) . Thermal interruptors like bimetallic strips serve as a protection from an extended current overload e.g. excessive motor drag. International standards (IEC 60898-1) classify MCBs by their nominal current I_N which defines the maximum current at which the device can be operated continuously and their instantaneous tripping current which is a multiple value of I_N . Type B (3-5 I_N) and Type C (5-20 I_N) are mainly used for domestic applications. Type D (10-20 I_N) can be used for devices with high starting currents like electric motors. Every branching circuit must have its individual fault protection.

MCBs and RCDs cannot be reset manually as long as the fault cause is not repaired (trip-free mechanism). It must be emphasized that this chapter does only provide a general overview on electrical safety devices. Proper and safe operation of electrical units can only be guaranteed if the installation has been done and commissioned by a certified professional installer.

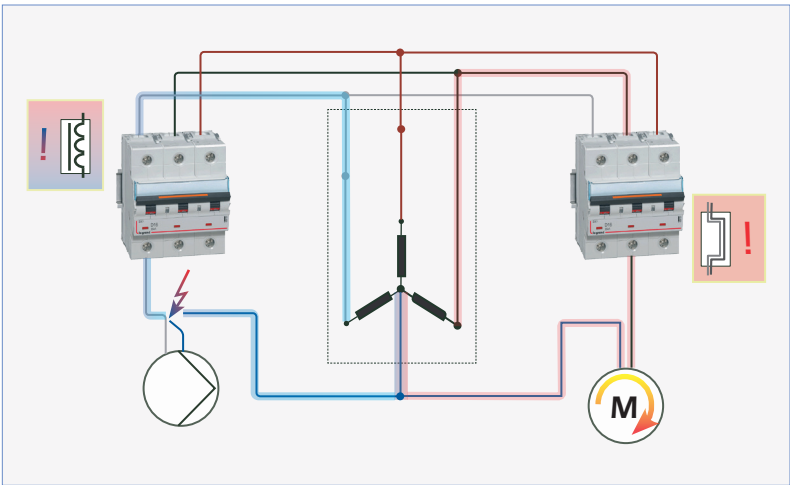


Fig.80 Short circuit (left) and overload protection (right) by MCBs

Ingress Protection

Depending on the purpose and the location, the casing of an electrical device must ensure protection against contact, solid particles and liquid ingress. Categories are defined by the ingress protection (IP) two number code. Solar equipment for outdoor use must provide at least IP65. Inverters and distribution boxes that are installed in an open but weather proof location should have at least IP54.

Safety work rules for low voltage (230/400V) systems	
Measure system voltages	Fault detection and proper check of measuring device
Disconnect all voltage sources	Remove fuses, switch off RCD and MCBs
Make sure voltage is zero	Use of two pole measuring device
Secure against reconnection	Lock distribution box, put up warning tags

12 SOLAR POWERED COOLING

The term Solar cooling involves a number of different technologies which can be generally classified by the form of their energy source. Solar cooling by sorption (absorption and adsorption) is using Solar thermal energy as its energy resource. A detailed description on this technology can be found in the transcript "Solar Powered Cold Rooms and Refrigeration". Solar powered cooling uses PV generated DC current which can be either converted by an inverter into alternating current (AC) to drive a regular AC cooling compressor. For the second option the DC power is used directly to drive a series of small DC compressors with an additional latent enthalpy thermal storage unit.

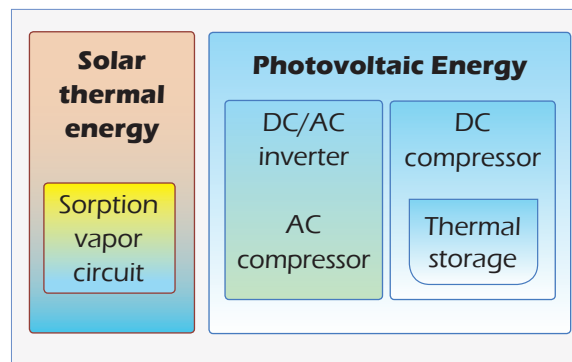


Fig.82 Overview on Solar cooling technologies

12.1 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.

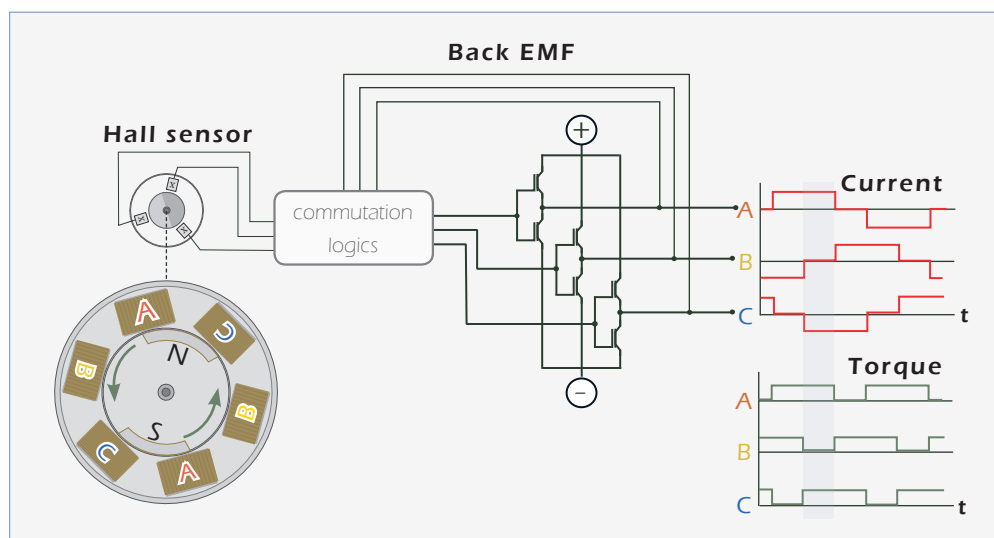


Fig.81 BLDC Motor with electronic commutator control

12.2 Solar Battery Systems

Fig. 83 shows the procedure to size and design a Solar powered cold room with lead battery bank as an energy backup. The calculation starts with the total required daily energy output which is determined by the total daily cooling load (Fig. 45) divided by the real COP of the cooling system (see Fig. 22).

The sizing calculations should always depict the calendar month with the least average Solar daily radiation. When daily irradiance (kWh/m^2) is divided by the STC (kW/m^2) the result is **full load hours** per day (hrs/d) which means the PV system will operate so many hours at its nominal power output.

The daily energy demand (kWh/d) minus the estimated losses for temperature, orientation and system divided by full load hours (hrs/d) will give the required size of the PV generator (kWp).

To cover a 24/7 cooling demand a lead acid battery bank must provide power during off-PV hours. The calculation include a loss by battery efficiency and a depth of discharge (DoD) factor. The usual DoD for lead acid batteries should not be below 50%. The result in Fig. 83 shows that a pure PV/Battery cooling system would require quite a huge battery bank (18kWh which is equal to fifteen units of 12V/100Ah batteries).

The example does yet not include a safety margin for **reserve days** i.e. the number of days when adverse weather will not provide any PV power and the batteries will be the sole energy providers. Adding one full reserve day into the calculation would even double the number of required batteries.

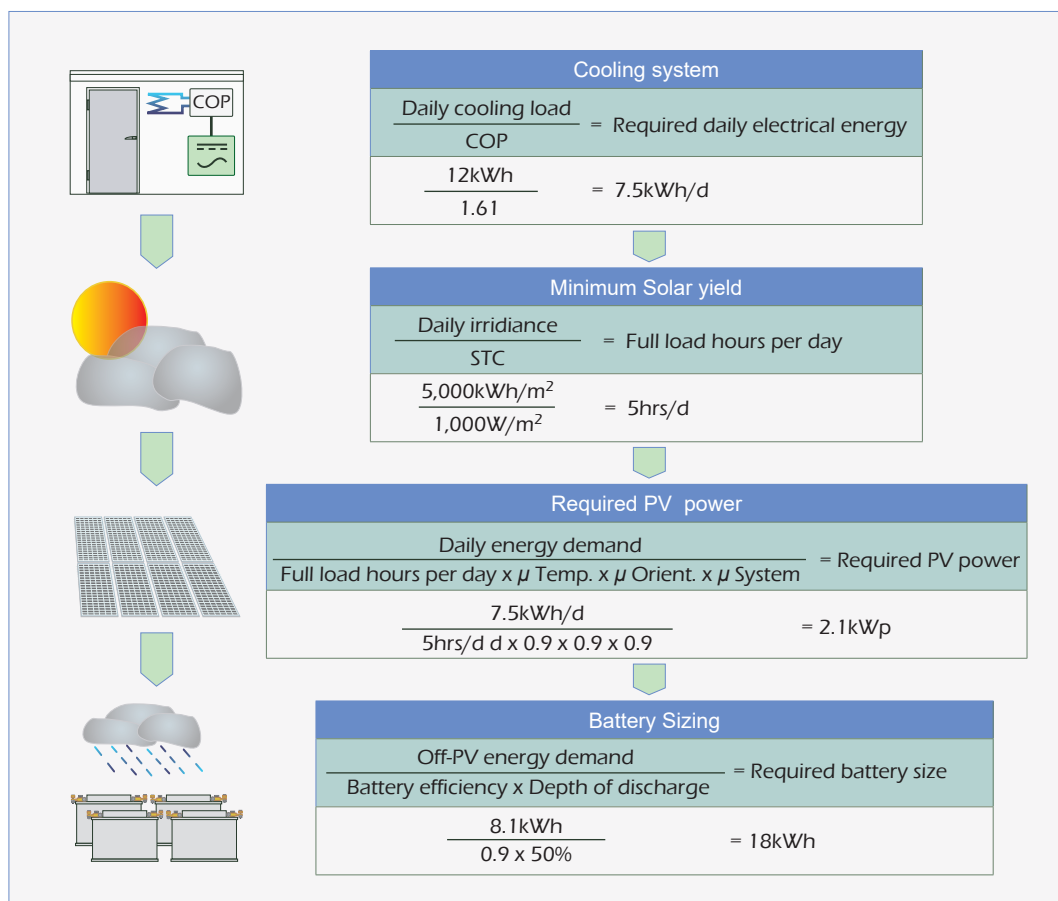
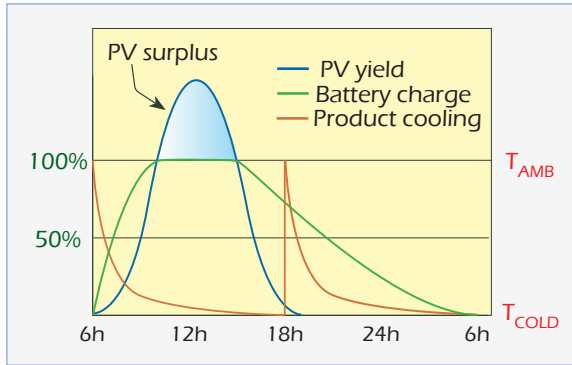
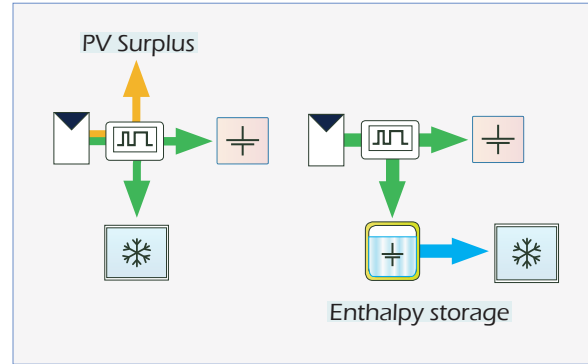


Fig. 83 Design steps for a Solar powered cold room with battery backup


Fig. 84 Problematics of Solar battery charging

Fig. 85 Improving PV yield by enthalpy storage

12.3 Solar Cooling with Latent Enthalpy

Another major problem of a sole PV/battery cooling system is shown in Fig. 84. With increasing Solar radiation in the morning hours, an adequately sized PV generator will provide enough power for product cooling and to recharge the batteries. 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 products have reached their cooling temperatures (T_{COLD}), the 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.

An effective and economical solution for an improved yield of 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 (liquid to solid ice) has been used as a cooling medium for centuries. The main task of the lead acid batteries is to stabilize the system voltage level and as an occasional energy backup during off-PV hours.

Thermal Enthalpy DC Cooling Unit

Fig. 86 shows such a DC powered Solar cooling unit that uses a water chiller as its main thermal storage element. A standard foam isolated polyethylene 500l dry ice box container (LC) is filled with water. Six (2x3) evaporator plates are completely submerged in the water to provide an extended cooling surface. Since the 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 (D1) that pumps the cold tank water via a flexible hose to the heat exchanger unit in the cold room.

Solar power comes from three separate PV strings. Each string consists of two 380Wp panels connected in series ($2 \times 42V_{OC}$) and has its own MPP charge controller (C1). To provide the system output voltage of 24VDC, each tracker provides charging power to two lead acid batteries (B1) which are connected in series ($2 \times 12VDC$). The three 24V battery packs are then connected in parallel to raise the current output. Since the MPP trackers do not have a separate load terminal with an integrated DoD control their output lines must be connected to a deep discharge protection device (DDP). From there every cooling compressor is connected via a separate 15A thermal fuse overload protection.

The cold water distribution consists of a 24VDC pump (D1) that circulates the ice water to a heat exchanger (D2) which is installed inside the cold room. This cold water/air heat exchanger distributes the cooled air via a fan into the cold room. Pump and heat exchanger are controlled by a thermostat (D3) which can be set manually to the required temperatures of the cold room. The power supply for the whole distribution unit comes from a separate MPP tracker with a load terminal that contains an internal deep discharge protection. Power supply for the distribution unit comes from two 380Wp panels in series ($2 \times 42V_{OC}$) and two lead acid batteries in series ($2 \times 12V$).

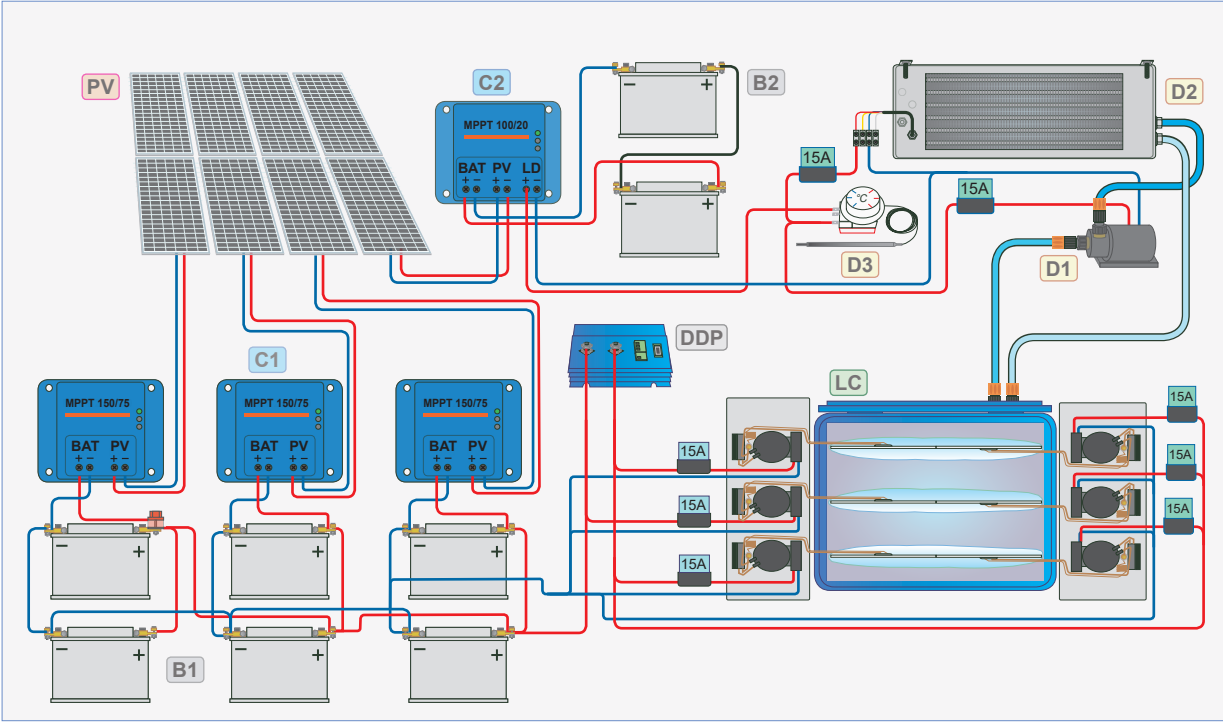


Fig. 86 Solar DC powered fusion enthalpy cold storage system

Enthalpy Cooling Efficiency

Fig. 87 shows the additional cooling enthalpy when a cold box is included to the Solar cooling system. The required daily cooling demand (12kWh) is divided by the cooling capacity of water (0.09kWh/kg/K) generated by a phase change from liquid to solid ice minus a certain loss (~ 10%) in system performance. The result will be the required ice mass production by day (144kg). Estimating an ice product ratio of 50% will also give the required standard tank size.

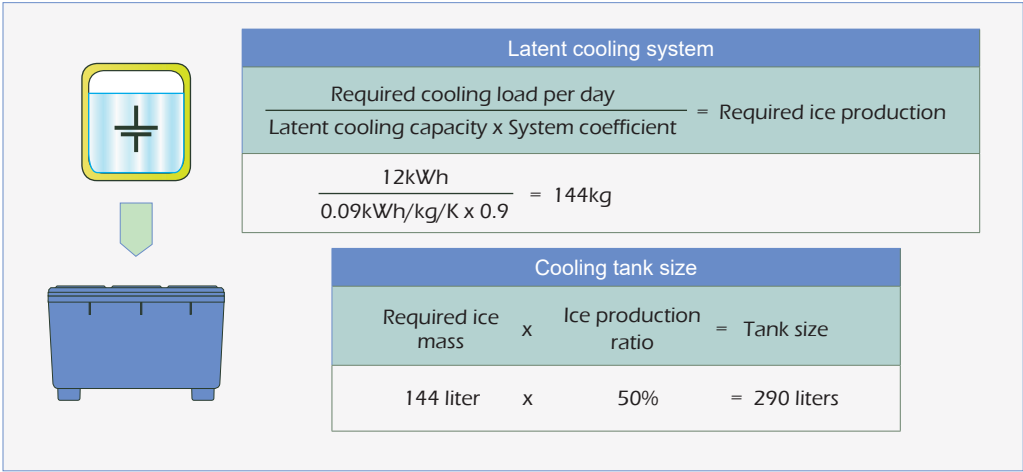


Fig. 87 Calculation how to include a lathent enthalpy cooling system

With the average efficiency of a PV panel (~ 17%) and the real COP for cooling (200% i.e. 1 unit of electricity generates 2 units of ice, one square metre of PV can produce 18kg of ice, which can be used to cool down 100kg of product from 30°C down to 10°C (Fig. 90).

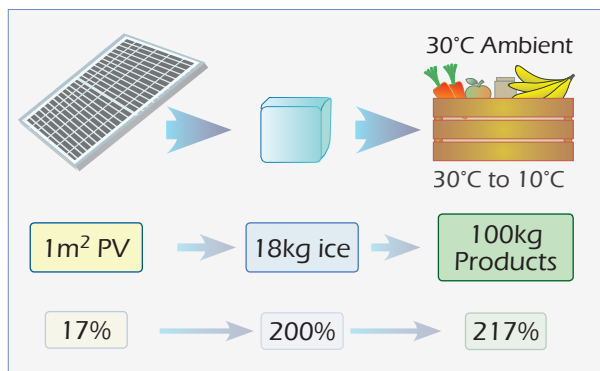


Fig. 90 Overall efficiency of DC enthalpy cooling

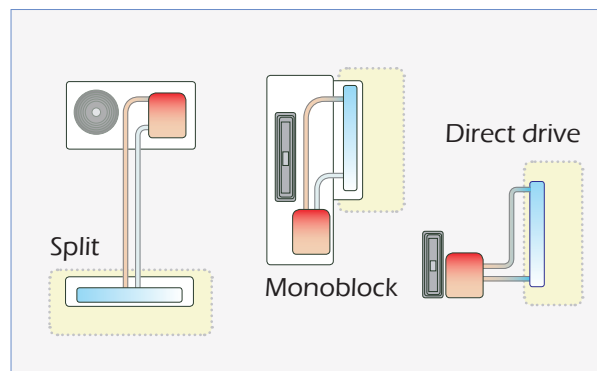


Fig. 89 AC cooling system classification

12.4 AC Cooling Unit

Besides the DC coupled Solar cooling (top of Fig. 88) which is well suited for off-grid applications, a DC/AC coupled option can be implemented as well especially in areas of where a public utility grid or a mini grid system is available (lower graph of Fig. 88). The DC generated Solar power is transformed to alternating current by an inverter to AC voltage (220-240V) which is used to run a monoblock (Fig. 89) cooling compressor. The inverter has an additional AC input which can be connected to the grid supply. The grid power can be used as a pure backup supply or by setting the DoD level of the battery controller as hybrid system.

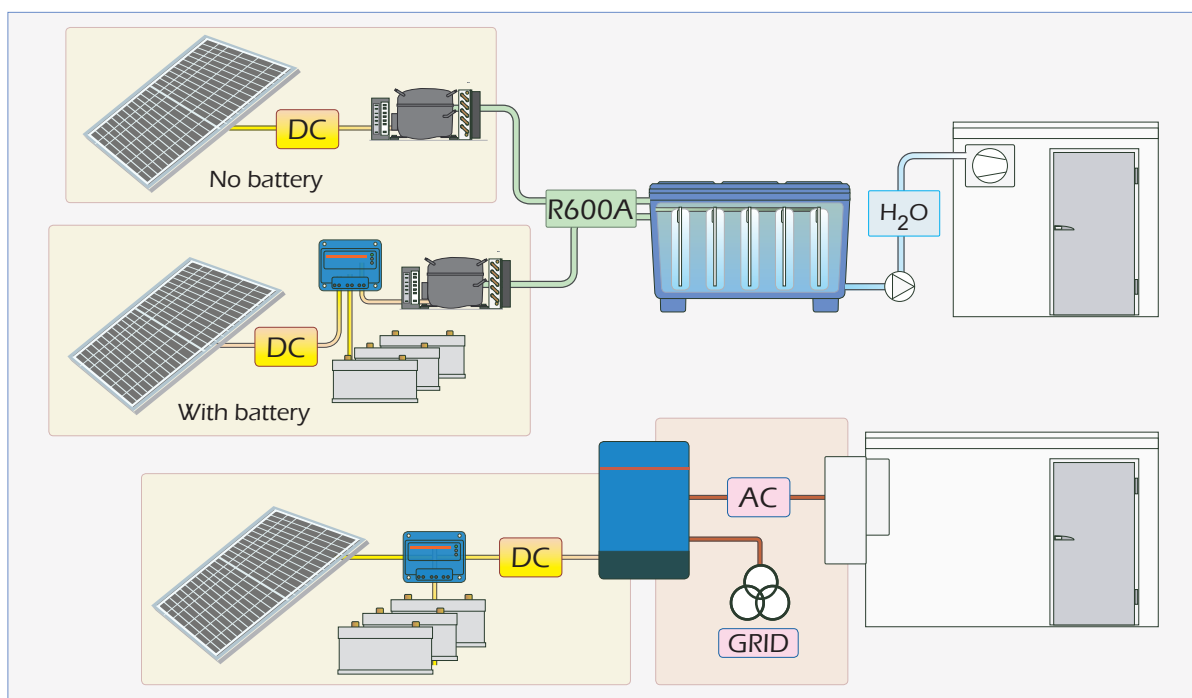


Fig. 88 DC and AC Solar powered cooling applications and their main technical units

Fig. 91 shows a Solar cooling AC system with four 415Wp PV panels in series that form one string. Each of the two MPP trackers is connected with two strings in parallel which raises the input current. The total 3,3kWp power per MPP requires a generator junction box (GJB) that the control unit can be safely disconnected from the PV generator at any time. The red plus cables of the MPP output to the batteries are secured against short circuiting with a fuse holder bus bar.

Energy storage consists of six Lithium Iron Phosphate (LiFePo₄ or LFP) battery modules that stacked in a low voltage configuration i.e. in parallel connection. The internal battery management system (BMS) of the LFP batteries can be connected to the auxiliary input of the hybrid inverter. Setting the depth of discharge voltage will determine when the hybrid inverter will switch from DC (battery) to AC (grid) power supply. A higher DoD will extend the battery life (see Fig. 75) but increase operational costs. Both cost factors need to be compared to the prospective income when designing a Solar cooling system.

PV generator					Hybrid inverter		
	415Wp	String 1	String 1 2	TotaPV	DC in	Voltage range	
Power	415Wp	1,660Wp	3,220Wp	6,440Wp		38-66V	
Voc	37.25V	149V	149V	2x149V	AC out	Nom. power	Max. peak
Imp	13.19A	13.19A	26.38A	2x26.38A	230VAC	3000VA	5500VA

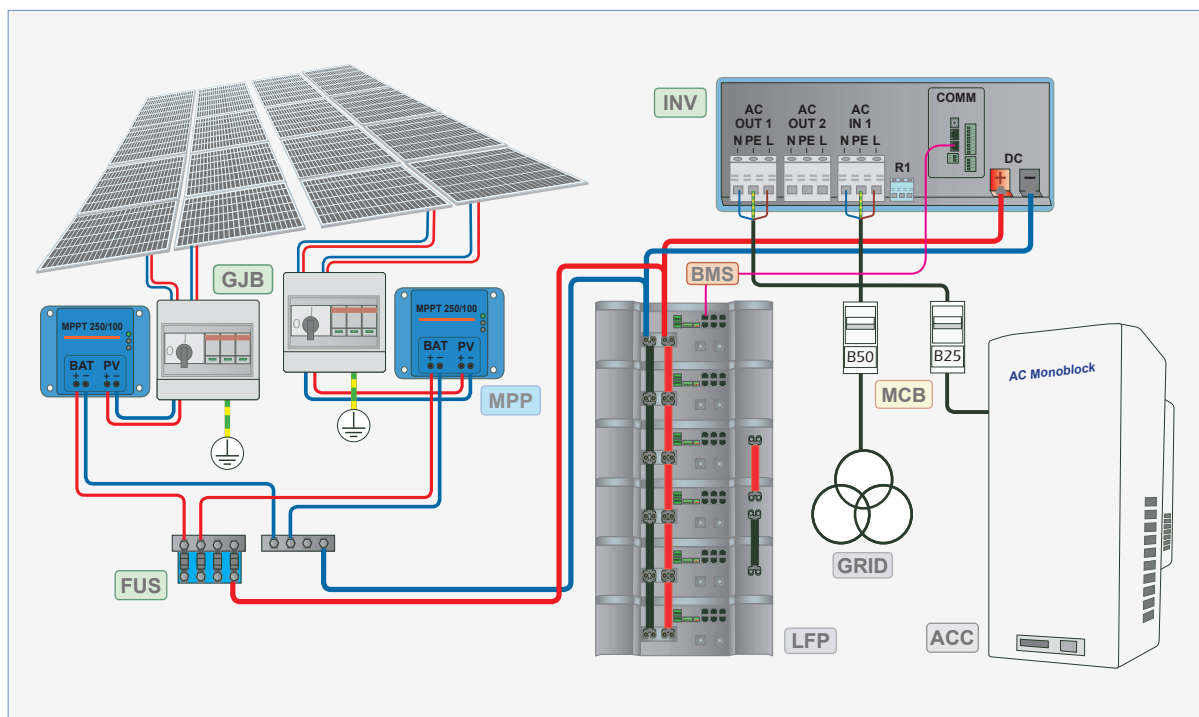


Fig. 91 Solar powered DC/AC coupled cold room

PV charging unit				Li-ion battery bank			AC monoblock		
	GJB	MPP charger	Fuse holder		LFP battery	6 LFP	Voltage	Fused	Nom. power
Vmax	1,500V	250V	1,000V	Vout	52V	52V	230VAC	25A	1560W
I _{max}	25A	70A	500A	Capacity	100Ah	600Ah			

13 CONSTRUCTION AND INSTALLATION

Both DC thermal storage unit and the AC monoblock system are installed in a similar final construction design. The concrete foundation with its steel frame serves as a substructure for the cold room (see chapter 7.1). A patio or concrete or stone tiles next to the cold room can be used for the control and cooling units. In areas with occasional floodings the ground level should be well above the imaginary flood line. For the DC unit the whole equipment should be placed on shelves to the ice tank (Fig. 92) to keep all power cables and fluid lines as short as possible.

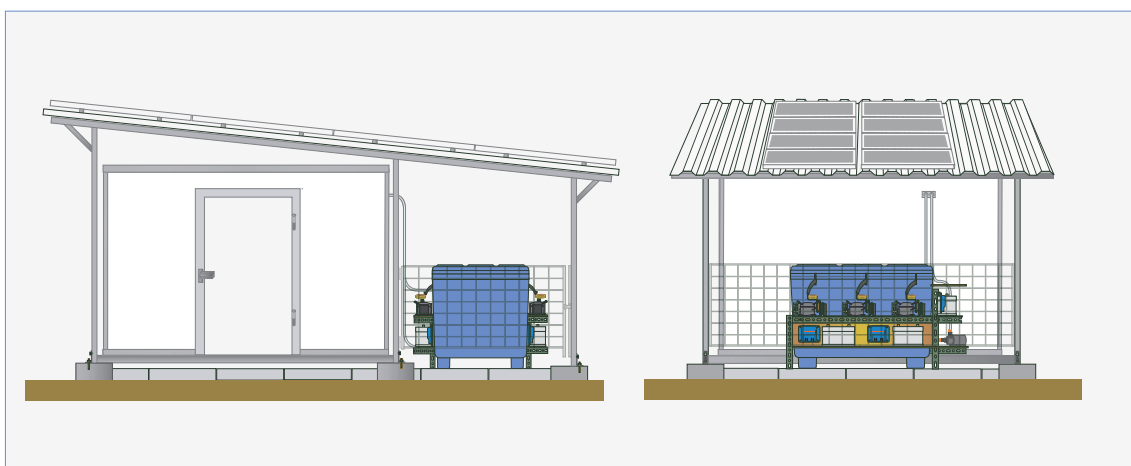


Fig. 92 DC unit with compressor, PV controller and batteries on shelves fixated at the ice tank

For the AC unit, a cut-out to fit the evaporator part of the monoblock compressor needs to be made at the upper part of the cold room wall. After fixation of the frame with stainless steel bolts, gaps can be filled with silicone or styrofoam. AC inverter and MPP tracker can also be securely mounted on the cold room walls. The Li-Ion battery packs should be positioned on a shelf with adequate free ventilation.

An extra protective fencing with a lockable access gate is recommended as a minimum spatial protection of the equipment. The geographical location will determine the slope steel tube roof construction (see Tab. 14) but even in equatorial regions, a minimum roof slope should be applied to facilitate cleaning options. The major advantage of this combined construction design is that the PV generator will provide shade protection. Inserting vulcanized rubber T stripes into the gaps between PV panels can even provide a certain waterproofing rain protection of the generator roof construction.

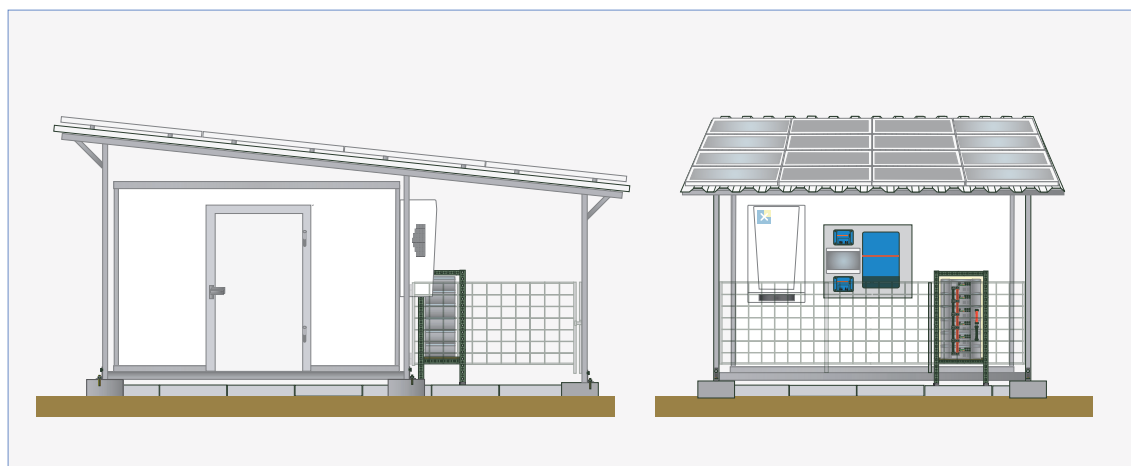


Fig. 93 AC cooling unit with Li-Ion battery bank and controller/inverter unit

13.1 Biogenic Cold Room

Based on the use of biodegradable construction panels (Chapter 7.2) as building materials, the first biogenic cold rooms have been built and successfully operated in various pilot projects. For an improved efficiency of DC units, ice tanks are placed inside of the cooling room. The roof for the PV panels consists of a wooden construction in butterfly design with a central rain gutter. Scandent plants which can grow on the outside walls will provide additional shading.

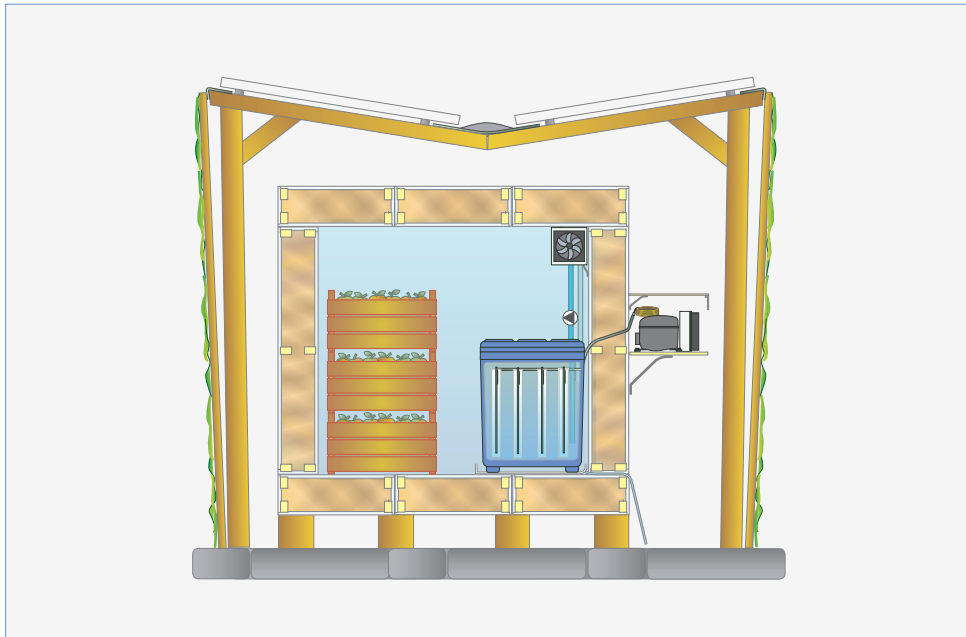


Fig. 94 Biogenic cold room with double wall construction in butterfly design

14 MONITORING AND DATA LOGGING

A central monitoring and control unit oversees the operational parameters of the cold room and manages the setpoints of the thermal storage water chiller. The metal housing offers IP54 protection and should be placed next to the DC thermal storage under the PV roof. A SIM card can be inserted to provide remote system monitoring via GSM.

Temperature and Humidity

The predefined maximum temperature limit (e.g. 4°C) is reached, the controller starts the circulation pump and the evaporator fan. Once the lower setpoint (e.g. 0°C) is reached the controller stops the cooling circuit. The outdoor temperature sensor provides a comparison parameter.

The temperature sensor in the water chiller can activate the compressor units to provide enough cooling capacity for the cold room cooling circuit.

Additional sensors (16xdt) can be placed to measure particular product temperatures or place them at various location in the cold room interior. Similar to a certain temperature, humidity must also stay with a predefined range to provide product quality. The controller can start the humidifier via an internal relay until humidity reaches its setpoints.

Door Sensor

Exceeding a certain time limit (e.g. 60 seconds) the controller can send out a warning message or activate an optional surveillance camera.

Battery Control

If the battery voltage sensor measures that the battery voltage has dropped below a critical limit, the controller can disconnect all consumers via the battery protect unit. Data collection of voltage levels also provides monitoring of proper charging cycles.

Additional Ports

The control units as optional ports to connect extra sensors and monitoring equipment to enhance the data logging capabilities of the cooling system.

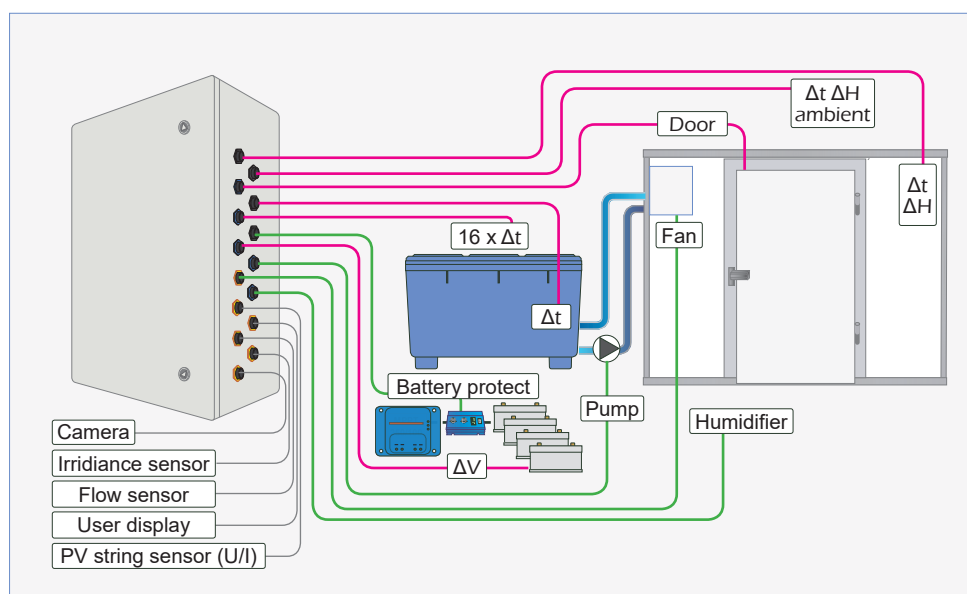


Fig. 95 Standard monitoring (red) and remote control (green) features

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