Temperature control units with Peltier or Compressor technology

Technology guide for laboratory use

Memmert Whitepaper | 02/2021

Contents

1. Summary

Cold is a state of disequilibrum, not a form of energy. Heat must be extracted from the place where cold is to be generated. The heat flows from the energy surplus in the warm environment towards the energy deficit in the space to be cooled. From a technological viewpoint, this process is much more complex than heat generation which has been mastered for hundreds of years.

The first functioning refrigeration machine in the world was constructed in 1845 by the American doctor, John Gorrie, to cool hospital rooms.[1] However, it was a commercial failure. In the 1870s, Carl von Linde made use of the principle of the refrigeration machine. He developed compression refrigeration systems for breweries to revolutionise and simplify the storage of beer.[1]

Cold is also irreplaceable in the laboratory. Peltier temperature-controlled units are available alongside refrigerators, cooled incubators, and climate chambers. The climate chambers are cooled by a compression refrigeration system. It is quite an advancement from Linde's day. Above all, they promise reduced energy consumption in constant part-load operation which is important considering the issue of climate change and scarce resources. This paper shows how the two technologies differ, their advantages and disadvantages and the ideal cooling units needed for respective laboratory applications.

2. Physical Principles

2.1. Thermoelectric effects

Thermoelectrics deals with the direct conversion of heat into electrical energy and vice versa. In modern technical applications, energy converters such as thermoelectric elements (TEC) are used to generate electricity and Peltier elements are used for heating and cooling. The Seebeck effect and the Peltier effect describe the two most significant thermoelectric phenomena.

The Seebeck effect was first observed in 1821 by the German physicist Thomas Johann Seebeck. His test setup was virtually the first known thermocouple – a metallic conductor made of two differently conducting materials.[2]

In an open electrical circuit, one end point of a conductor made of two differently conducting materials is heated. The charge-bearing electrons on the hot side move faster and diffuse to the cold side (thermodiffusion) where there is now an excess of electrons with a negative charge. Due to the specific material properties alone, this temperature gradient generates a thermoelectric voltage. When the circuit is closed, electrical current flows.

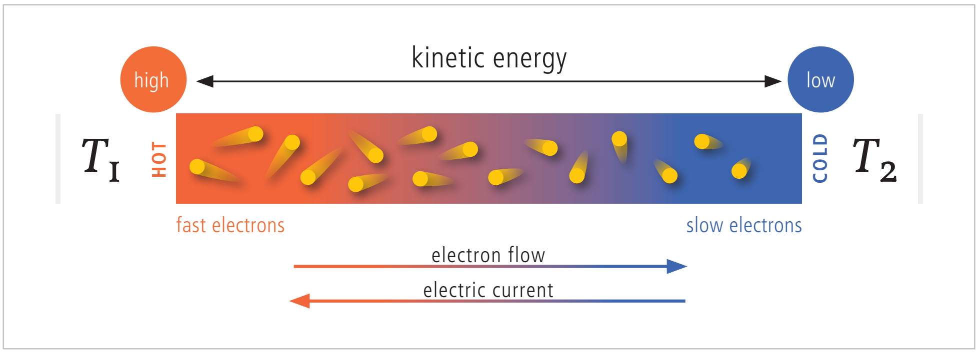

Figure 1: Electron flow in a conductor due to a temperature gradient (thermodiffusion)

If the Seeback effect is reversed and energy is fed in from outside, the thermocouple becomes a Peltier element. The Peltier effect was discovered in 1834 by the French physicist Jean Peltier.[2]

In an electrical circuit, a temperature difference is created at the contact points of two differently conducting materials: one side becomes cold, the other side warm.

Seebeck and Peltier both worked in the 19th century. However, commercially successful applications only emerged with the development of semiconductors. This is because simple metallic conductors have a decisive disadvantage: they are also good heat conductors. The temperature difference between the two sides creates an undesirable heat backflow. In addition, at higher temperatures the ohmic resistance increases and the energy introduced is converted into heat loss. Heat recovery and heat loss both reduce the cooling capacity. Therefore, the achievable temperature differences are less than one Kelvin. Semiconductors work in the opposite way: their resistance decreases with increasing temperature and conductivity increases. In modern thermocouples, predominantly differently doped semiconductors are used.[3]

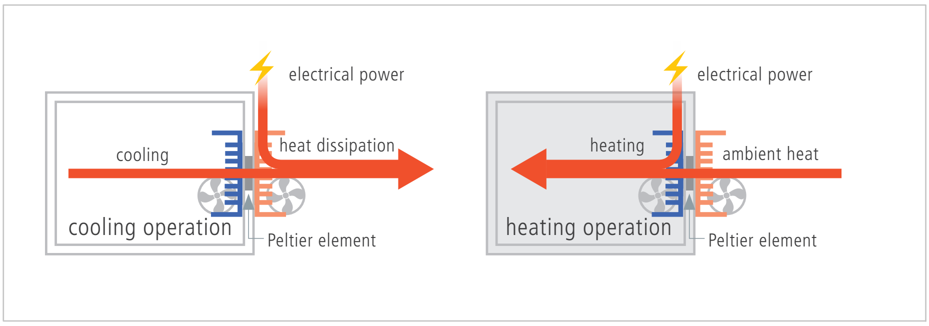

Figure 2: Functionality of a Peltier element

2.2. Functional principle of a Peltier element

In principle, the Peltier element works like a heat pump. Energy is pumped from the cold to the hot side. The total quantity of waste heat that must be released on the hot side is the result of the electrical energy supplied and the cooling capacity. By reversing the polarity of the current the hot and cold sides can be reversed.[3]

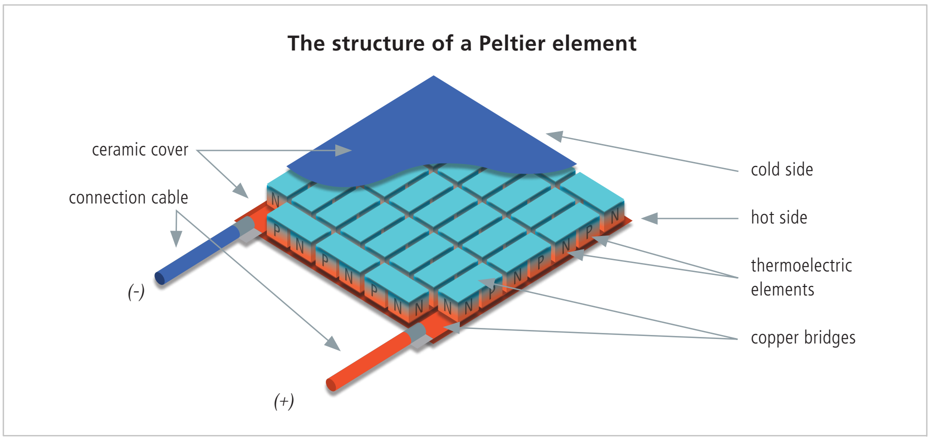
The structure of a Peltier element

Figure 3: Structure of a Peltier element

In a Peltier element, thermocouples of different conductivity are electrically connected in series and linked by ceramic-insulated copper bridges. When direct current flows through the element, a temperature difference builds up (Peltier effect). The cold side of the Peltier element extracts heat from the environment and releases it to the opposite side.

Conventional, single-stage Peltier elements have their physical limits at a temperature difference of about 70 Kelvin between the warm and cold sides at nominal power Imax (see Figure 4). With new types of highly conductive materials and/or the use of multi-stage Peltier elements, temperature differences of more than 130 Kelvin can also be achieved for high-tech applications in electronics.

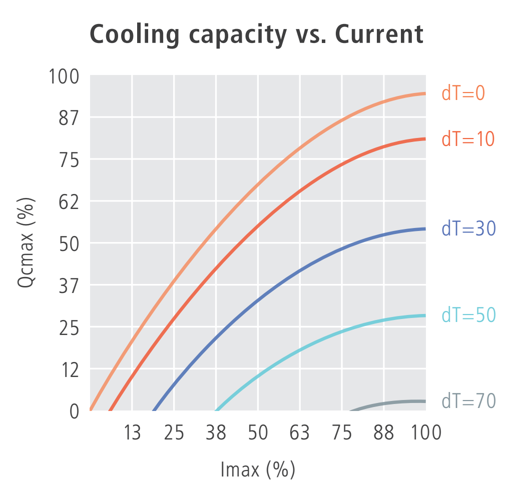

Figure 4: Cooling capacity in contrast to the applied current and the temperature difference within the Peltier element (Meerstetter Engineering, 2016)

The actual cooling capacity is reduced

1. due to the lost heat (increases quadratically with the current intensity).
2. due to the heat reflux to the cold side (proportional to the thermal conductivity of the material and the temperature difference).

2.3. Structure of a Peltier cooling unit

In a Peltier-cooled incubator or climate chamber, Peltier elements are integrated into cooling units. To avoid overheating of the Peltier elements, to optimise efficiency and, above all, to enable the greatest possible temperature difference between the cold and hot sides, the waste heat must be removed as efficiently as possible. This is done with an (demand-controlled) external fan and a sufficiently dimensioned cooling element. Ideally, the internal fan motor should introduce as little heat as possible into the interior.

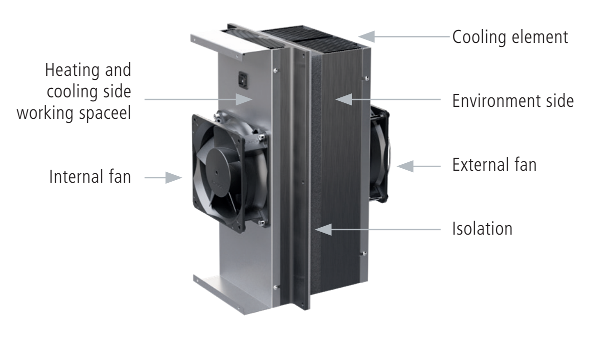

Figure 5: Structure of a Memmert Peltier element

2.4. Linde-type refrigeration machine

Like household refrigerators, laboratory-cooled incubators are based on the principle of the compression refrigerating machine. The refrigeration unit extracts heat from the inside of the unit and then releases it into the environment. However, unlike a Peltier cooling unit, the cooling machine is mechanically driven by a motor. In most cases, this is an electric motor.

The compressor principle makes use of the fact that thermal energy is required during the transition from the liquid to the gaseous aggregate state.

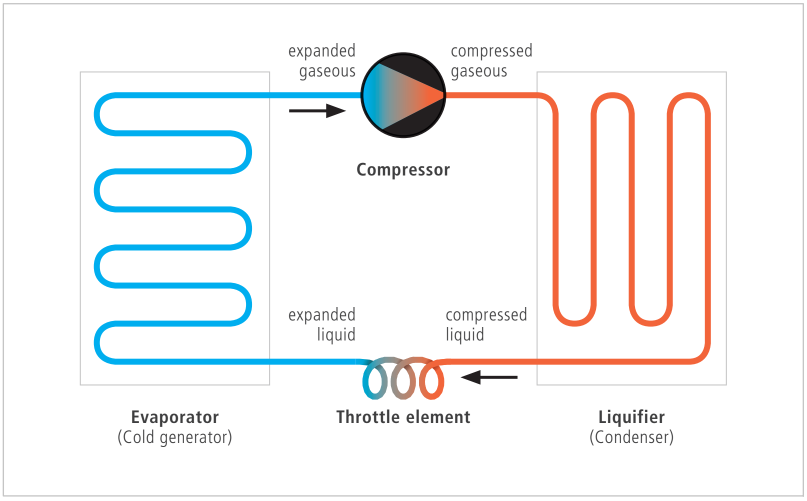

Figure 6: Refrigeration circuit in a compression refrigeration machine

A refrigerant circulates through the machines piping system. At normal pressure, this refrigerant has a boiling point well below the freezing point of water and can change from a liquid to a gaseous state even at low temperatures. In the evaporator in the interior of the unit, it absorbs the heat from introduced samples or food, whereupon it evaporates. The compressor then compresses the refrigerant under high pressure, raising the boiling point to room temperature. Then the condenser on the exterior of the unit releases the absorbed heat to the environment. The refrigerant cools down and changes to the liquid state. In the throttle valve, the pressure is reduced again, the boiling point drops and the process starts again. It is these constantly repeating phase transitions between liquid and gaseous that makes cold generation according to the compressor principle so energy-intensive.[4]

3. Technology comparison between Peltier and compressor cooling

3.1. Construction

The construction differences between the two cooling technologies have specific benefits for the user. A Peltier unit can be built more compactly since no additional installation space is needed for a refrigeration machine. A smaller number of mechanical components such as pumps, filters and piping mean that the likelihood of failure is lower and maintenance easier. Maintenance on refrigeration compressors must only be carried out by experts with special certification. In addition, speed-controlled fan operation means that Peltier units work almost vibration-free and low-noise. Having no refrigerant has an impact on ongoing operating costs and climate friendliness.

By reversing the current flow, Peltier elements are also used for heating in many devices. This eliminates the need for a dedicated heat source in the cooled incubator or climate chamber. In addition, temperature cycles can be run with the same heating-cooling unit.

3.2. Controllability

In laboratory technology, both compressor-cooled and Peltier units provide high control accuracy. However, Peltier elements react immediately and without cooling medium as everything is electrically operated. So they can be controlled extremely accurately.

4. Cooling technologies in laboratory use

4.1. Peltier technology for heating and cooling in the cooled incubator and climate chamber

Now there is a wide range of Peltier-cooled laboratory equipment on the market. Some operate with a single heating/cooling system, others heat with an electric resistance heating element. The units have their strengths primarily close to the ambient temperature, as with low heating and cooling requirements, Peltier technology also requires only small quantities of energy.

The Memmert solution

In 2000, Memmert was the first manufacturer introducing a high-performance Peltier temperature-control unit for heating and cooling, the Peltier-cooled incubator IPP, to the market. This was followed in 2008 by the constant climate chamber HPP.

There is no air exchange between the chamber and the environment. The unavoidable condensation during the cooling process does not therefore occur in the working space but outside on the heatsink. The fans integrated in the Peltier elements ensure rapid transport of energy away as well as an optimal temperature distribution.

After extensive optimisation of the overall system consisting of electronics, construction and control technology in 2020, the HPPeco and IPPeco appliances expand energy-efficient operation across the entire temperature range.

Figure 7: A glance into the Memmert constant climate chamber HPPeco: During heating, energy is extracted from the environment and transferred into the chamber. For cooling, the polarity of the semiconductor is reversed and the energy is removed from the interior.

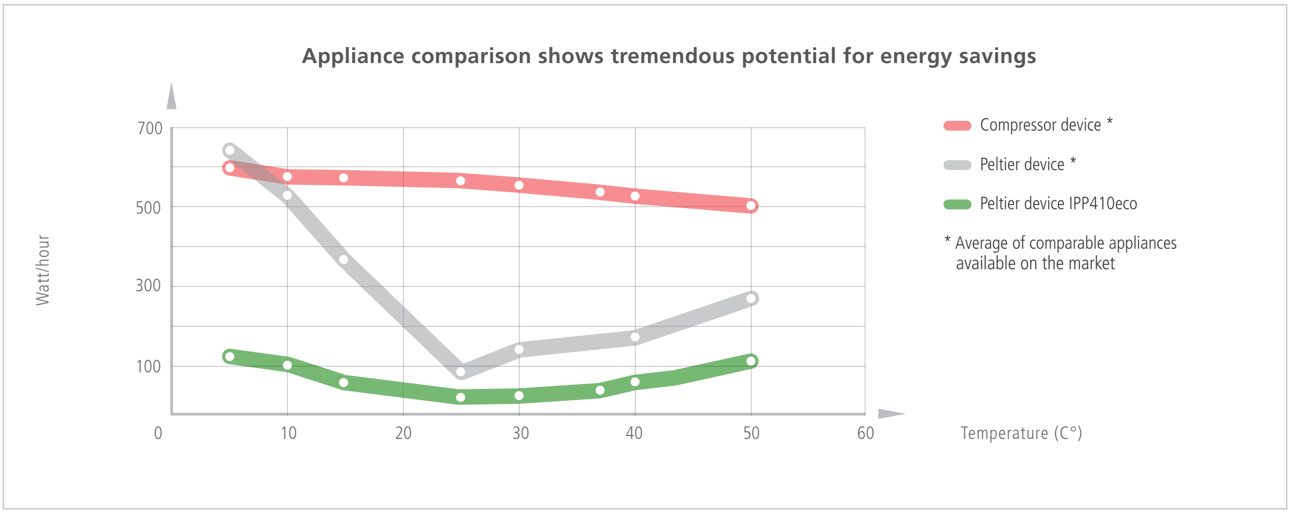

Figure 8: Comparison of energy consumption of Memmert cooled incubator IPPeco with Advanced Peltier Technology (introduced in 2020) with comparable appliances available on the market

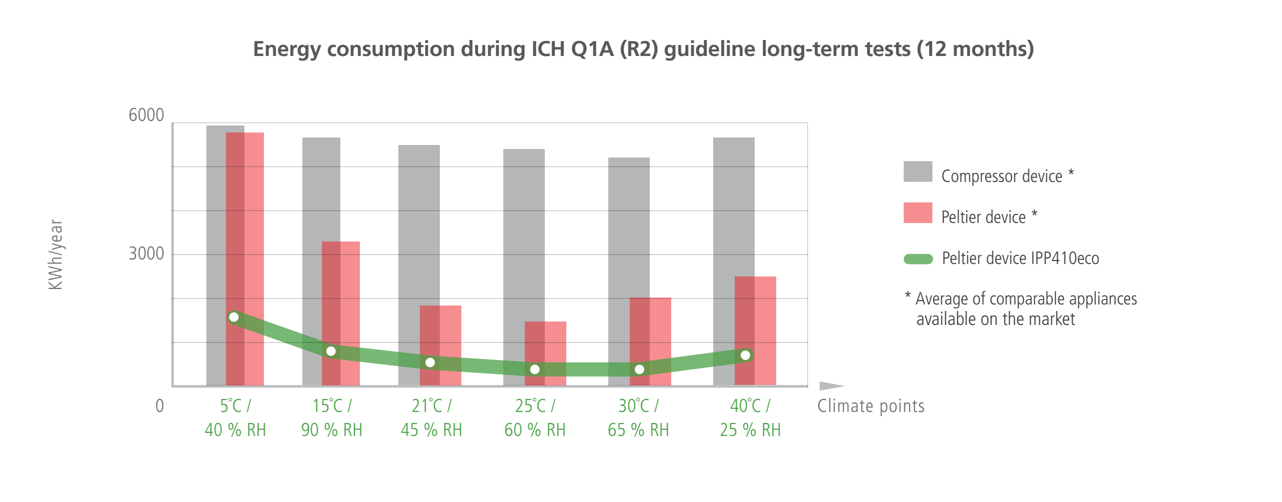

Figure 9: Comparison of energy consumption of Memmert constant climate chamber HPPeco with Advanced Peltier Technology (introduced in 2020) with comparable appliances available on the market

4.2. Compressor technology in the cooled incubator and climate chamber

In some cooled incubators and climate chambers, tempered air circulates in an air jacket around the working space. Cooling is carried out with compressor technology and heating with a ring heater. In the working space, a fan supports optimum temperature (and humidity) distribution. However, there is also a whole range of other technical solutions existing on the market. Other manufacturers place the evaporator or the system for airflow in the interior.

The Memmert solution

The Memmert cooled incubator ICP and climate chamber ICH have a closed system. The arrangement of the cooling unit and heating in a circulating air jacket prevents the occurrence of „hot and cold spots" as well as dehumidification of the working space. Defrosting cycles counteract the icing up of the evaporator. Targeted and controlled dehumidification takes place in the climate chamber via Peltier humidity traps on the rear wall.

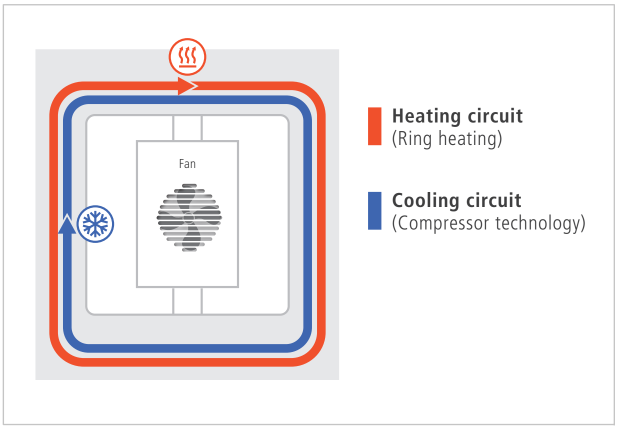

Figure 10: Air jacket temperature control system in the Memmert cooled incubator ICP and cliamte chamber ICH

5. Decision criteria in practice

When deciding for and against compressor or Peltier technology, no general statements can be made. The focus is always on the specific application and the appliances are normally designed for defined processes. Manufacturer data on energy consumption, cooling capacity, heating up and cooling down times and other measured values are helpful here.

5.1. Energy efficiency

The energy efficiency of climate chambers and cooled incubators always depends on the individual design, construction, control and, above all, the application. Because of the wide variation of Peltier units available, it is recommended to have the manufacturer calculate the heat output for the specific application. A compressor-driven climate chamber is often the fitting choice due to its higher heat compensation, unlike the Peltier-cooled unit. Such a climate chamber aids applications that introduce heat into the working space, i.e. electronic assemblies or halogen lamps.

5.2. Temperature homogeneity and consistency

Is the temperature in the entire working space evenly distributed over the entire process duration and how high are the deviations from the set values? These questions are answered by measurements according to DIN 12880:2007, which every manufacturer can provide for its cooled incubators and climate chambers.

The temperature consistency, i.e. the temperature variation in time reflects the deflection of the measuring point with the largest temperature variation in time.

The temperature homogeneity, i.e. the temperature uniformity in chamber, results from the difference between the temperature variation in time averages of the two measuring points with the most different results.

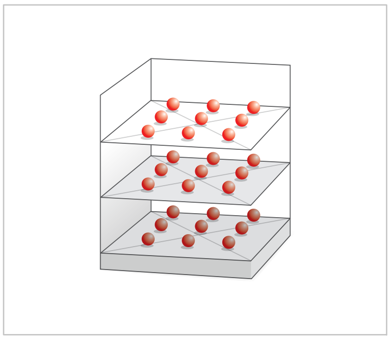

Figure 11: Measuring setup with 27 measuring points for appliances with more than 50 litres working volume according to DIN 12880:2007

5.3. Heating up and recovery times

The conditions in temperature-controlled units should remain constant or, if possible, not deviate from the set target conditions. Rapid heating, cooling and recovery times are important when cooled incubators are opened several times in daily practice, causing the temperature in the interior to rise.

According to DIN 12880:2007, measurements are taken until 100% of the set temperature is reached; the actual temperature is not allowed to exceed defined limit deviations from this point.

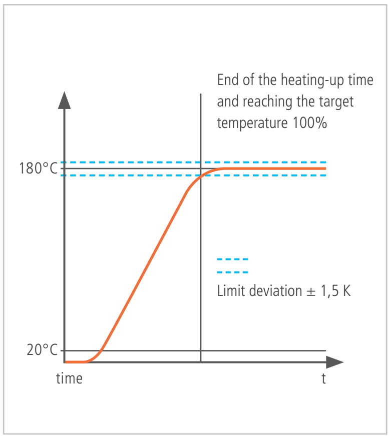

Figure 12: Determination of the heating up time of a heating oven as an example for 180°C according to DIN 12880:2007

5.4. Quiet running and noise level

The sound pressure level expressed in dB (A) is determined according to DIN EN ISO 3743-1:2010.

The decibel is a logarithmic quantity. The sound intensity of a sound at the human pain threshold of about 130 dB(A) is therefore not 130 times as high as that of a sound at the threshold of audibility, but 10 trillion times higher. A doubling of the sound intensity is already reached with a volume increase of three decibels.

For classification: In Germany, the noise level at a VDU workplace must not exceed 55 dB (A). A whisper comes out at about 30 dB (A), a normal conversation about 50 to 60 dB (A) and the noise on a major road about 80 dB (A).

Peltier-cooled appliances have advantages in terms of both noise and vibrations. The vibrations in a compressor-cooled incubator are primarily due to the compressor, the noise is from solenoid valves and condenser fans.

5.5. Ambient temperature

As the heat in the environment increases so does the energy consumption of a cooled incubator or a climate chamber. Above a certain temperature, units with compressors can no longer fully dissipate the waste heat from the compressor to the environment. Henceforth, the cooling capacity decreases. In Peltier units, the waste heat is generally forced out of the unit by a fan. The cooler the warm side of the Peltier temperature-controlled unit, the colder the cold side. Thus, even if the air conditioning system fails, even during summer, Peltier units still function reliably up to a temperature difference of approximately 25 K. In any case, it is advisable to consult the manufacturer if the unit is to operate in extreme ambient temperatures.

5.6. Temperature ranges (minus degrees)

Cooled incubators and climate chambers with Peltier technology are limited by the maximum achievable temperature differences between the environment and the working space in their application at low temperatures. In contrast, compressor appliances can safely reach temperatures below freezing – with the limitation of the permissible ambient temperature.

5.7. Refrigerant

The ability to cool without refrigerant is certainly one of the greatest advantages of the Peltier technology. Compressor appliances use different refrigerants which contribute to global warming to a greater or lesser extent when released. The GWP value (Global Warming Potential) serves as a guide. It relates refrigerant to climate-neutral CO_2. An example: The CO_2 equivalent of R134a refrigerant is 1430 over a 100-year period. One kilogram of the refrigerant R134a contributes 1,430 as much to the greenhouse effect within the first 100 years of its release as one kilogram CO_2.

5.8. Service and maintenance

As a Peltier climate chamber or cooled incubator is simpler in design and does also not require the handling of refrigerants, these units are less complicated to maintain compared with their compressor-cooled counterparts.

6. Example applications in the climate chamber

6.1. Stability and climate tests

Main advantages of the compressor climate chamber:

High level of flexibility with a wide range of requirements: temperature ranges from minus to plus, photostability tests in combination with many temperature-humidity combinations, alternating tests, heat compensation at Q1B

Main advantages of the Peltier climate chamber:

At constant storage climate high energy efficiency, lower likelihood of failure of the Peltier elements and quiet operation

6.2. ICH Guidelines Q1A and Q1B

Stability test in the climate chamber under ICH Guideline Q1A (R2)

This guideline describes the controlled storage conditions (temperature and humidity) and the storage period for stability tests of finished pharmaceutical products and active substances for the different climate zones on earth. The chemical-physical stability after the end of the tests enables statements to be made about the shelf life and the storage conditions.

Stability test in the climate chamber under ICH Guideline Q1B, Option 2 (Photostability)

With a lighting unit combining daylight lamps and UV light, additional testing can be conducted under ICH Guidelines Q1B, Option 2 (Photostability). The Guidelines do not specify moisture content and temperature during the test. Nevertheless, with a climate chamber with controllable temperature, humidity and separately controllable illumination for daylight and UV light, the possibility can be kept open to also test photostability for defined humidities. In addition to the high flexibility in testing, the low heat input from the illumination units compared with the xenon lamps under Option 1 speaks in favour of these appliances.

6.3. Stability tests in the food and cosmetics industries

Stability tests are also standard and sometimes mandatory in the food, cosmetics and packaging industries. Microbiological tests usually take place at defined temperatures in the cooled incubator, but some stability tests are also carried out in the climate chamber in the same way as for medicinal products in defined standard or test climates.

6.4. Climate tests and humidity storage in industry

Metal and plastic electronic parts and components are subjected to a whole range of corrosion, climatic and temperature tests in industry in order to investigate the influence of temperature and humidity on material and functionality. A compressor refrigerator is recommended for defined climates and alternating climates. If the test specimens are only stored in a constant climate, a Peltier climate chamber is advantageous because of its energy efficiency, fail-safe and maintenance-free operation.

7. Example applications in the cooled incubator

7.1. Protein crystallography

Main advantages of the Peltier-cooled incubator:
Almost vibration-free and low-noise operation
High-precision control

Protein crystals are extremely sensitive. The slightest vibration can negatively affect growth. The sensitive crystallisation preparations grow as slowly as possible and vibration-free at constant temperatures between +4 °C and +20 °C over a very long period of time in the cooled incubator. In addition to low noise and minimal vibration levels, the highly precise controllability of the cooled incubator plays an essential role in the crystallisation, as temperature fluctuations, especially during the nucleation phase, impair the reproducibility of the crystals.

7.2. Model organisms

Main advantages of the Peltier-cooled incubator in cultivating zebrafish:
Almost vibration-free and low-noise operation

Main advantages of the compressor-cooled incubator in cultivating Drosophila:
Reliable temperature ramps

Both zebrafish and Drosophila normally require light during cultivation and maintenance.

It is important for zebrafish to grow up in as stress-free and low-noise environment as possible at constant temperatures around +28 °C. Therefore, a Peltier cooled incubator is recommended for this application.

If climatic influences on the model organisms are being investigated, the ability to run precise temperature ramps in a compressor refrigerator can be advantageous.

7.3. Swing tests

Main advantages of the compressor-cooled incubator:
Rapid heating up and cooling down times
Rapid and precise alternating from heating up to cooling down phases
More economical energy consumption
Suitable for high temperature differences

In food and pharmaceutical development, new formulations are often subjected to heat-cold cycles in thermal stress tests to investigate the influences on stability. At these considerable temperature differences of 40 °C and more, the use of a compressor cooled incubator is recommended.

7.4. Cultivation above and below room temperature, microbiological tests, germ count determination

Main advantages of the Peltier-cooled incubator:

- Compact design
- Low-noise operation
- More economical energy consumption

Main advantages of the compressor-cooled incubator:

- Rapid heating up and cooling down times
- Fast recovery times

In principle, both technologies are equally well suited to cultivation tasks above and below room temperature. Therefore, other decision criteria play a role in common microbiological applications without temperature ramps. If the unit doors are opened several times a day in daily practice, this can lead to a temperature increase in the unit. So, rapid heating up, cooling down and recovery times are important. With the technical optimisation of the Peltier cooled incubators, the statement that compressor appliances are superior is no longer universally true. The manufacturers’ measurements for the individual appliances are of a good guide here as they are usually tested according to specifications of DIN 12880:2007-05 and are therefore comparable.

Sources:

[1] Plank, Rudolf (Publ). Handbuch der Kältetechnik (Refrigeration technology manual). Springer-Verlag, 1954.

[2] Irrgang, Klaus. Altes und Neues zu thermoelektrischen Effekten (Old and new on thermoelectric effects). Springer-Verlag, 2020.

[3] Dr. König, Jan. et al. Thermoelectrics: Strom aus Abwärme (Electricity from waste heat). BINE Informationsdienst, 2016.

[4] Danfoss company. Kältetechnik-Einführung in die Grundlagen (Refrigeration technology introduction to the basics). 2007.

Now in its third generation, Memmert has been developing and producing climate chambers, heating and drying ovens, incubators, medical devices as well as water baths at two locations in southern Germany (Schwabach and Buechenbach) for a very wide range of applications. Around 450 employees from about 30 nations are involved in the success of our company. In over 190 countries all over the world, hundreds of thousands of Memmert products have been permanently in use for decades. Therefore Memmert is one of the most innovative and leading manufacturers of climate and temperature control devices worldwide.