



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Energie BFE

APPLICATION OF MAGNETIC REFRIGERATION AND ITS ASSESSMENT

OVERVIEW OF EXISTING TECHNOLOGIES AND THEIR COMPARISON WITH MAGNETIC REFRIGERATION

Final report: Appendix 1

Performed by

Andrej Kitanovski, Marc Diebold, Didier Vuarnoz, Cyrill Gonin, Peter W. Egolf

Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud

Route de Cheseaux 1,

CH-1401 Yverdon les Bains

SWITZERLAND

peter.egolf@heig-vd.ch

www.heig-vd.ch

Impressum

Datum: 5. Juni 2008

Im Auftrag des Bundesamt für Energie

Forschungsprogramm Elektrizitätstechnologien und -anwendungen

Mühlestrasse 4, CH-3063 Ittigen

Postadresse: CH-3003 Bern

Tel. +41 31 322 56 11, Fax +41 31 323 25 00

www.bfe.admin.ch

BFE-Bereichsleiter, thilo.krause@bfe.admin.ch

BFE-Vertrags- und Projektnummer: 101776 / 152191

Bezugsort der Publikation: www.energieforschung.ch / www.electricity-research.ch

TABLE OF CONTENTS

1. Magnetic household refrigeration and freezing appliances.....	4
1.1 Household refrigerators.....	4
1.2 Household freezers.....	5
1.3 Household refrigerators with freezer.....	5
1.4 Wine beverage refrigerators.....	6
1.5 Hybrid devices.....	6
2. Magnetic cooling and air-conditioning in buildings and houses.....	8
2.1 Small cooling (air-conditioning) units.....	8
2.2 Central cooling systems	12
3. Cooling and Freezing in medicine.....	18
3.1 Refrigerators in medicine.....	18
3.2 Freezers.....	18
3.3 Other medicine refrigeration/freezing equipment.....	20
4. Cooling , heating and freezing in food industry and storage.....	22
4.1 Food production.....	22
4.2 Food processing before storage.....	24
4.3 Food storage.....	26
5. Cooling , heating and freezing in transportation.....	28
5.1 Air-conditioning in land transport.....	28
5.2 Marine air-conditioning (cooling).....	32
5.3 Refrigeration and freezing of food or other goods in transportation.....	33
6. District cooling systems.....	40
7. Cooling and heating in industrial processes.....	41
8. Supermarket applications.....	42
9. Electronics cooling.....	43
10. Results of the analysis.....	44
10.1 Smaller magnetic refrigeration units.....	45
10.2 Larger magnetic (industrial) refrigeration units.....	49
10.3 Smaller magnetic cooling and air-conditioning units (buildings, marine).....	50
10.4 Large (central) magnetic cooling and air-conditioning units.....	54
11. Conclusions.....	64
12. References.....	65

1. MAGNETIC HOUSEHOLD REFRIGERATION AND FREEZING APPLIANCES

1.1. Household refrigerators

a) Conventional household refrigerators

The world production of compressors for household refrigerators and household freezers in 2003 was approximately 100 millions units [1]. The estimated world market is approximately 4 billion US \$ per year. The room temperature for household refrigerators varies between 16 to 32 °C. The lowest temperature in the cooling compartment is usually around 4 °C, depending on the specific application. One should note that the operating conditions strongly depend on the outer or/and inner temperature level. Usually a free convective heat transfer occurs in the inner compartment as well as on the condenser side out in the room. Because these heat transfers are low, the evaporation of the refrigerant in conventional household refrigerators occurs approximately 10 K below the required temperature in the internal space of the refrigerator. The same is true for the condensing temperature: it is usually at least 10 K higher than the temperature of the ambient air. These two temperature differences lead to high irreversibilities and they influence negatively on the efficiency of the cooling machine; so it is not surprising to get *COP* values lower than two. Household refrigerators without a freezing compartment do not require a very high cooling power: the maximal values are around 200 W.



Figure 1: Examples of a conventional household refrigerator [2]. The condensing tubes are mounted to the back side of the refrigerator. It is highly insulated and has a low power consumption. The minimal temperature is usually 4 °C, depending on the specific application. Such types of refrigerators have a low cooling power (less than 100 W).

b) Magnetic household refrigerators

In the case of an application of the magnetic refrigeration technology, water or brine should be taken as heat transfer fluid. It has to be emphasized that this has to be related to the design of the condenser as well as to the “cold” heat exchanger, which replaces the evaporator. Therefore, one may assume that the development of magnetic household refrigerators will lead to slightly different internal designs of refrigerator containers. Figure 1 shows an example of a conventional refrigerator without a freezing compartment and Figure 2 a schematic drawing of a magnetic household refrigerator.

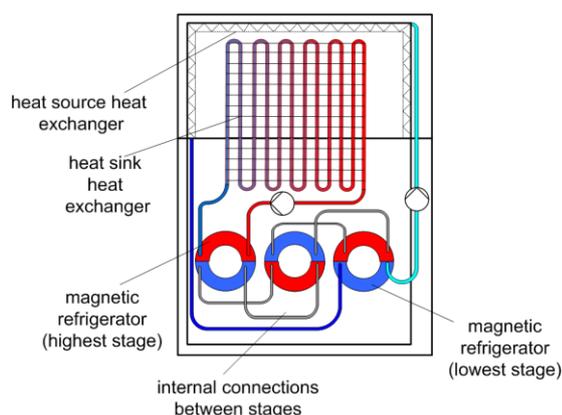


Figure 2: A first schematic sketch shows how a three-stage magnetic household refrigerator could be designed, if it is based on a patent which was deposited by HEIG-VD/SIT. The three red/blue rotor wheels are connected to perform regeneration cycles. Notice that this design permits to have only two pumps in such a multi-stage machine.

1.2. Household freezers

a) Conventional household freezers

The usual temperature at the heat sink side varies between 16 and 32 °C. The lowest temperature at the heat source side is around -20 °C. The temperature difference between the heat sink and the heat source varies therefore from 36 K to 52 K. However, similar as in household refrigerators, to achieve such temperature difference between heat source and heat sink, the working fluid has to have lower and higher temperature level for heat transfer, respectively. Therefore the evaporation of refrigerant in conventional household refrigerators is running some 10 K below the acquired temperature in the internal space of the refrigerator. Similar, the condensing temperature is usually 10 K higher than the ambient temperature. The maximum cooling power of household freezer appliances reaches around 500 W.



Figure 3: An example of a single conventional household freezer [2]. This kind of domain is hardly feasible at the present stage of development of magnetic refrigeration technology, especially because of the very large temperature spans which would be required on the side of the working fluid.

b) Magnetic household freezers

In the household magnetic freezer, the working fluid should be a liquid not poisonous secondary refrigerant. On the external side, at the heat source, the heat transfer to the cooled space is due to the free or even slightly forced convection of inner air (note that this may be performed also in a household refrigerator). The heat transfer at the heat rejection to the room (ambient) is usually done by free air convection. However forced air convection would substantially influence the efficiency of a magnetic household freezer. Magnetic household freezer applications are at the present stage of development of the magnetic refrigeration technology hardly feasible, because of the large temperature span between the temperatures of the heat source and the heat sink. Considering this, the better chance for commercialization would be to have freezers with forced convection and to place them in non-heated spaces like cellars.

1.3. Household refrigerators with freezer

a) Conventional household refrigerators with freezer

This kind of household appliances is most frequently used in homes. The temperature of the freezer may reach -25 °C and the temperature of the refrigerator varies between 0 and 5 °C. The temperature of the heat sink is in our cases between 16 and 32 °C. Because of the inefficient heat transfer between the refrigerant and the cooled space or ambient air, the condensation temperature is some 10 K above the heat sink temperature and the heat source temperature is some 10 K higher than the actual temperature of the refrigerant. The maximum total cooling power for the household refrigerators with freezer is around 400 W for home appliances.

b) Magnetic household refrigerators with freezers

Like freezers the magnetic household refrigerators with freezing compartments are hardly feasible. Despite that one may assume that the first commercially available devices will present a kind of cascade system. The first magnetic refrigerator will be used for pre-cooling or as a higher cascade stage (connection in parallel and connection in series, respectively) or as a refrigerator without freezer. The other magnetic refrigerator will present a lower cascade stage of the freezing part. Such example of a magnetic household refrigerator with a freezer is shown in Figure 4.

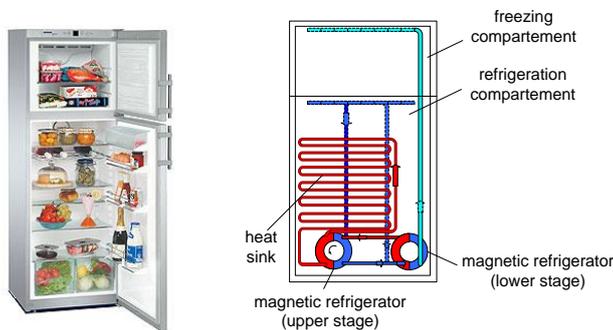


Figure 4: Left: An example of a conventional combined household refrigerator with a freezer is shown in this picture [2] Right: An example of the back side of a magnetic refrigerator with a freezer is presented.

1.4. Wine/beverage refrigerators

a) Conventional wine/beverage refrigerators

This kind of refrigerators may comprise free or forced convection of air inside the cooling space. The normal heat sink temperature may vary between 16 and 32 °C. The temperatures required for cooling wine are 13 °C for red wine and 7 °C for white wine. The minimum temperature inside the refrigerator should be around 5 °C. As in other cases the temperature difference between the refrigerant and ambient or inner air is some 10 K. The cooling power is rather low (around 50 W).

b) Magnetic wine/beverage refrigerators

The working fluid in a magnetic wine refrigerator should preferably be liquid (water is possible). However an additive as for instance ethanol (methanol) may be added to water to prevent freezing. This kind of refrigerator is one of the most favourable for the magnetic cooling technology since the temperature span between the heat source and the heat sink is rather low and the heat sink temperature is in many cases very stable.

1.5. Hybrid devices

By hybrids one means the combination of two (or more) different technologies like the conventional vapour-compression technology and magnetic refrigeration technology. The magnetic refrigeration technology or vapour compression technology may be used as a pre-cooling stage in any of the above described appliances. It is also known that some of the conventional household refrigerators with freezers use two compressors, one for the freezing part and the other for the refrigeration part. Since the working fluid in the magnetic refrigerator is a liquid and secondary refrigerants usually present higher viscosity with lower freezing temperatures, it makes sense to apply a magnetic refrigerator for the pre-cooling phase and then a vapour-compressor for the freezing phase. On the other hand, an upper stage with compressor would enable a very stable (and low) temperature of the heat sink. A schematic example of such a hybrid device is shown in Figure 5.

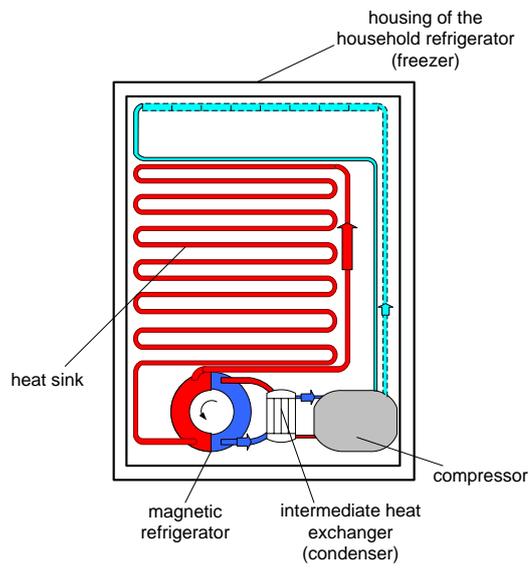


Figure 5: An example of a hybrid type of refrigerator. The magnetic refrigerator in this case realizes a pre-cooling stage, which may have two functions: pre-cooler for the refrigerant from compressor or pre-cooler and refrigerator for the part of a refrigerator without freezing.

2. **MAGNETIC COOLING AND AIR-CONDITIONING IN BUILDINGS AND HOUSES**

2.1. **Small cooling (air-conditioning) units**

The world production in 2003 of compressors for room air conditioners and dehumidifiers was around 70 millions units (rotary type 1 cylinder, reciprocating, scroll) [1]. The average annual growth is estimated around 10 %, what presents a worrying figure concerning the electric consumption and also refrigerants effect on global warming. It is well known that the use of room air-conditioning units should be avoided as much as possible, especially because of their large and uncontrolled consumption which may be drastically reduced by the implementation of central cooling systems or more radically by the introduction of district cooling systems. Despite these facts, an alternative technology such as magnetic air conditioning could bring not only benefits considering its low power consumption, but also because of its strong impact on reducing the use of environmentally harmful refrigerants.

Portable units

a) Portable indoor conventional cooling devices (with flexible duct for warm air evacuation)

This kind of device is compact since the heat source and heat sink are placed in the same housing. The use of portable devices is usually limited to a room or an office. Air of rooms flows through the heat sink part where it is warmed up and then flows through a flexible duct out to the ambient surroundings. The heat source part is warmed up by passing through the room (air may condensate) and then the air is cooled and turned back to the room. The cooling power is usually low (up to 5 kW of cooling). The conventional portable cooling devices enable cooling of the air in the rooms to some 16 °C. The indoor temperature should be maintained around 22-24 °C.



Figure 6: *An example of a conventional portable indoor cooling device [3].*

b) Portable indoor magnetic cooling devices (with flexible duct for warm air evacuation)

The small temperature difference between the heat source and the heat sink (or temperature difference between the working fluid and the air) starts at 20 K, what makes magnetic cooling apparatuses with permanent magnets feasible. Liquids or air can be used as working fluids. The last may be advantageous in order to have a direct heat transfer between the air and the magnetocaloric material. However, one may expect difficulties due to the low heat transfer rate which may disable higher frequencies of the operation (heat would need more time for its transfer). Furthermore, some magnetocaloric materials – such as Gadolinium – are not suitable for a direct use.

Portable evaporative units

a) Conventional portable indoor evaporative cooling devices

The evaporative cooling devices are based on the evaporation of water. The water from the inner tank of the device is sprayed through the structure of the heat exchanger and on the other side of this structure room air is pushed by the fan through it. The efficiency is lower than the one of other conventional cooling technologies. This kind of device should preferably be used in dry climates where the relative humidity is lower than 50%.



Figure 7: An example of a conventional portable indoor evaporative cooling device [4].

b) Magnetic portable indoor evaporative cooling devices

The evaporative cooling presents an alternative technology to conventional cooling technologies. A magnetic-evaporative cooling device could be built and would use a hybrid system. Here magnetic cooling is applied in order to further reduce the temperature of the cooling air. This kind of device would actually present a cascade system or a hybrid system. Several advantages could be achieved besides lowering the cooling temperature (which strongly depends on the humidity of the air), for instance a dehumidification due to the strong condensation (lower temperatures due to the combined magnetocaloric and evaporative effect). The magnetic-adiabatic or magnetic-evaporative hybrid system may also be used for air-conditioning in large scale systems. We show here an example and description of such hybrid system.

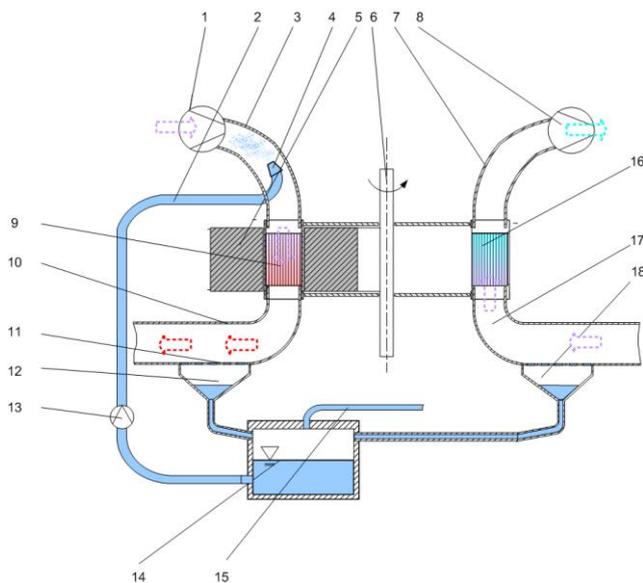


Figure 8: An example of a hybrid magnetic-evaporative cooling device (1- ventilator, 2-water pipe, 3-air duct for cooling air, 4-nozzle, 5-magnet, 6-rotating shaft, 7-air duct for chilled air, 8-ventilator, 9-magnetocaloric material (wheel) in the magnetic field, 10-air duct for evacuation of the waste heat, 11-openings for water, 12-collector, 13-pump, 14-water tank, 15-fresh water supply, 16-magnetocaloric material (wheel) outside magnetic field, 17-air duct of ambient (room) air, 18-collector).

Figure 9 shows an example of the Brayton cycle, which is used for the illustration of the process in Figure 8. The cycle between states 1-2-3-6 presents a normal cycle without the adiabatic cooling process. The $h-x$ diagram in Figure 9 shows the corresponding temperature-humidity variation of the air in the process. In the stages 2 to 4, water is injected into the ambient air, so its temperature decreases and the relative humidity increases (I. to IV.). The air is then flowing through the magnetocaloric material, which is in the magnetic field in order to cool it down, so the temperature of the magnetocaloric material decreases from 2 to 4, while the one of ambient air increases from IV. to V. (waste heat). When the magnetocaloric material leaves the magnetic field its temperature further drops from four to five degrees due to the magnetocaloric effect. Opposite the ambient air is entering the cold part of the magnetocaloric material which is outside of the magnetic field. The temperature of the magnetocaloric material therefore increases from 5 to 1, and the one of the ambient air decreases from I. to III. In order to avoid entering in the space cooled by the fog (cold air with very high relative humidity close to 100 %, as presented by point III.), different possibilities of preheating and reusing the cold are possible.

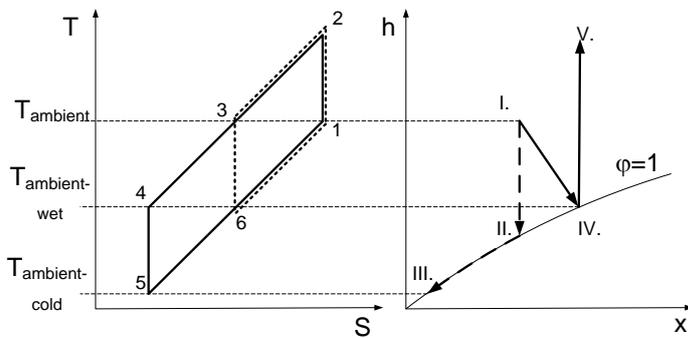


Figure 9: An example of a thermodynamic process in the hybrid magnetic-evaporative cooling device.

One should note that already conventional high-power cooling systems present hybrid technology of vapour compression and evaporative cooling. This is very often the case for connection of water cooled chillers with cooling towers.

Window mounted (room) cooling devices

a) Conventional window mounted cooling devices

This kind of air conditioning or cooling devices is one of the most frequently used and may be seen on windows of many houses, which usually have neither central air conditioning nor cooling system. In many cases these kinds of devices are heat pumps. The cooling power is usually low (up to 3 kW of cooling). A problem occurs with such devices when they are positioned outside at the place with high solar radiation or on walls of high buildings, where temperatures in summer time exceed ambient air temperatures by much more than 10 K. This kind of devices may comprise different solutions, e.g. mixing of inner and ambient air, which flows then through the evaporator and then back to the room. Another option is the recuperation, where a part or all of the room air exchanges its cooling energy with the fresh ambient air. The minimum temperature of the indoor air may be around 16 °C.

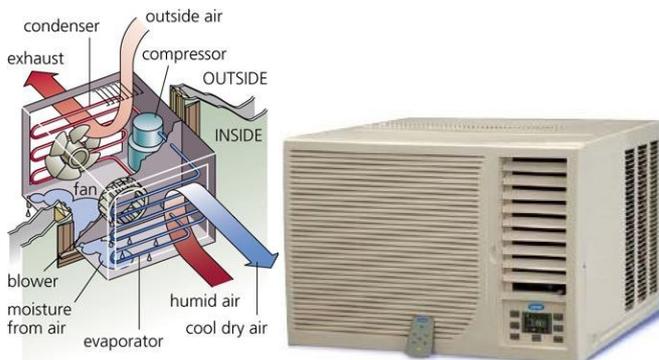


Figure 10: A typical window-mounted air conditioner. The cooling power usually does not exceed 3 kW of cooling power. The heat rejection unit (condenser) is mounted in such a way that it is outside the wall of the building (see picture on the left-hand side). Some room air conditioners enable also cooling of additional fresh air and distribution into desired space (room) [5,6].

b) Magnetic window mounted cooling devices

The magnetic window-mounted cooling devices contain one of two kinds of working fluids, namely air or water (brine). Using air leads to a direct heat transfer between air and the magnetocaloric material, so the frequency of operation is not expected to be as high as it would be if using water as working fluid. This is due to the heat transfer coefficient of air which is much lower than the one of water. On the other hand, a direct use of air does not require additional heat exchangers, as it would be the case between the water and air; so this device could be more compact. However, this would require a comprehensive analysis on safety data of magnetocaloric materials.

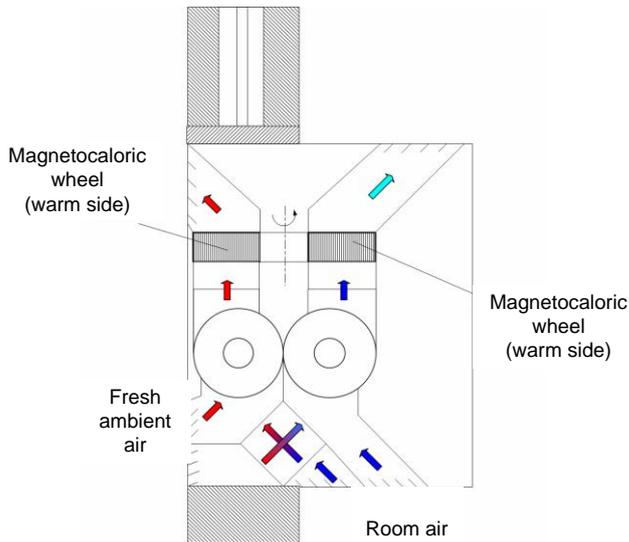


Figure 11: Simple schematics of a magnetic window (room)-mounted air conditioner with heat recuperation between room and fresh ambient air (direct use of air).

Split cooling systems

a) Conventional indoor split cooling (wall or ceiling console or cassette) systems

Beside the window-mounted cooling devices (air conditioner), the split system is also one of most frequently used cooling systems in buildings which have no central cooling. A split system is an application of separate condensers and evaporators. There may be several evaporators (housings) and they provide cooling for different rooms or offices. The condensing unit (housing) is usually a single one placed or mounted on the outer wall of the building. Like for the window-mounted cooling device, the condenser of the split system is rather placed in an area where the sun radiation does not strongly affect the condensing temperature. Usually split systems do not enable the use of fresh ambient air, but are rather recirculating the internal room air through the coils of the evaporator. Considering that the temperature of the ambient does not exceed 32 °C, this kind of system enables rather higher temperatures of the heat source (15 °C or even higher, depending on the specific form of the heat source unit, air temperature and its relative humidity). Different devices may be found on the market, where the cooling power per one unit (split systems may involve one or several units) varies between 1.5 kW and 6 kW. Usually, these kind of cooling devices (if they are used individually) cover smaller cooling loads. The secondary working fluid is usually air (the primary fluid is the refrigerant), but there exist also units which enable a secondary liquid refrigerant.



Figure 12: An example of a conventional indoor unit console-ceiling cooling and two different possible air or water cooled outdoor-condensation units (the second and the third picture, respectively) [5].

b) Magnetic indoor split cooling (wall or ceiling console) systems

In the magnetic split cooling system, the working fluid is preferably a liquid (water), which flows through the magnetocaloric material. The refrigerant (magnetocaloric material) cannot be “split” in two different units as this is the case in the conventional system. If the unit, comprising the magnetocaloric material, is positioned outside, the shading and the prevention of heat gains has to be carefully designed. From the “cold” part of the magnetocaloric material the working fluid flows to the heat exchanger of console units through which room air flows as well. Another option of positioning the main unit (one, which comprise magnetocaloric material) is inside the building, preferably in the room which is not cooled to prevent possible heat gains from the “hot” part of the magnetocaloric material. An example of a magnetic split system unit is shown in Figure 13.

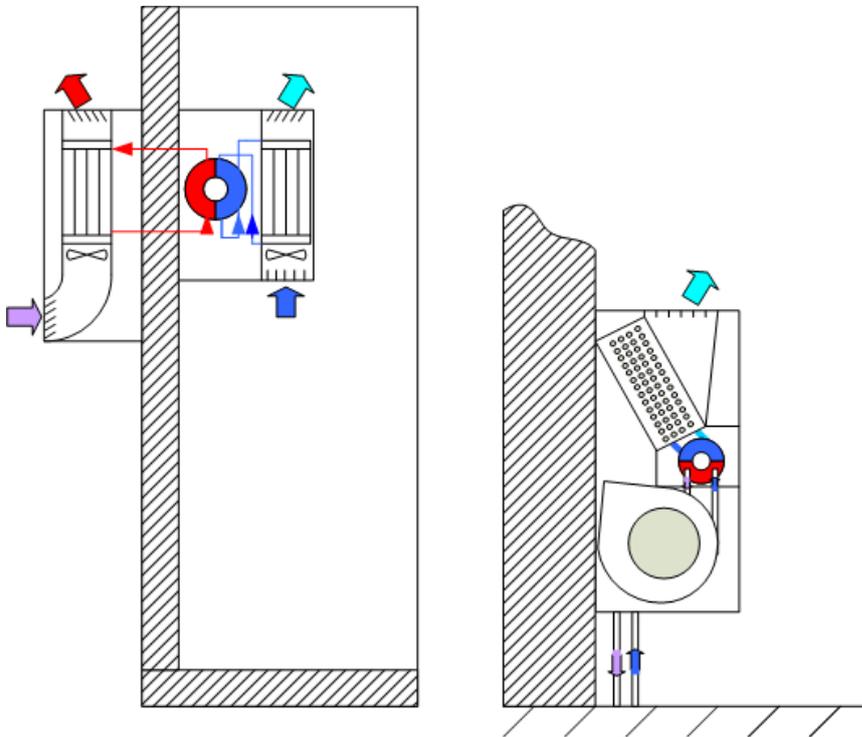


Figure 13: A simple examples of a wall-(or window) mounted magnetic air conditioning unit (left) and the fan coil, operating with the split system (right). In split systems, a central magnetic cooling unit could serve by its cooling for direct implementation into fan coils or other kinds of cooling applications (e.g. cassettes, ceiling cooling, etc) or by indirect implementation, where a system would present a kind of a cascade system, with small magnetic units operating in each cold source in the room.

2.2. Central cooling systems

In 2003 the world's production of compressors (centrifugal, screw, scroll, reciprocating and the rotary type with two cylinders) for air conditioning was around 22 millions units and for refrigeration around 18 millions units [1]. The world market estimated for both is approximately 3 billion US\$ per year. Conventional central cooling systems, vapour-compression and sorption chillers (usually hot water and gas absorption chillers, rarely adsorption and steam driven absorption chillers) are found in practical applications. Figure 14 shows an example of a centrifugal chiller. Such are used for large volume flows and smaller temperature spans.

At present one may detect a small number of R&D activities of the industry in the domain of magnetic cooling or air-conditioning in buildings and houses. However this domain has many advantages compared to smaller magnetic refrigeration units, e.g. for household appliances. The first advantage is that the temperature spans between the heat sink and the heat source are usually not so large. Furthermore, a large scale cooling (especially in centralized or decentralized district cooling systems) enables the use of superconducting magnets since the relative price of the high temperature (Nitrogen) superconducting system would not present a so large investment as this would be the case in smaller units. As proven, one can see large activities in development of superconducting motors with very high efficiency in the domain of ship propulsion systems (see also in chapter 6.2).

In conventional central cooling systems, vapour compression (reciprocate, screw turbo-compressors) and sorption (usually hot water and gas absorption chillers, rarely adsorption and steam driven absorption chillers) chillers are used. The heat rejection to the ambient is in many cases provided by use of additional adiabatic cooling via cooling towers. This is also the reason why the efficiency of water cooled systems is much higher than the one of air-cooled systems. The temperature level on the cooling side of the water cooling loop usually varies from 5 to 10 °C for supply and from 10 to 18 °C for return from heat sources. The temperature level of the heat rejection loop usually varies between 18 °C and 35 °C. One should note that certain buildings, or at least parts of buildings, need cooling all the year (for instance IT centrals), even in transition period or winter time. The temperature of the refrigerant in the water/water system is usually closer to the temperature levels of the water or secondary refrigerant than in the case when air is used as a working fluid.



Figure 14: *Top: A typical centrifugal chiller [5] of large size. These chillers are usually used for large cooling powers (large refrigerant volume flow and low pressure ratio). The nominal cooling capacity may be kept in a wide range of operating characteristics. Beside electric energy, also other kinds of sources may be used, e.g. gas or steam turbine driven compressor chillers.*



Bottom: Left: An air cooled Carrier liquid screw compressor chiller. Right: A McQuay water cooled liquid screw compressor chiller [7].

The operating conditions are favourable for the use of a magnetic central chiller, especially working with water/water or brine/brine, since the required temperature span is not so large. Additionally it has to be emphasized that for large scale units of the central cooling systems, other kind than magnetic refrigerators with permanent magnets may be used, e.g. with the use of superconducting coils. The cooling system for superconducting coils (preferably high temperature superconductors) may be used for several coils, providing magnetic field sources for several chiller units. The larger the required cooling power is the lower the relative costs of such system will be. Furthermore the use of superconducting coils enables the use of single stage magnetic chillers, because the magnetocaloric effect, which strongly depends on the magnetic field change, is much larger.

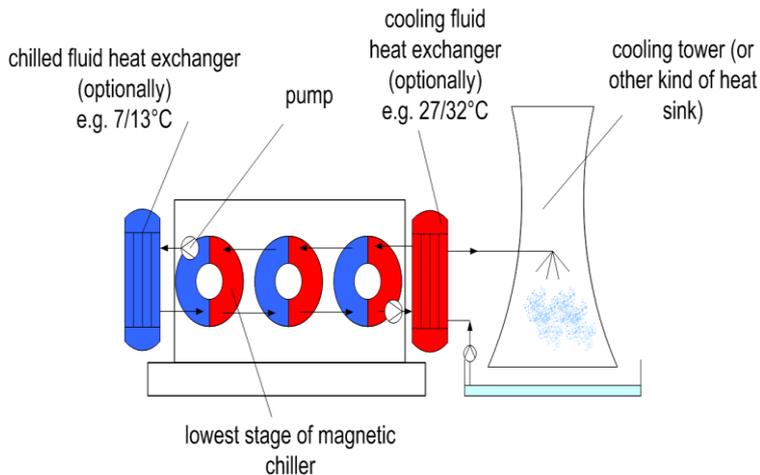


Figure 15: An example of a three-stage magnetic chiller unit is shown. For a typical water/water or brine/brine conventional compressor chiller the cooling water temperatures for the supply and return circuits are usually 27/32 °C and the chilled water temperatures of the supply and return circuits are 7/13°C. This technology may present a serious alternative to central cooling systems, especially in larger systems, such as district cooling systems.

The magnetic cooling technology enables one-loop or two-loop systems considering the transfer of the working fluid. Namely, the working fluid (liquid as water or some other conventional liquid secondary refrigerants) can be used in a magnetic refrigerator and then directly applied to the system in the case of a one-loop system. The disadvantages are the regulation/control system of such a device as well as the required pressure. An advantage is a possible higher efficiency (no intermediate heat transfer between two loops). There is no doubt that for large central systems in buildings the two-loop system should be used. In this case the most preferable is the use of water or some other secondary liquid refrigerant in the first loop (magnetic refrigerator) and similar in the second loop, separately. For air conditioning, if the system is large, the best would be to use water or liquid secondary refrigerants in the first loop (magnetic refrigerator) and then to use a water/air heat exchanger and consequently air in the second loop. There exist many different possibilities of using magnetic refrigeration technologies in central systems. This includes also a kind of decentralized cooling system, where a central unit (primary cooling system) is used for the pre-cooling and then local cooling devices for further cooling, depending on the temperature level, that a local cooling systems requires (e.g. ceiling panel cooling temperatures usually do not require so low temperature levels as fan-coils). Such an example is seen in Figure 16.

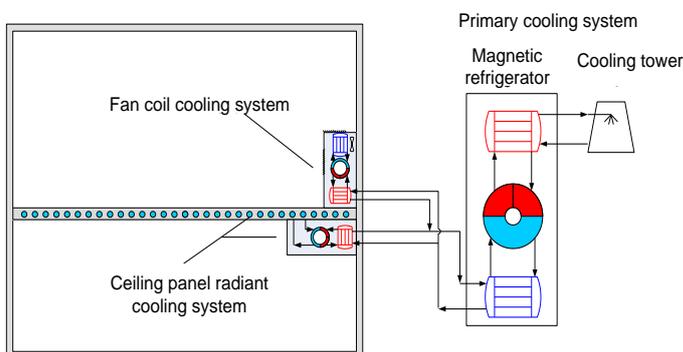


Figure 16: An example of cascade decentralized cooling system with the use of magnetic refrigerators.

Ceiling panel radiant cooling

a) Conventional ceiling panel radiant cooling

The temperature of the heat source in a panel radiant cooling system depends on the air characteristics in the building such as temperature and relative humidity. Therefore, the temperature of the heat source part of the system is rather high, above 15 °C. Considering the water/water central system with the cooling tower, the temperature of the secondary refrigerant (or water) on the condensing side is operating around 27/32 °C. Therefore, the temperature difference between the temperature of the heat source and the heat sink would be rather small. The COP of such a system could be very high.

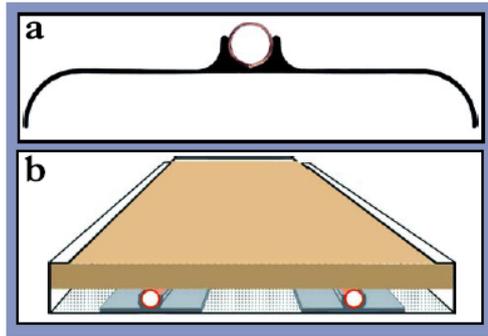


Figure 17: A typical ceiling panel construction: a) free hanging panel design for enhanced upper surface heat transfer; b) "drop-in" panel with back insulation and acoustical perforation.[8].

b) Magnetic ceiling panel radiant cooling

This kind of cooling is advantageous for magnetic cooling, because of small temperature differences between the heat source and the heat sink temperature. Many different applications are possible; the most convenient would be to use water or other liquid secondary refrigerants as a working fluid in both, the refrigerator and the system in the building. In the ceiling cooling system, the system could be divided into two loops (a kind of cascade system), where the first loop presents a central system (operating e.g. at 20 °C / 25 °C of the heat source and 27/32 °C of the heat sink) and the second loop the ceiling cooling system, (e.g. operating at 15/20 °C of the heat source and 20/25 °C of the heat sink from the first loop) This would enable the very small temperature differences required in single refrigerator units and consequently give a very high efficiency, a very flexible control system, different kind of devices, adjusted to a local condition on the secondary loop without changing parameters of the first loop. In both loops magnetic refrigerator or a combination with conventional cooling may be used. Since the magnetic refrigerator is a noiseless device, which may also become very compact, the use of a local refrigerator in the secondary loop for the ceiling cooling would not present a disadvantage.

Fan coil cooling

a) Conventional fan coil cooling

Fan coils are elements which are mostly used in central or split water/water cooling system in buildings. They may be floor-mounted, ceiling-mounted, wall-mounted, etc. They operate at a lowest temperature level of 4 °C (possibly higher) and usually the fan-coil temperature difference between the inlet and the outlet of water is 4 to 7 K. Fan coils may use 2 or 4 pipe systems (e.g. 2 for heating and 2 for cooling). They are using the forced convection of the inner air (possible use also of the fresh air) through the internal heat exchanger, which is cooled or heated by the main system.



Figure 18: An example of a fan coil [5] apparatus.

b) Magnetic fan coil cooling

Considering magnetic cooling, fan coils enable many different possibilities, similar as in the case of a ceiling panel cooling system. Beside the use of conventional fan-coils, connected to the central magnetic cooling system, there is the possibility to use a special fan-coil, which comprises the magnetic refrigerator. Because of its almost noiseless operation, this kind of device could present a substantial improvement in flexibility as well as in the performance of a magnetic refrigerator. If the cooling system is divided into two loops (a kind of cascade system) where the first loop presents a central system

(operating at 20 °C/25 °C of the heat source and 27/32 °C of the heat sink) and the second loop a fan coil cooling system (e.g. operating at 6/12 °C of the heat source and 20/25 °C of the heat sink from the first loop), this would enable the small temperature differences required in one refrigerator. That leads to a better efficiency, a very flexible control system, which enables different kind of devices adjusted to a local condition on the secondary loop without changing parameters of the first loop. In both loops, a magnetic refrigerator or a combination with a conventional cooling may be used in order to achieve a better efficiency and to lower the operating and the investment costs (see also Figure 13).

Magnetic air conditioning systems

Air conditioning systems usually comprise cooling, heating, humidification, dehumidification, filtering, heat recovery or the regeneration of the air. An air conditioning system therefore comprises several devices.



Figure 19: An example of an air-conditioning device is shown after reference [9].

In the air conditioning system, magnetic refrigeration may be utilized in different manners, for instance:

a) Air is used as a working fluid in a magnetic refrigerator (direct use of air in the secondary loop/indirect use with air-to-air heat exchanger in the secondary loop)

In the case of a direct use of air, the advantage is that there is no need for additional heat exchangers (lower investment costs), because the heat exchanges are performed directly in the magnetic refrigerator. The disadvantage is the pressure and air flow control, which is limited with the operation of the magnetic refrigerator. The temperature level in this case depends on the system. In general, the temperature difference between the temperature of the heat source and the temperature of the heat sink is rather low. Since a portion of fresh air may be replaced by the inner one, recuperation (regeneration) of cold would increase the efficiency. One has to note that when air is used as a working fluid the heat transfer irreversible losses between the working fluid and magnetocaloric material will be higher than when using water. Furthermore the heat transfer rate by using air cannot reach the one using liquid as a working fluid, so one may expect also a lower frequency of operation since a certain time period, longer than for the fluid, is needed for the heat transfer between the magnetocaloric material and the working fluid. A comprehensive study on safety properties of magnetocaloric materials should be made in such a case.

b) Water or other secondary refrigerants are working fluids in magnetic refrigerators (use of water/air heat exchanger on the secondary loop)

This leads to an advantage compared to the case where the working fluid is air. The cooling capacity per unit mass of the refrigerator will be higher (a more compact chiller). Heat transfer in the case of the water/air heat exchanger is better, so the irreversibilities are smaller. With the working fluid water the central cooling system may supply different kinds of cooling systems like air conditioning, fan coils, ceiling panel cooling, etc.

c) Hybrid magnetic refrigerator and heat regenerator in one (may use air or water as working fluid) is used for heating or cooling

In this case the magnetic refrigerator has functions of cooling and cold recovery comprised together. The cold (replacement of room air with fresh ambient air) recovery may be done directly (room air passes as working fluid at one side through the magnetic refrigerator, and from another side, fresh air is introduced into the system) or indirectly (room air exchanges heat with fresh air in a separate recuperator and then fresh air is further cooled in a magnetic refrigerator). This kind of system enables a large number of different applications and usually presents a small temperature difference between the temperatures of the heat source and heat sink.

d) Hybrid refrigerator by use of evaporative and magnetic cooling

In this case, a magnetic refrigerator has two functions of cooling: magnetocaloric and evaporative. Air is used as a working fluid. Fresh or room air (depending on a variety of applications), which passes through the magnetocaloric material (wavy, honeycomb structure) is cooled by the heat transfer between air and the magnetocaloric material and at the same time (more convenient on the heat sink side of the magnetocaloric material) by evaporative cooling. This may be done for instance by water spraying into the structure, so the evaporative cooling effect occurs. This kind of system enables a large number of different applications and usually presents small temperature differences between heat source and heat sink (see Figure 8 as the case of a hybrid device and Figure 20 as the case of combined device, which enables cold recovery as well as magnetic and evaporative cooling).

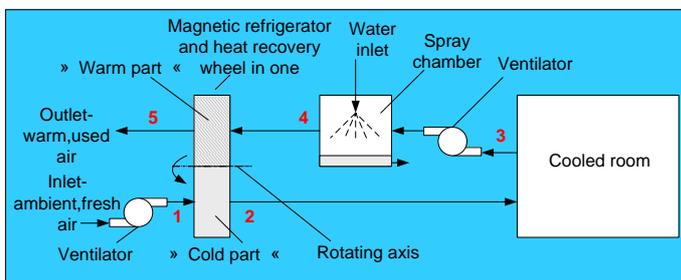
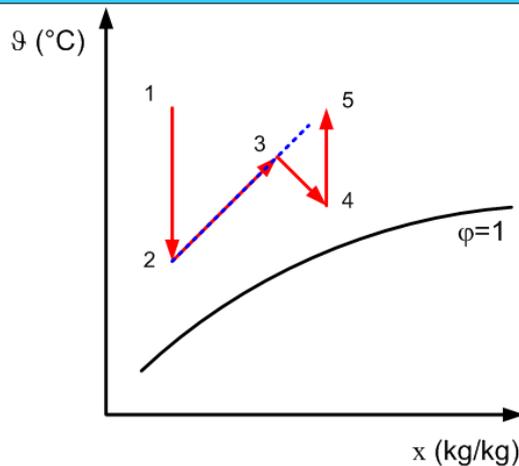


Figure 20: An example of a hybrid adiabatic-magnetic cooling system (magnetic cooling and heat recovery are comprised in one unit). The process of the air is shown in the picture underneath.



e) Magnetic refrigerators (heat pumps) used for air (de)humidification

Cooling of air, where condensation occurs, enables one to use a magnetic refrigerator as a dehumidifier of air. The temperature difference between the heat source and the heat sink depends on the relative humidity and temperature of the entering air (it may be fresh or room air, depending on the application). One may expect that the temperature difference, which is needed in this particular case, is not very high (some 10 K), so the magnetic air dehumidifier presents a very interesting solution.

3. COOLING AND FREEZING IN MEDICINE

A variety of applications may be found in medicine from refrigerators to freezers with very low temperatures. Refrigeration and freezing in the medical area are used in many applications such organic treatment and storage, blood and plasma storage, blood and plasma freezing, body storage, storage of premixed/frozen epoxies, sperm banks, chromatography, enzyme freezers, walk in rooms, ice for nursing stations and nursing homes, portable freezer boxes, incubators, cooling and freezing cabinets, etc. Here we will divide them according to their temperature levels.

3.1. Refrigerators in medicine

a) Conventional blood plasma storage refrigerators, chromatography and other laboratory refrigerators

The usual temperature range inside these refrigerators goes from 0 °C up to 10 °C. The usual type of refrigerator is an air-cooled condenser with a free or more often a forced convection evaporator. Usually hermetic compressors are used. The maximum cooling power reaches 500 W.



Figure 21: Examples of blood plasma storage and chromatography refrigerators (after reference [10]).

b) Magnetic blood plasma storage refrigerators, chromatography and other laboratory refrigerators

For magnetic refrigeration the liquid should be used as the working fluid with a possible forced convection on the side of the heat source and heat sink heat exchangers. The temperature difference between the heat source and the heat sink, as well as other characteristics, allows this kind of technology to be applied in the magnetic refrigeration area.

3.2. Freezers

Freezers in medicine may be divided into three main groups: conventional (-20 °C), low temperature (till -40 °C), and ultra low temperature (till -100 °C or below). The large required temperature differences between the heat source and the heat sink lead to multi-cascade or multi-regeneration magnetic cycles and consequently the irreversibilities are expected to be very large unless very high magnetic field changes are possible. However, in medicine laboratories, where very low temperature freezers have to be available (e.g. at the temperature of liquid nitrogen of 77 K), an option of a cryogenic freezer, which provides also cooling for the high temperature superconducting coils of the magnetic refrigerator seems possible. Another option to reach low temperature could be a hybrid system between a conventional refrigerator and a magnetic refrigerator.

Conventional medicine freezers (-20°C)

The usual type of refrigerator is an air-cooled condenser with a free but more often a forced convection evaporator. Hermetic compressors are usually used. Depending on the application a transparent or a no-transparent door is used.



Figure 22: *Examples of conventional medicine freezers (after references [10, 11]).*

Low temperature medicine freezers (up to - 40°C)

The usual type of a refrigerator is an air cooled condenser with a free, but more often a forced convection, evaporator. Hermetic compressors are usually used. An example of use is the freezing of blood or plasma.



Figure 23: *An example of a cold medicine freezer after [10] is shown.*

Ultra low temperature cold freezers (< - 40°C)

The usual type of refrigerator is an air-cooled condenser with a free or a forced convection evaporator. An example of use is the storage of biological products.



Figure 24: *An example of an ultra cold medicine freezer [10] is presented.*

Magnetic medicine freezers

Magnetic medicine freezers based on permanent magnets (at the present stage of development of the technology), presents certain difficulties due to the large temperature span between the temperatures of the heat source and the heat sink, which requires a multi-regeneration or a cascade system leading to very large irreversible losses due to the heat transfer and the fluid dynamics. An alternative to such a case may be the development of a hybrid magnetic-vapour compression device, where the magnetic cooling would be used preferably as a precooling phase. The interest of a precooling phase is that it leads to a much higher viscosity of the working fluid, which should, in this case, present a water solution with the deep freezing depressant of higher volume fractions. The dynamic viscosity of such fluids

usually increases with the content of the freezing depressant, so if the temperature of freezing is low the dynamic viscosity will be high (higher pressure losses). Another option, which is mentioned already at the beginning of this chapter, is to perform a kind of cascade system with a high-temperature superconductor. In medicine laboratories cryogenic refrigerators are sometimes required. If the cooling power of such refrigerators is designed to supply cold also to the high temperature superconducting magnets of a magnetic refrigerator, this then could be used for a kind of a cascade cooling system.

3.3. Other medicine refrigeration/freezing equipment

Combined refrigerator-freezers

This kind of devices do not differ much from the conventional household refrigerators with freezers. However, the cooling power in the medicine refrigerators with freezers may be larger (up to 500 W).

Cold or warm rooms, cabinets, chambers

These rooms, which are available for refrigerated or frozen storage in a broad range of configurations and sizes, can be enlarged or relocated as the refrigeration needs change. Environmental walk-in rooms and stability chambers reproduce and closely monitor any environment with a precise combination of humidity, temperature and light. In the sense of magnetic refrigeration or air-conditioning many different kinds of devices, which were already described in previous chapters, may be applied.

Portable freezing and refrigeration boxes

A portable refrigerator holds a steady interior temperature and is perfect for small spaces or used as an emergency back up for transportation or in the laboratory. The portable freezing boxes or refrigerators are ideal for long-term freezing applications and can easily be trucked or added to larger mobile units for access to more common items.



Figure 25: An example of a portable refrigerator taken from reference [11] is shown.

The cooling technology used in this kind of devices is often the thermoelectric effect. The cooling power is around 50 W for a 10-18 l volume. For the refrigerator, the inner cooling temperature should be kept between 0-5 °C, depending on specific application. For freezing, inner temperatures should be kept down to -20 °C, what also depends on the specific application. It is known, that this kind of cooling presents very low efficiency ($COP < 1$). Because of the large surface to volume ratio, the refrigeration/freezing boxes are expected to have larger relative heat gains than household refrigerators. In the case of magnetic portable refrigeration or freezing boxes different solutions could be applied:

- a) Magnetic refrigerator or freezer inside the box (working fluid water/brine or air)
- b) Use of external magnetic refrigerator/freezer for cooling charge of the box (use of phase change material in the box)
- c) Use of pulsed magnets with an electric (super) capacitor for magnetic refrigerator/freezer instead of use of permanent magnets
- d) Hybrid thermoelectric-magnetic refrigerator.

However, this kind of technology seems hardly feasible for magnetic cooling where mass, volume and also limitations on temperature spans play a crucial role.

Heating/cooling of incubators

This kind of devices are, for example, used for overnight preservation of BOD (Biochemical Oxygen Demand) samples, fermentation studies, drug-stability tests, entomological incubations, fermentation studies, standard culturing at 37 °C, etc. The laboratory refrigerator incubators can manually cycle between a heating period and a refrigeration period and are often used for culturing and monitoring the growth of bacteria. Use of magnetic cooling technology in this kind of devices would lead to the development of magnetic heat pumps with possible inverse operation.

4. COOLING, HEATING AND FREEZING IN FOOD INDUSTRY AND STORAGE

Food preparation and storage require cooling, freezing and also heating processes. These domains enable several different applications of the magnetic refrigeration/heat pump technology. The production is mainly associated with the dairy products, breweries and other kinds of beverage production, including wine. The preparation of food for the storage comprises a variety of products such as meat and fish products, vegetables and fruits. The storage may be associated with the household (already described in the 1. Chapter), supermarket (see Chapter 9) and warehouses (including cold rooms). Since food preparation includes also many heating processes, it is meaningful to emphasize the importance of a possible application of magnetic heat pumps in these technologies.

4.1. Food production

Dairy products

The dairy industry is one of the more intricate and diverse and requires refrigeration and temperature controls that are reliable throughout all its aspects. Refrigeration is needed in the production and storage of a wide range of products like milk, cheese, yogurt and butter. Here we will focus primarily on the ice-cream and butter production.

Ice cream production

When the milk arrives in the ice cream plant, it is pumped into large storage silos (e.g. $>10\text{ m}^3$), which maintain the temperature around $2\text{ }^\circ\text{C}$. This presents the first cooling process. Then the milk is mixed in stainless steel blenders with eggs, sugar and additives, pasteurized to $82\text{ }^\circ\text{C}$ and homogenized to produce a uniform texture. This mixture is brought back to the pasteurizer where cold water at approximately $1\text{ }^\circ\text{C}$ flows on one side of some plates as the mixture passes on the opposite side. In this manner, the mixture is cooled to $2\text{ }^\circ\text{C}$. Then it is pumped into large tanks (e.g. $>10\text{ m}^3$) in a room set at $2\text{ }^\circ\text{C}$ where it rests for four to eight hours to allow the ingredients to blend. After the flavouring of the ice-cream mixture, the mixture has to be frozen. Therefore, it is pumped into continuous freezers that can freeze up to few cubic metre per hour. The temperature inside freezers is kept at $-40\text{ }^\circ\text{C}$, usually using liquid ammonia as refrigerant. While the ice cream is in the freezer, air is injected into it. When the mixture leaves the freezer it has the consistency of soft-serve ice cream. After preparation of the ice-cream, the hardening process starts before storage or shipping, where the ice-cream has to be hardened to $-23\text{ }^\circ\text{C}$. The conveyer system moves the ice cream cartons to a tunnel set at $-34\text{ }^\circ\text{C}$. Constantly turning ceiling fans create a wind cold of $-51\text{ }^\circ\text{C}$. The cartons move slowly back and forth through the tunnel for two to three hours until the contents are rock solid. The cartons are then stored in refrigerated warehouses until they are shipped to retail outlets.

The magnetic refrigeration technology in ice-cream production may be performed in all above mentioned processes. However at this stage of development of technology, the refrigeration process would be much easier performed than the freezing one. Large water or brine cooled tanks for cooling of milk or mixture for ice cream enable use of magnetic refrigerators with rather low temperature spans between the heat source and heat sink. Usually in such industry, cooling towers are used for the waste heat rejection from the chiller, unless some other waste heat utilization process is performed. Figure 26 shows an example of a milk cooling in a large vessel by use of the magnetic refrigeration technology.

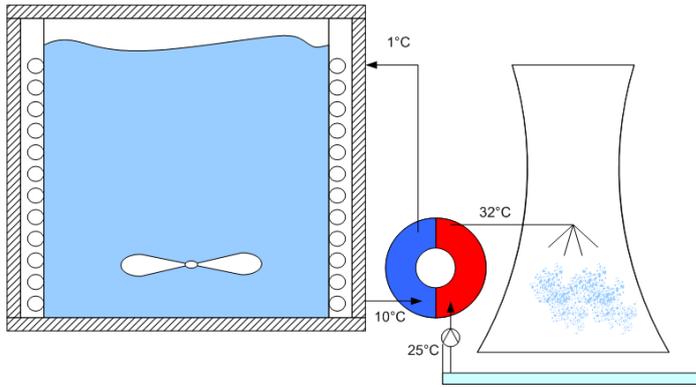


Figure 26: A simple example of a milk cooling system by the use of a magnetic refrigerator combined with a cooling tower.

Butter production

Following pasteurization, a rapid cooling promotes fat crystals outside and liquid fat inside the fat globules. If the cream is churned after this step the loss of fat to the buttermilk will be high. Thus a tempering step is used in which the cream is kept at about 10 °C to allow rearrangement of the fat crystals. This kind of temperature level is advantageous for magnetic refrigeration, which may be used in such steps of process engineering.

Wine production

One of the most important processes for the wine production is the fermentation. During the basic fermentation process of wine, the two grape sugars (glucose and fructose) are converted to alcohol (ethanol) by the action of yeast. The by-products of the primary fermentation are aromas, flavours, gas carbon dioxide and heat because fermentation is an exothermic process. The production of heat during fermentation means that the temperature will rise unless cooling is performed. White wine fermentation is usually conducted in the range of 8-19°C and the red wine fermentations are allowed to run between 25 and 32 °C. At temperatures higher than this there can be a loss of desirable aroma and flavour compounds and unattractive aroma in the spectrum of caramel, burnt or cooked characters can be produced.

Following temperature levels of the wine fermentation, the magnetic refrigeration technology presents an ideal technology, since the temperature spans between the temperature of the heat source and the heat sink may be very low, especially in the case of red wine. Further, the working fluid for the vessel cooling is preferably water, so the heat transfer rate is much higher when compared to the case where air acts as working fluid.

Beer production

Similar as for the wine, beer fermentation requires cooling as well but at different temperature levels for different kinds of beers. For instance the traditional lager brewing [12] involves pitching the yeast between 5 and 6 °C and allowing the temperature to rise between 8 and 9 °C. This generally results in a better quality beer, because a low fermentation temperature retards the development of by-products – esters, fusel alcohols, and diacetyl, all of which are inappropriate in lagers. However, the lag period is generally longer at lower fermentation temperatures. At the end of primary fermentation the temperature is reduced by 1 to 1.5 °C per day and transferred to the lager cellar between 4 and 5 °C. More commonly, the yeast is pitched between 7 and 8 °C, and after a couple of days the temperature is increased to 10 to 11 °C. Some brewers use the same starting temperature but then increase the temperature to 14 to 15 °C. Other breweries are known to pitch between 12 and 14 °C and then increase the temperature to 18°C. The most commonly used system for fermentation of lagers and ales is the cylindro-conical one, which is a vertical cylinder with a conical base and a dished top. The size of these systems ranges from 100 to 7000 hl.



Figure 27: Cylindro-conical fermenters are shown in the picture on the left-hand side (see references [13, 14]).

One of the processes where cooling is also required is beer carbonation. The carbonation is a process which is very often performed for soft drinks, sparkling water, wine, etc. The time required to reach a desired carbon dioxide concentration depends on a number of physical factors. Temperature and pressure play an important role in determining the equilibrium concentration of carbon dioxide in a solution. At equilibrium the same amount of carbon dioxide is diffusing out of the liquid (beer) as is being dissolved back into the solution. Increasing the pressure leads to a linear increase of the weight of carbon dioxide dissolved in the beer or water. Decreasing the temperature gives a nonlinear increase in carbon dioxide solubility in beer. Consequently, the equilibrium concentration cannot be attained without either increasing the pressure or decreasing the temperature. Thus the closer to 0 °C the carbonating temperature is and the higher the pressure is, the greater the carbon dioxide absorption will be.

Fixing the temperature and pressure at appropriate settings will bring the desired carbon dioxide concentration. For example, at 0 °C a beer containing 2.5 volumes of carbon dioxide will have a pressure of 0.56 bar (above the ambient pressure), whereas at 16 °C the pressure increases to 1.6 bar. The amount of carbon dioxide that dissolves is a function of time, with the rate decreasing exponentially as equilibrium is approached. For the same volume at ambient temperature of 32 °C, the pressure in the vessel should be kept at 2.7 bar above the ambient pressure.

Use of magnetic refrigerators in beverage carbonation (for beer, soft drinks, water) presents a large market niche, especially when required temperatures are not too low but at some 10-20 K below ambient temperature.

4.2. Food processing before storage [15]

Cooling of food before storage comprise technologies, such are air free or forced convection refrigeration/freezing, hydro cooling, cryogenic freezing, spray chilling, vacuum cooling, hydro cooling, etc. Here we will focus on some important technologies, which are used for the food preparation before a short or a long-term storage.

Air blasting freezing (convection)

In this method cold air at high velocities is circulated over the product. There are different methods of air blast freezing, which may be divided into two main groups:

- Batch
 - o cold storage room
 - o stationary blast cell freezing tunnel, which is one of the simplest freezer
 - o push through trolley freezer
- Continuous / in-line
- Straight belt freezer
 - o single

- multiple

Usually these kinds of processes are performed in two stages. The first stage initially cools or crust freezes an outer layer to prepare the product before transferring it to the second stage. In the pre-cool section the first stage operates at some -10 °C to -4 °C and then the second stage operates between -32 °C to -40 °C. In the case, that products need to be frozen from their hot state (e.g. French fries at some 80 to 95 °C), an additional cooling stage is used before the pre-cooling stage. In this particular case the air has a temperature around 10 °C.

Other types of freezers

Other types of freezers are fluidized bed freezers, where the product flows in a fluidized bed, where the air temperature is usually between -35 and -40 °C. The heat transfer is very good. The process rapidly crust freezes the product. Other types are spiral bed and carton (carrier) freezer. There exists also cryogenic freezing, which serves for rapid cooling. Usually it is used for products of a small scale, launching new products, handling overload situations and for the use with seasonal products. The most common kinds of such freezers are:

- Liquid nitrogen freezers (-195 °C), the “warm” vapour coming out of freezing (around -45 °C) is used then for other processes
- Liquid carbon dioxide freezers (temperature lower than -79 °C, operation as for nitrogen).

One should note that in industry, which comprises also liquid nitrogen cooling devices, there is a large potential to cool high temperature superconducting magnets of magnetic refrigerators. In this case larger magnetic field changes could enable larger temperature spans with high efficiency. This kind of technology may be especially applied in larger cooling warehouses, where the cooling power of the different processes is large and the relative costs of superconducting magnets could be substantially reduced.

Methods of pre-cooling, cooling and freezing of fruits, vegetables and cut flowers

Usually fruits and vegetables require higher temperatures of cooling, what is advantageous for magnetic refrigeration technology at its present stage of development.

a) Hydrocooling

There exist different types of hydro cooling. These are flooding, spraying or immersing of the product. Usually hydro cooling is used for peaches, tart cherries, cantaloupes, etc. This kind of cooling process is not proper for citrus fruits. Other vegetables which may be cooled are: corn, celery, radishes and carrots. The cooling temperature does not exceed -2 °C and its level strongly depends on the specific fruit or vegetable.

b) Forced air cooling

Similar as freezing, the forced air cooling may be used for fruits and vegetables where the temperature varies between -10 to 10 °C depending on the specific type. Forced air may also be used for cooling of flowers.

c) Package icing

This method works with top icing or use of ice slurry, crushed ice, etc. It is used for temperatures between -10 and 0 °C and is applied to freeze spinach, broccoli, collards, kale, Brussels sprouts, radishes, carrots and onions.

d) Vacuum cooling

These kinds of processes are used for vegetables with high ratio of surface to volume. This is a batch process where the temperature is around -2 °C. Types of vegetables for such process are: spinach, endive, escarole, parsley, asparagus, snap beans, broccoli, cabbage, celery, sweet corn, mushrooms, etc.

Fresh meat preparation after slaughter

Animal body temperature varies between some 35 °C to 40 °C. In this case a rapid heat removal is required and this may be performed by different methods, which are:

- Spray chilling (e.g. beef), with spraying of cold water at some 1 to 2 °C
- Dry air coolers (0 °C)
- Brine systems (may also introduce ice slurry), where the meat is directly immersed into a bath (this kind of preparation is also used in the fish industry).

4.3. Food storage [15]

Food storage may be distinguished as short term and long term storage. In food industry it is usually related to the batch storage in warehouses or cold rooms. Freezing is one of most common processes for long term food storage of meat products, vegetables and fruits.

The table bellow shows some examples of freezing temperature depending on the time of storage for different kinds of meat products.

Table 1: Storage life of meat products (months) (after reference [15]).

	-12 °C	-18 °C	-23 °C	-29 °C
Beef	4 to 12	6 to 18	12 to 24	12+
Lamb	3 to 8	6 to 16	12 to 18	12+
Veal	3 to 4	4 to 14	8	12
Pork	2 to 6	4 to 12	8 to 15	10
Chopped beef	3 to 4	4 to 6	8	10
Pork sausage	1 to 2	2 to 6	3	4
Smoked ham and bacon	1 to 3	2 to 4	3	4
Beef liver	2 to 3	2 to 4		
Cooked foods	2 to 3	2 to 4		

Freezing of vegetables and fruits require temperatures from -18 °C to -25 °C, however, some of the fruits and vegetables require temperatures above the 0 °C even for long term storage. Therefore, storage for certain fruits or vegetables at different temperature levels may be much longer, as follows:

Group from 0 to 2 °C

This group contains the majority of products in food-handling operations, including most leafy vegetables, cole crops and temperate-origin fruits and berries. The relative humidity is between 90 % and 98 %.

Group from 7 to 10 °C

This group contains citrus and subtropical fruits and many fruit-type vegetables. The relative humidity is between 85 % and 95 %.

Group from 13 to 18 °C

This group contains common root-type vegetables, winter (hard-rind) squashes and most tropical fruits and melons. The relative humidity is between 85 % and 95 %.

For short-term storage of meat products (< 1 week), batch rooms are used for beef or other kinds of meat (temperatures vary from -4 to -1 °C for the starting process of storage, however in general there is a need to keep room temperature between 0 to 1 °C).

Since storage of food is only one of the processes which concern the food industry, an example of a combination of different processes, which could be used in magnetic refrigeration is shown in Figure 28. In this particular case, magnetic refrigerators and freezers do not need to operate with large temperature differences, especially when a kind of cascading system is applied.

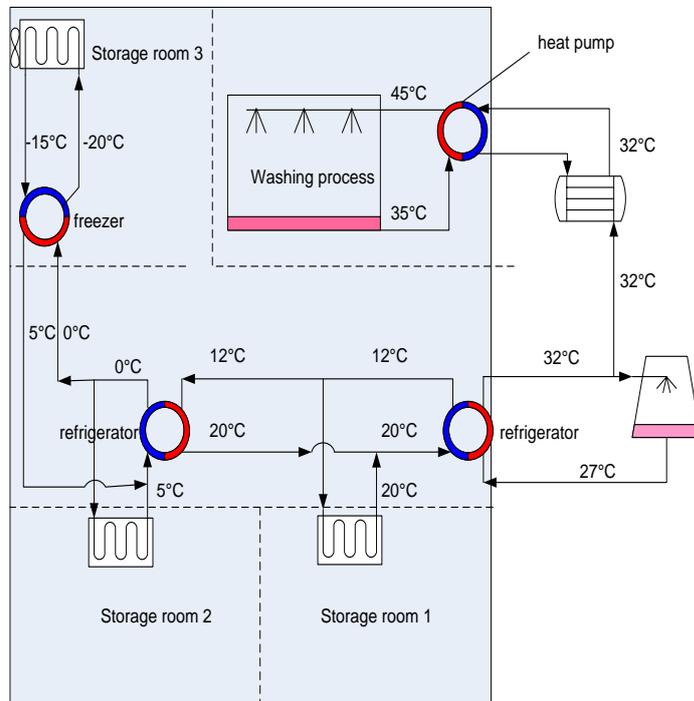


Figure 28: An example of a multilevel magnetic refrigeration (decentralized cascade system) in a warehouse. This enables the operation at small temperature differences for each unit between the temperatures of the heat source and the heat sink. The central cooling system operates between the ambient temperature of 32 °C and the heat source temperature of 15 °C. The rejection of waste heat may be used directly or as a pre-heating phase for washing products or defrosting heat exchangers. Other units use cooling energy from the central unit for heat rejection. Since the cooling of fruits and vegetables in storage (without freezing) requires usually higher temperature levels the cooling unit for this kind of operation would require rather a small temperature difference. Such units may be over-designed in order to provide heat sinks for units with lower temperature levels (e.g. for long term freezing storage, pre-cooling phases of freezing or for the phase of the preparation of food for storage). Another cooling unit uses this kind of heat sink for a freezing process, e.g. to -32 °C.

5. COOLING, HEATING AND FREEZING IN TRANSPORTATION

In opposite to rail vehicles, which may have direct electricity utilization for cooling or its air-conditioning system, there are at least three different possible energy sources which enable driving of the cooling or freezing and air-conditioning systems in combustion engine driven vehicles (e.g. cars, trucks, buses, ships). These are listed in the following sections:

Heat from exhaust gases occurs mostly in catalyst. It is approximately 40 % of the primary energy in a car. The temperature of the exhaust gases strongly varies (200-800 °C) depending on the position in the car (exhaust pipe behind engine, catalyst, centre muffler, rear muffler). Temporary research to exploit this kind of heat source is primarily focused on thermo-electric generators. However, their very low efficiency cannot compete with magnetic-powered generators, especially when low temperature differences between the heat source and the heat sink are considered. The magnetic power generator could be the driving device for a cooling system, where two possibilities exist: a) power generator and refrigerator are comprised in one single unit or b) the magnetic power generator (this may be also another system, e.g. a Stirling engine, a thermo-electric generator, etc.) and the magnetic refrigerator present two different units. Since in this case the primary heat source is gaseous, they should pass through the heat exchanger or be directly used in the magnetic power generator. In the case of the existence of an intermediate heat exchanger, on the secondary side (magnetic power generator working fluid), liquids, ferrofluids or others may be applied. A special case is a magnetocaloric fluid which would be present as a working material (instead of a solid one) in the power generator as well as in the refrigerator.

Heat from engine cooling water is approximately 30 % of the primary energy used in a car. It is transformed to mechanical work of a magnetic refrigerator. The temperature of the cooling fluid in the engine usually goes up to 110 °C. This kind of heat source may be used directly as a working fluid in a magnetic power generation unit or indirectly using an intermediate heat exchanger. In the first case, also other kinds of fluids (instead of water) may be used, such are ferrofluids or others. In a special case, a working fluid could be a magnetocaloric fluid, which would have different tasks depending on its position in the system (as cooling fluid in the motor, as working material in the magnetic power generator). The temperature differences in this case of cooling of the motor are rather small, so there will not be a need for multi-regenerative thermodynamic cycle or a cascade system.

Electricity from the alternator or engine drive is used to perform work for the magnetic refrigerator. This is also a conventional way in transport means. In the case of railroad air conditioning, the electricity would power the magnetic refrigeration/air conditioning unit.

5.1. Air-conditioning (cooling) in land transport

Conventional air-conditioning in cars and buses

Air conditioning in surface transport vehicles comprises cooling and dehumidifying. While the cooling power in cars reaches a few kilowatt of cooling, the urban buses (e.g. with fifty seats) require a cooling power between 20 and 50 kW. The difference is also in the location of the air-conditioning system. In cars the whole system is located at the engine (usually in the front part of the car), whereas in buses different types exist: The motor drive and the compressor units are usually located at the back of the bus (bulkhead) or behind (below) the engine of the bus. The condensing units can be located on the roof, at the back of the bus and sometimes below (behind) the engine. The distribution of cold can be provided through evaporators which can be a part of the split system or can be attached together with the condenser on the roof as a rooftop unit. Another option is the preparation of air and the flow of air-conditioned air through ducts to passengers. The *COP* of the car or bus air conditioning device does not exceed a *COP* of 2.5, depending on its operation characteristics. Figures 29-32 are helpful to illustrate different design solutions.

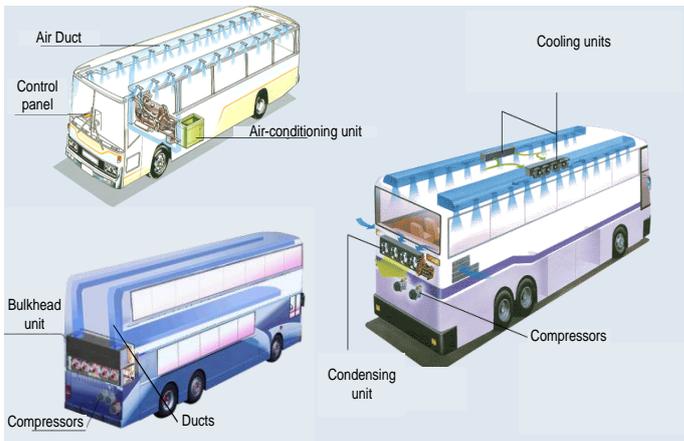


Figure 29: Some design principles of the bus air-conditioning system [16]. The cooling units are mounted in the ceiling air ducts. Therefore they do not take up floor or luggage space. Installation is easy because there is no need to access from the bus exterior. It is also possible to mount cooling units at the front, middle or back of the bus. The condenser can be either bulkhead or roof top type. Both types of units enable free space under the floor for extra luggage space.



Figure 30: The split system components [17]. Other types may be represented by individual air conditioning units, located at several positions in the bus, usually roof mounted. In some cases, the air conditioning units may represent heat pumps, which also provide heating during the winter season.

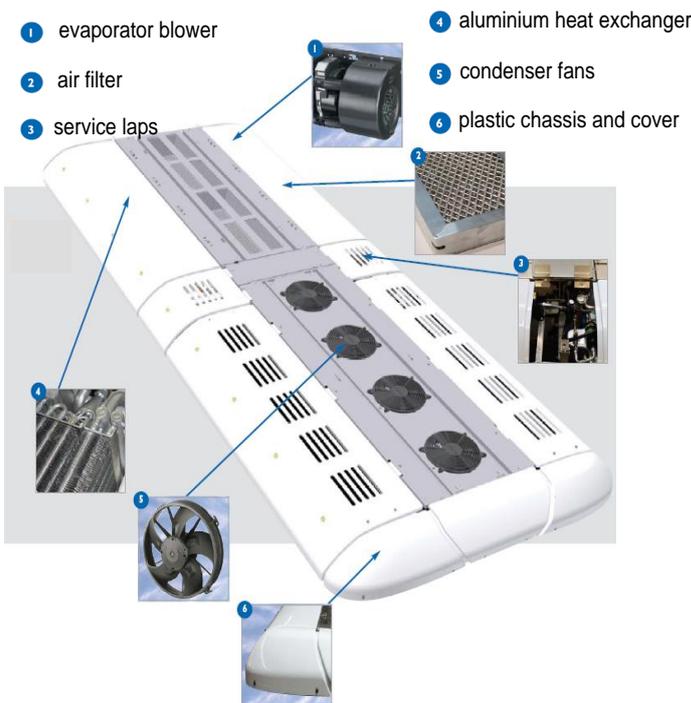


Figure 31: The compact individual unit mounted on the bus roof (after reference [17]).

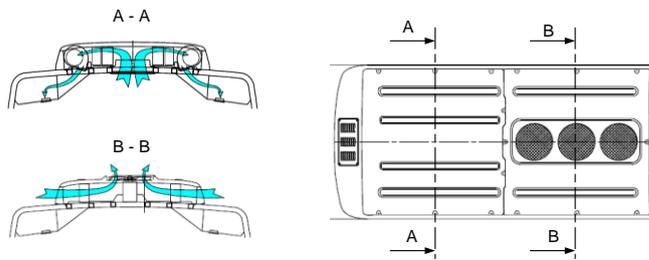
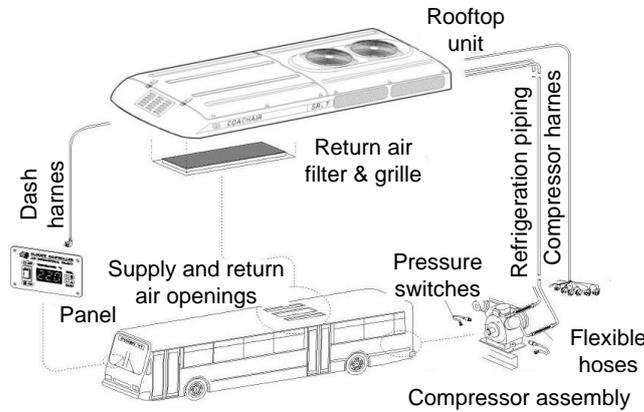


Figure 32: An example of a rooftop compact unit (see reference [18]).



Magnetic air conditioning in cars and buses

The temperature spans between the heat source and the heat sink with normal conditions of operation are not large. However, one should note that the temperature in a standing car or bus on the road in summer time without use of ventilation or air conditioning can reach some 70 °C. This kind of problem is a rather large obstacle for the present state of development of the magnetic cooling technology. One solution is to perform a multi-regenerative process or a cascade one, but the efficiency would be low because of the numerous heat transfer processes and pressure losses due to the fluid flow. Another option is to perform a hybrid cascade system. An example showing a hybrid car air conditioner is presented in Figure 33.

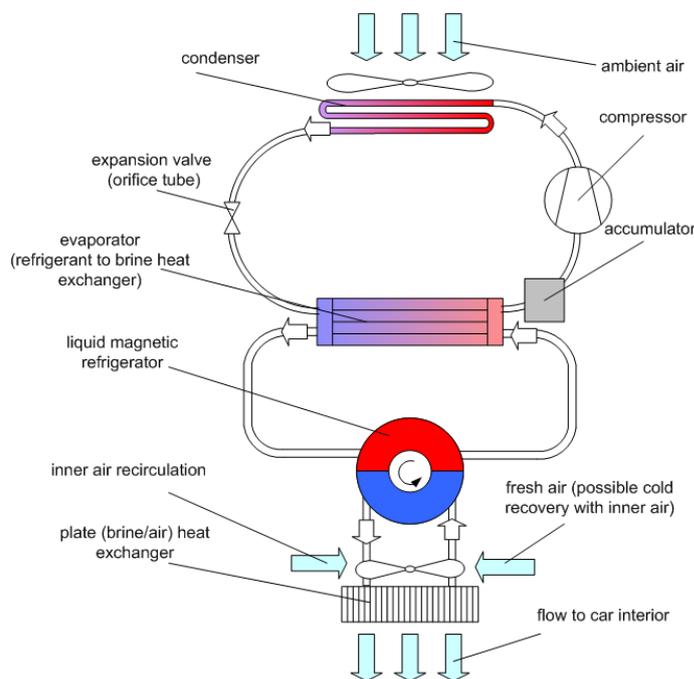


Figure 33: An example of a cascade vapour compression/magnetic air conditioner. The vapour compression system is designed to operate in extreme conditions, where the condensation temperature reaches some 60 °C. Its evaporation temperature is designed to be adapted to the magnetic refrigerator's heat sink. In extreme conditions for instance, the evaporation temperature could reach some 20-30 °C. The heat transfer in the heat exchanger between the refrigerant (metal) and the working fluid (water or brine) in the magnetic refrigerator is rather good. Therefore, the temperature of a brine or water in such a heat exchanger would be close to the evaporating one at the exit. The cooling temperature of the brine (water) exiting the cold part of the magnetocaloric material would be 5 to 20 °C, depending on the specific application. In such a way the magnetic refrigerator would become a feasible application in car air-conditioning systems.

Several possible solutions exist to use magnetic refrigeration technology in buses. At the heat source side (cooling), one possibility is to perform a multicascade or multiregenerative magnetic refrigeration system in order to cover the large temperature span due to the extreme conditions. Another option is to perform a hybrid vapour compression/magnetic air-conditioning system. The heat rejection system as well as the heat source (air-conditioning system) could be performed with water or brine as the working fluid instead of a gaseous refrigerant. In extreme conditions the compressor system would present a lower stage used for covering the temperature span between the ambient air at a very high temperature and the temperature level needed for the heat sink of the magnetic refrigerator. In such conditions the magnetic refrigerator would always operate in the limited temperature span between its heat source and heat sink. If the ambient temperature corresponds to the one of the heat rejection of magnetic refrigeration, the compressor unit could switch off and thus the magnetic refrigerator would operate the whole cooling process. For this kind of solution two intermediate heat exchangers are needed: one acting as the evaporator of the refrigerant (on the secondary side a brine or water from the heat rejection part of magnetic refrigerator would be applied) and one for the heat rejection of the compressor unit (condenser, on the secondary side water or a brine would be present, which flows through the heat rejection system of the bus with fans).

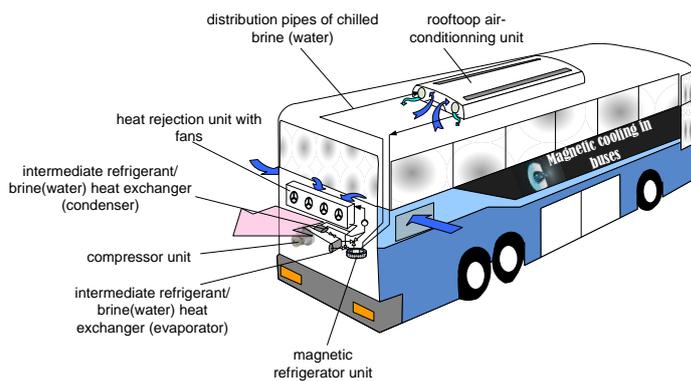


Figure 34: An example of the cascade vapour compression/magnetic air conditioner in buses. The heat rejection unit may be placed at the back of the bus or may be positioned on the roof top with the air-conditioning unit. Chilled water or brine may be used for the central preparation (conditioning) of air and the air is distributed through conduits in the bus. Another option is the distribution of chilled water or brine from the rooftop air conditioner or a distribution to individual units, similar as what is done in the split system, with the exception that here no gaseous refrigerant flows through the pipes.

As the working fluid in magnetic refrigeration, there are possibilities of using air (directly or indirectly by an intermediate heat exchanger) or water or other kinds of fluids. The use of air in direct contact with the magnetocaloric material will most probably lead to lower frequencies of operation, because the heat transfer rate is not as high as for water.

Conventional air conditioning in trains and other rail cars

A typical rail car has a control package and two self-contained heating/cooling units mounted in the equipment rooms. Split, underfloor and roof-mounted package systems are less common. Subway cars commonly use split air-conditioning systems, where evaporators (heat source) usually are placed at the roof level and condensers (heat sink) are mounted under floor.

Light rail vehicles have the same air-conditioning equipment as subway cars. Because the interior space is premium, especially in rush hours, these cars use roof-mounted air-conditioning packages. The operating conditions are very similar to those in buses. The cooling power of units vary from 10 to 40 kW. Figure 35 shows some examples of rooftop air-conditioners.



Figure 35: An example of a rooftop air conditioners for trains is shown (reference [17]).

Conventional air-conditioning of cabins in land transport

The market in this domain comprises a variety of different land-transport vehicles such as building and other working vehicles (cranes, dredgers, trucks, tractors,...). Important is also cabin cooling of bus drivers, truck drivers, rail drivers, etc. In almost all above mentioned cases the rooftop air-conditioners are most common.

5.2. Marine air-conditioning (cooling)

Marine cooling is one of the largest domains of air-conditioning and refrigeration. This chapter is dedicated to the living comfort air-conditioning (air-conditioning, refrigeration and freezing of food and other goods are presented in Chapter 6.3).

Conventional marine air conditioning

In cruisers the central cooling units can reach some 20 MW of cooling power. The inner cooling and air-conditioning systems usually comprise almost all the variety of systems used in buildings and houses. Sea cruisers are carrying usually more than thousand people on board and the living comfort for those passengers has to be provided. The requirements are usually higher than in buildings.

In yachts, depending on the size, a central cooling or air-conditioning unit may be present as well as a split system. The operating conditions are advantageous on the side of the heat sink (condensation) because in most cases sea water is used for the heat rejection. However, one should note that as in land transport, the sun radiation can substantially increase the temperature in the ship cabins.



Figure 36: *The cruiser Oriana carries 1800 passengers and 760 crew members on board. The central cooling unit for air conditioning comprises three water chillers with a total capacity of 16.5 MW (after references [19,20]).*

Magnetic marine air conditioning

The silent operation of magnetic refrigerators enables an additional comfort which could lead to a very high standard in marine air conditioning. In the large-scale cooling units, such as those required in sea cruisers, there would be the possibility to apply a superconducting magnetic refrigeration system. Despite the high investment costs for the superconducting magnet system, the relative costs at so large cooling power may be neglected. Furthermore, there may be a substantial progress in the ship propulsion systems if superconducting motors are used instead of conventional motors. Since these kinds of motors require special high temperature superconducting systems, a part of such a cryo-cooler could be dedicated for cooling of the superconducting magnetic refrigeration unit(s).

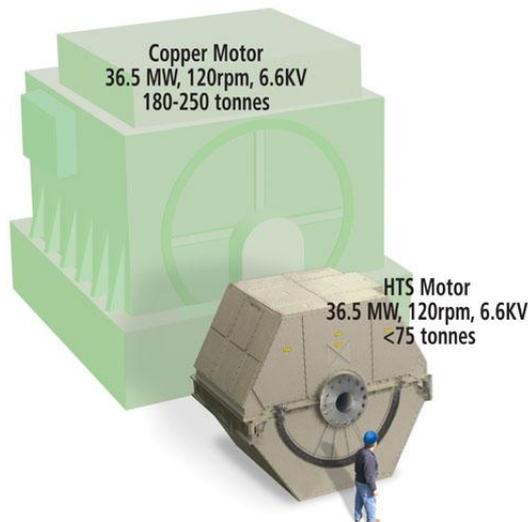


Figure 37: The use of high temperature superconductors (HTS) in ship propulsion systems provide a very efficient and compact energy conversion. On the left-hand side is an illustration of a conventional copper 36.5 MW ship propulsion motor. On its right-hand side for comparison one sees a HTS 36.5 MW ship propulsion motor (taken from reference [21]).

The use of magnetic refrigeration technology for central cooling in marine applications would be a more efficient way than further applying air conditioning or fan coil systems connected by a distribution network containing water or brine. Depending on the sea water temperature (see Figure 38), the heat rejection temperature of a magnetic refrigerator would be lower than in many cases presented in previous chapters. Because of the salt water, an intermediate heat exchanger should be mounted into the system. The heat transfer rate of such water/water heat exchangers can be very high; so one may expect that the temperature of the heat sink doesn't exceed 35 °C. For permanent-magnet-based and especially superconducting-magnet-based magnetic refrigerators this would lead to a small number of heat transfer processes, and thus the irreversible losses would be expected to be small.

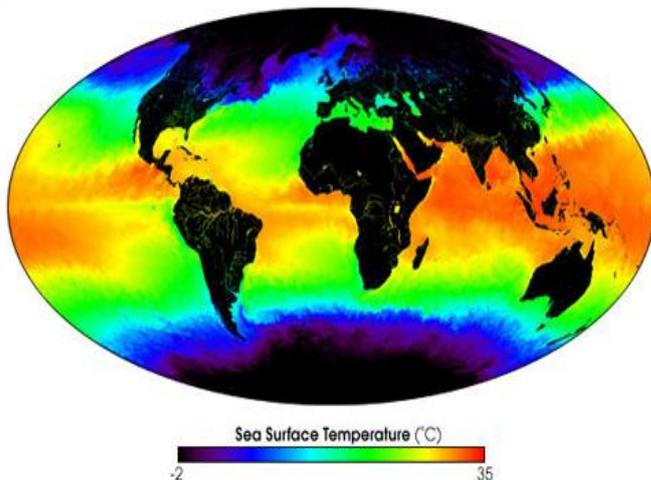


Figure 38 The surface temperature of the sea measured by the Moderate-resolution Imaging Spectroradiometer (MODIS). This image shows a one-month composite for May 2001 (after reference [22]).

5.3. Refrigeration and freezing of food or other goods in transportation

This chapter is dedicated to storage of food and other goods in different transport means. We will focus on compact small box-size refrigerators and freezers for a use in cars and buses and cold compartments or rooms in trains, trucks or ships.

Small box-sized refrigerators and freezers

Small box-sized refrigerators and freezers for use in medicine have already been presented in Chapter 4.3. For a more conventional use in cars, the small box-sized portable refrigerators usually occupy a volume between 4 and 20 litres. The cooling technology applied in these kinds of refrigerators or freezers is based on the thermo-electric effect. So the efficiency is very low ($COP < 1$). Usually these kinds of devices are not used for deep freezing, but rather for chilling or freezing at low temperatures. The maximum temperature difference achieved by this kind of refrigerators/freezers is approximately 30 K (refrigerators operate at around 20 K below the ambient temperature (heat rejection temperature)). The cooling power varies with the size of the refrigerator, but the maximum is around 80 W. For magnetic refrigeration applications, see Chapter 4.3.

Figure 39: Examples of box-sized refrigerators for cars (after reference [23]).



Conventional refrigeration and freezing in trucks

Refrigerated road vehicles fall into two basic categories [24]. A first one is large semi-trailers with refrigeration units that can be run independently of the tractor unit. A second is rigid-bodied vehicles of various sizes, which can have independent refrigeration units, units driven from the vehicle engine (or axles) or depending on eutectic storage media. Semi-trailers are used for long-distance or bulk movements, generally with only one or a few destinations. The journey times can vary from two hours for a supermarket distribution to several days for fresh product transportation. Most such vehicles use diesel engine drives with optional electric alternatives and some use total-loss refrigerant tanks (liquid nitrogen or carbon dioxide) to reduce both capital cost and noise levels in sensitive areas. In most developed countries, semi-trailers are designed for a use in ambient temperatures of 30 °C or above with a thermal insulation with an overall value of 0.7 W/m²K or better. If frozen goods are transported, an insulation of less than 0.4 W/m²K is applied. Increasingly, multi-purpose multi-compartment vehicles are being produced. They are capable of carrying frozen, chilled and fresh products simultaneously in different compartments. Rigid-body vehicles vary from large vehicles very similar in use to the semi-trailers to small delivery vehicles for multiple deliveries of chilled foods to corner shops. The refrigeration units can be driven by diesel or electric motors, by hydraulic drive from the vehicle chassis or can be based on either total-loss or eutectic systems. The latter two are more often used for frozen food transport, because they are relatively difficult to control at chillers temperatures. Delivery vehicles may require walk-in access for order selection from fixed shelving and may have to operate with large numbers of daily door openings. Commercial requirements have led to the development of multi-compartment vehicles with independent temperature control in each compartment. These vehicles are suited to distribution from stores to retailers as they can simultaneously move frozen, chilled and ambient-temperature goods. Such vehicles may have separate cooling coils in each compartment or depend on fans to transfer a limited amount of cold air from the coldest to a warmer compartment. Generally, refrigerated vehicles control the temperature of the air supplied to the cargo space and monitor the temperature of the air returning to the refrigeration units with an external gauge or display or a display within the vehicle cabine. Some older vehicles primarily designed for frozen foods can only control the temperature of air returning to the refrigeration unit with the risk of freezing chilled foods that are loaded too warm.

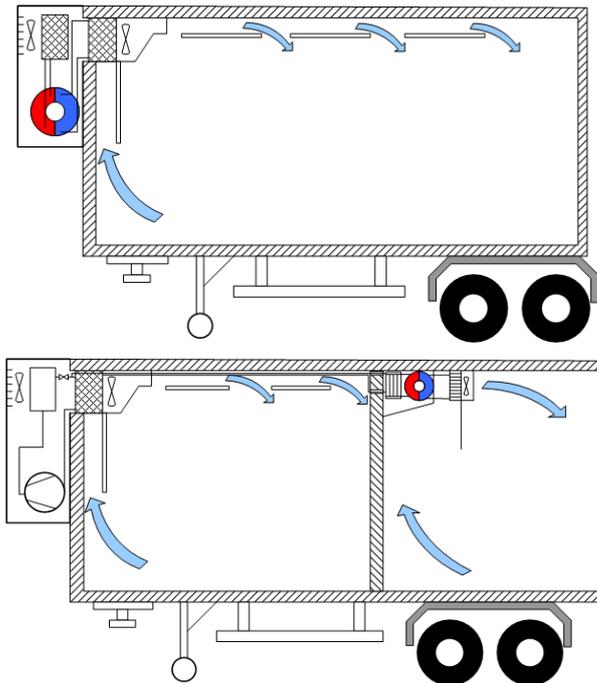
Figure 40: *Examples of refrigerated trailers, trucks and vans are shown in these pictures (after references [25,26]).*



Magnetic refrigeration and freezing in trucks

Magnetic refrigeration/freezing offers different kinds of solutions. However, the same problem as in the case of other vehicles may arise, because in extreme conditions, especially when deep freezing has to be provided, temperature differences between heat sink and heat source can be up to some 80 K. That presents a large obstacle for the application of the magnetic refrigeration technology. Therefore for low temperature cooling, the use of combined vapour compression technology is more convenient (e.g. as the stage with the heat sink of the whole system or the stage which operates between the heat source of the magnetic refrigerator and the real heat source of the freezing part of the compartment). In the case of transport of vegetables, cut flowers or other goods, which require higher temperatures of cooling (e.g. up to 15 °C), the application of the magnetic refrigeration technology as the only applied technology is actually feasible.

Figure 41: Examples of designs of a trailer with a magnetic refrigerator and a cascade vapour compression/magnetic refrigeration hybrid system are shown.



Conventional refrigeration and freezing in trains

Beside air conditioning for comfort of passengers, trains also have cooling and freezing to transport goods. In the past, this was usually performed by storing ice in special compartments. Nowadays ice or other kinds of phase change materials storage are still used in some applications. However, most of the transport of goods with trains is based on refrigerated rail cars (e.g. containers), where each of them is having its own cooling system using conventional vapour compression. Another option, which may be seen more often, is the use of trailer cars (see Figure 40), which usually also have an independent cooling system. In the 1960's the use of liquid refrigerants for low temperatures started to increase (nitrogen or later in the 90's CO₂). This kind of cooling systems use the Joule-Thompson effect for the cooling of refrigerated cars; so the real cooling system is actually not placed on the rail car.

During the 1990's some railcar manufacturers experimented liquid carbon dioxide (CO₂) as a cooling agent [27]. The move was in response to the rising costs of fuel and was an attempt to eliminate the standard mechanical refrigeration systems that required periodic maintenance. The CO₂ system can keep the car's load frozen solid as long as 14 to 16 days.

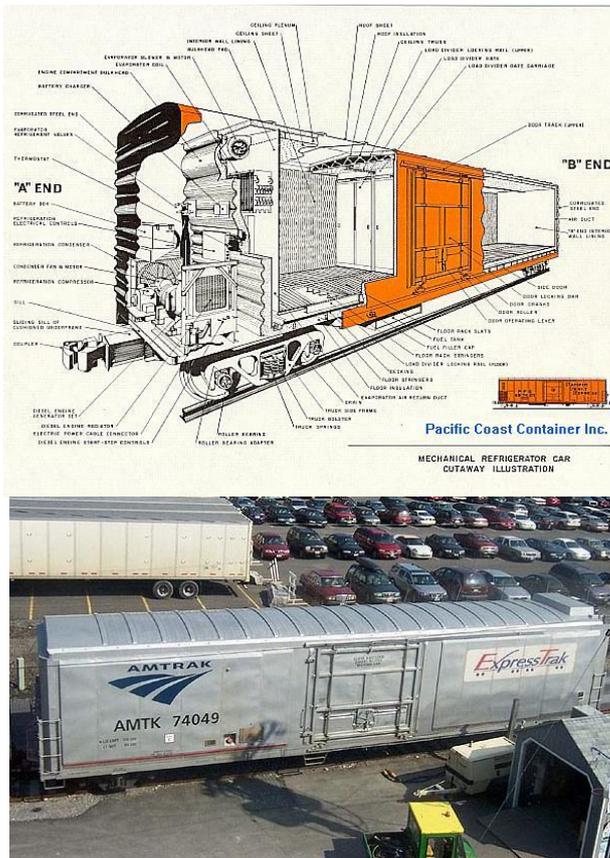


Figure 42: An example of a refrigerated mechanical rail car (after reference [27, 28]).



Figure 43: Train wagon content cooled by liquid CO₂ (see reference [28]).

Magnetic refrigeration and freezing in trains

Magnetic cooling technology as refrigerators or freezers in rail cars is in general – at the present state of development – hardly feasible. The problems are associated with the large heat gains in summer time due to the ambient air and sun radiation, which may substantially increase the temperatures of the heat sink for refrigerators. Especially freezing solutions would require a large number of heat transfer processes due to the regeneration or cascading, especially when taking into consideration also extreme conditions, which may occur as this is the case considering other land transport devices. Therefore, the magnetic refrigeration technology should preferably be used as a hybrid vapour-compression/magnetic refrigerator.

Conventional refrigeration and freezing in marine vehicles

Refrigeration and freezing of food and other goods in marine transport comprises container cooling (similar as containers in train transport, see Figure 44) with individual cooling systems or the use of passive Joule-Thompson cooling (expansion or sublimation) with e.g. liquid CO₂. It comprises also cold rooms (as storage and freezing of food). Another very large domain of cooling is the one of cold compartments for food and other goods, similar as those in warehouses or other kinds of »static« food storages (see also in Chapter 5).

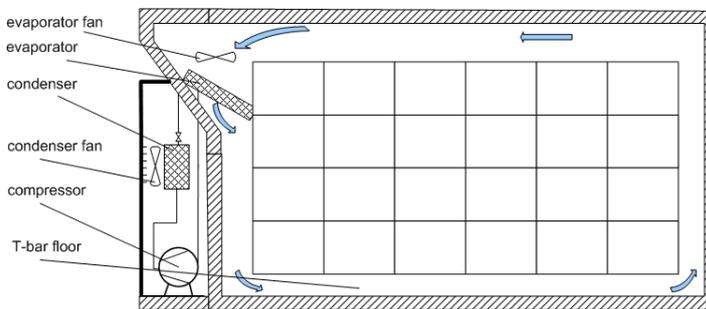


Figure 44: »ISO« Refrigerated containers using a vapour-compression system [25] Intermodal freight containers ('ISO' containers) with integral refrigeration machinery are widely used for the long-distance transport of fresh fruits, vegetables and chilled meat. The journey can last up to six weeks so they have highly developed refrigeration and control systems and are capable of operating over a wide range of conditions. They are normally used only for point-to-point international transport involving a substantial sea journey but there are occasions where the lease of such a container can be a very convenient way of providing a temporary chilled storage facility. Standard sizes are either 20 foot or 40 foot length (6-12 m) with capacities of about 28 or 60 m³. The refrigeration units are electrically driven either from the mains or from diesel generators. They differ from most road vehicles in that air is supplied to the load space from a 'T'-section floor grating.



Figure 45: A low-temperature container using the sublimation of the CO₂ [29]. With the Joule-Thompson cooling effect the freight container is refrigerated by the controlled sublimation of "food grade" solid CO₂ to cold vapour. In a unique process, the container employs cryogenic vapour to maintain frozen product over the shipping period.

Very large refrigeration or freezing »consumers« may be presented also by the sea cruisers, as is for example the cruiser Diamond Princess (see Figure 46).



Figure 46: A »floating town« with many different utilities carries 2670 passengers and 1740 crew members on board [19]. The cruiser comprises, beside the cooling system for living comfort, two different central units for cooling food and goods: one for refrigeration (two twin-screw compressor units with a capacity of 390 kW) and another one for freezing (two twin-screw compressor units with a capacity of 93 kW). Each cooling plant consists of a heavy marine base frame on which two condensing units are mounted. One plant is designed for the provision cooling rooms and the other is designed for the provision freezing rooms. Small cooling units are used to serve cooling stores in various areas such as bistro's and bars. Each system has been divided into two circuits. The brine circuit is used to serve chilled consumables and several remote-catering areas; brine is also used to serve some corridors. The refrigerant circuit is used for chilling the cold provision stores, the walk-in cold rooms and for direct expansion. The provision room freezing plant covers the heat load for the six consumers that operate below 0 °C, the walk-in frozen room and two walk-in blast freezers and direct expansion.

Cooling of the cargo in larger compartments on ship carriers (on-board refrigeration plants) comprises refrigeration, freezing and air-conditioning. Because of the variety of different solutions, the main classification would be deep freezing (<-40 °C), freezing (-40° to 0 °C) and refrigeration (> 0 °C). In deep freezing or freezing, fans or blowers are usually applied (also called direct expansion) and in refrigeration brine, which is then distributed, is often used.

Magnetic refrigeration and freezing in marine vehicles

Refrigeration or freezing of trailers may present a similar example as for magnetic cooling of »ISO« containers. For the magnetic refrigeration technology in marine applications central units are much more feasible: for instance a central on-board refrigeration plant (similar as land refrigeration plant with e.g. warehouses, cold or walk-in rooms) or central units, which supply smaller cold, refrigerated or freezing rooms. The total cooling power of such central on-board refrigeration plants usually varies between 1-5 MW, depending on their specifics. As noted before, the advantage when compared to the land refrigeration plant, is the use of the sea water for heat rejection. If focusing on Europe the sea water temperature on the surface in the Atlantic Ocean or the Mediterranean Sea usually does not exceed 30 °C. Compared to the air temperature, this lead to a lower heat sink temperature and consequently higher efficiency (also because a smaller number of regenerative or cascade processes are needed). Furthermore water-to-water heat transfer presents substantially better heat exchange as water/air or air/air solutions. This is also advantageous for the magnetic refrigeration technology, which is limited by the temperature span between the heat source and the heat sink. The possibility of using superconducting magnets was already mentioned above. This kind of technology – when considering very high powers of a few MW – makes sense, especially if the cryo-cooling system is applied also elsewhere (e.g. for special cryogenic freezing or for cooling of the superconducting coils of special motors for ship propulsion, etc.).

6. DISTRICT COOLING SYSTEMS

District cooling is a partly domain of district energy systems. Many times it is combined with other kinds of systems, as for example district heating. In some particular cases heat pumps are used with reversible operation, but here we focus primarily on cooling. District energy systems and especially district cooling systems are most developed in the USA, Japan and some Scandinavian countries. District cooling systems may be heat driven (centralized or decentralized by a use of absorption or adsorption chillers), compressor driven (also centralized or decentralized chillers) or even use natural cold sources.

The heat pump technology for district cooling and heating usually use a natural source, such as a lake or the sea, which enable higher temperatures of the heat source during winter or/and lower temperatures of the heat sink during the summer time.

In district cooling systems, the chilled water supply's temperature (usually water or brine, rarely phase change slurries, e.g. ice slurry, clathrate hydrates, etc.) is usually at about 5 °C and the return fluid temperature from the network pipes is usually around 15 °C. Small temperature differences present problems of large pipe diameters (large mass flow) to distribute a certain cooling power to the customers. The use of phase change material therefore leads to the advantages of lowering the pumping cost (despite higher friction losses) and the investment cost (use of much smaller pipe diameters, insulation and armatures) or even the cost due to the expensive land in urban places.

In most cases water/water chiller are used in district energy systems and one may assume the following operating conditions for a typical brine or water district cooling plant:

- supply and return of chilled brine or water from the network: 5 °C/15 °C
- supply and return of cooling brine or water: 25/32 °C (cooling tower) or 15/25 °C (deep sea or lake).

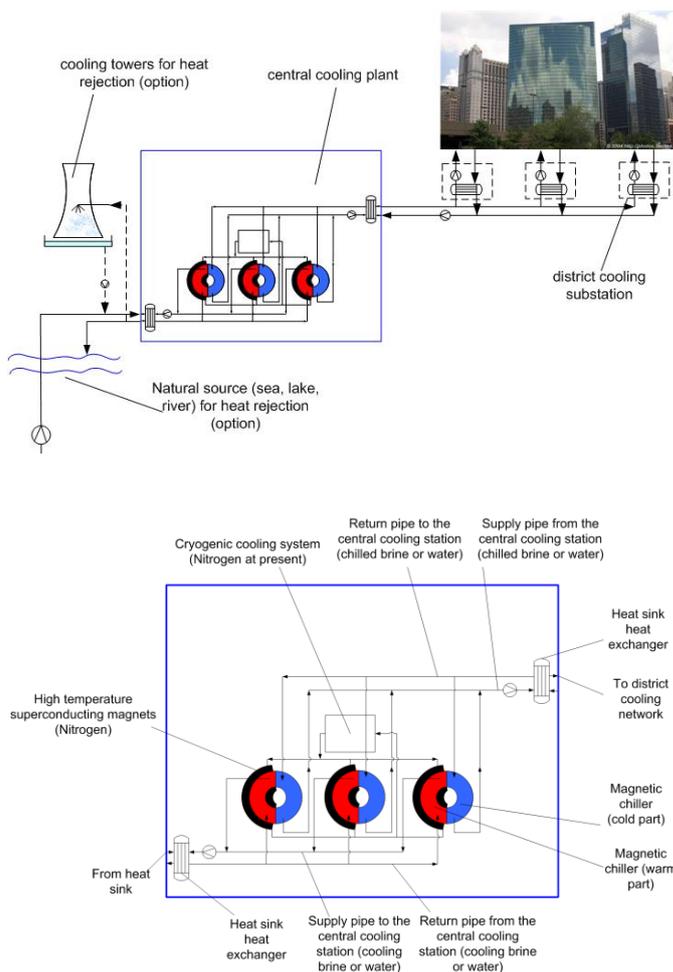


Figure 47: An example of a district cooling system using a central cooling plant of magnetic refrigerators based on high temperature superconductors (HTS). District cooling systems usually provide cooling power between 5 and 200 MW, depending on their characteristics. These systems offer a large opportunity for the magnetic cooling technology. The use of superconducting magnet systems in so large cooling plants presents relatively small investments, especially because the cryogenic cooling system could provide cooling to the superconducting magnets of several magnetic chillers. Beside the larger temperature difference due to the high magnetic field change, larger systems provide several opportunities to use natural sources (rivers, lakes, sea) as lower temperature heat sinks. That could lead to single stage devices without the necessary regeneration or cascade system for a required temperature span (note, that Ericsson or Stirling cycles require regeneration in any case). This in the end would lead to highly efficient magnetic chillers.

7. COOLING AND HEATING IN INDUSTRIAL PROCESSES

Cooling in industrial processes may be divided into cooling technologies above the ambient temperature and cooling technologies below the ambient temperature. Use of magnetic cooling for the first group of the temperatures above ambient brings further question of waste heat utilization and is therefore related to energy conversion of low or high exergy heat into mechanical or electrical work via a magnetocaloric heat engine. This kind of heat engine is presented in another report on magnetocaloric energy conversion and will not be described here. Below are some industrial processes listed, which require cooling at different temperature levels:

- Plastics: Injection molding, blow molding, extrusion
- Chemical & petrochemical process systems
- Environmental test chambers
- Metal anodizing
- Pharmaceutical
- Automotive: Plastics, laser, coolant
- Metal Working: Laser, stamping, welding, hydroforming
- Paint lines
- Bottling plants
- Water desalination
- Degasification of liquids
- Food industry
- Mine cooling.

Other processes, which require cooling at sub-ambient temperatures are mostly related to food (including beverage) industry (see chapter 5), as well as to pharmaceutical and chemical industry. Because of the variety of different processes, it is very difficult to generalize each of them. However, the present magnetic cooling technology is limited by the temperature difference between the heat source and the heat sink and the most interesting technologies are the ones where the temperature of cooling is stable, e.g. related to any kind of phase-change: evaporation, condensation, melting, solidification, etc. This requires cooling with small temperature spans between heat source and heat sink, what presents a great advantage for the present magnetic cooling technology.



Figure 48: *The V-Series screw compressor using the refrigerant R717 (Ammonia), manufactured by the Mycom company [30]. Such compressors enable very low temperatures of evaporation, suitable for deep freezing applications as well as a variety of other applications at higher evaporation temperatures (e.g. up to 5 °C).*

8. SUPERMARKET APPLICATIONS

Supermarket applications may be divided into different areas: living comfort, food storage, display cabinets (refrigerators and freezers) and glass-door or chest-types of refrigerators/freezers.

The first two domains (and also glass-door or chest refrigerators/ freezers, because of their similarity with household units), were already described in previous chapters, so here we will focus primarily on display cabinets, which may exist in a variety of sizes and solutions.

The refrigerated display cabinets used in retail premises fall into two distinct groups [24]. Most are vertical multi-deck cabinets for the display and self-service retailing of packaged chilled foods, fresh meat and poultry. There are also “delicatessen” or “serve over” cabinets for foods which are normally not packaged but cut and served. Multi-deck cabinets have a refrigeration evaporator in the base and it may be supplied either by a self-contained condensing unit or, in larger installations, be piped to a central store cabinet refrigeration system. The evaporator coil is mounted in the lower part of the cabinet behind or under the display area and fans blow cooled air from behind the shelves in a forward direction and also downward in an air ‘curtain’ from the top front of the cabinet. Warmed air is returned through a grille at the base of the cabinet. Modern multi-deck cabinets may be designed to maintain food temperatures at 5 °C or below. Food temperatures are not just a function of cabinet design: they also depend on their method of use. Very tight or untidy cabinet loading can bother proper air circulation, as can indiscriminate placing of large price or advertising tickets. High store temperatures or excessive radiant heating from lights can lead to warm foodstuffs. Good housekeeping allied to the use of some type of night covers when the store is closed will give the best results. Cabinets are designed to maintain temperatures and should not be loaded with foodstuffs which are warm. In some countries, cabinets with doors have largely superseded the use of open-fronted multi-deck cabinets. This provides more positive refrigeration at all time. Such cabinets have severe disadvantages for the retailer, both in loading time and in customer resistance. Some open-fronted cabinets also incorporate shelves for display of non-chilled goods related to the chilled products on display. Serve-over display cabinets have food displayed on a base over which cold air flows and normally have a glass front from behind which the food is served. Air from a rear evaporator may be gravity-fed or fan-assisted, but much of the food in these cabinets is not wrapped and excessive air speeds must be avoided to prevent dehydration and weight loss. For the same reason these cabinets are usually used for display only whilst sales are in progress and other storage cabinets are used to store food overnight. A variation on the serve-over cabinet is the chilled ingredient display and store used in some catering establishments. This type of cabinet stores refrigerated ingredients below the counter section, and cold air blown across the underside of the display pans keeps these cool, aided by a curtain of cool air blown across the surface of the pans. This is just one example of the way in which display equipment can be designed to meet the specific requirements. When selecting a cabinet the method of use, the standard of temperature control and the cost will be major factors. The ease of maintenance and cost of running are also important. Beside the use of refrigerants one may find indirect systems in which cabinets are cooled by cold liquids such as brine or glycol solutions, phase change slurries (e.g. ice slurry) cooled by a central plant.



Figure 49: Vertical and horizontal display cabinet (from reference [31]). The temperature ranges of display cabinets in supermarkets vary from freezing temperatures of -25°C up to +10°C.

Magnetic cooling technology could be performed in two different ways: centralized cooling (freezing) systems or decentralized ones. The working fluid depends on the temperature level; so many solutions from brine to water as working fluids are possible. In the very large supermarkets, the central cooling for the display cabinets and other kinds of cooling systems (e.g. food storage and living comfort) may be combined together. In such cases the use of superconducting magnets could be possible because their relative price would not present so large investments. Further the highest efficiency may

be obtained using magnetic heat pumps, which may serve also in the winter time for cooling and heating. Phase change slurries, as secondary refrigerants, may be used in a combination with magnetic cooling. For decentralized units the efficiency is expected to be high only for refrigerators, because such units use heat rejection in an air-conditioned space of 20-25 °C. Figures 50 and 51 show examples for decentralized (local) magnetic refrigeration (a display cabinet) and for centralized magnetic cooling (central cooling station).

Figure 49: A horizontal display cabinet cooled by a magnetic refrigerator

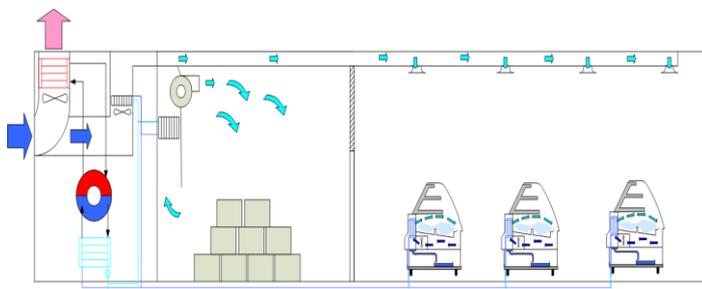
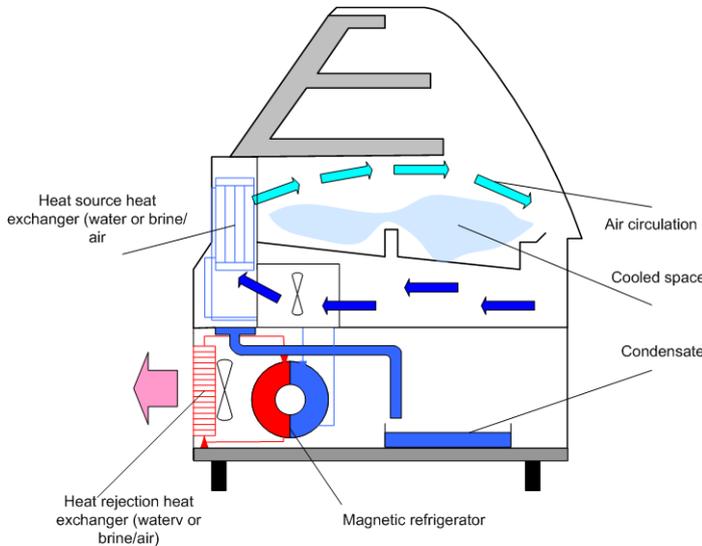


Figure 50: A central cooling plant in a supermarket using the magnetic cooling technology.

9. ELECTRONICS COOLING

Cooling of electronics is a special, rapidly growing domain in refrigeration. It comprises different kinds of systems, such as e.g. integrated cooling of electronic devices (directly and local) or cooling is provided by some central unit with distribution of refrigerant or secondary refrigerant to the heat sources. In computers (personal computers or laptops), usually Peltier elements (thermoelectric) cooling devices are placed and fans are used for the heat rejection to the ambient. Another option for cooling the CPU (Central Processor Unit), which is the largest heat source, is by using heat pipes. Use of magnetic refrigeration for cooling of personal computers or laptops at this stage of development seems not to be feasible, especially because this kind of system cannot be compact as the thermoelectric system is at this early stage of development. Furthermore, a perfect shielding of the magnetic field should be provided in order to not disturb electronic elements or even magnetic memory elements in computers. Therefore, cooling of computers by use of magnetic cooling technologies would be preferably done via a central cooling unit, but this is then rather related to larger cooling systems, e.g. for IT centrals or rooms in buildings.

10. RESULTS OF THE ANALYSIS

The procedures for the analysis of this project are presented in detail in Appendix 2. Many results are applicable for several devices. Therefore, the intention here is to list the most feasible applications and their characteristics such as the *COP*, the exergy efficiency, the mass and volume. According to the results the following groups of best possible magnetic cooling, air-conditioning and refrigeration applications are made:

a) *Smaller magnetic refrigeration units*

- Household refrigerator without freezer
- Wine/beverage refrigerator
- Blood plasma storage refrigerators, chromatography and other laboratory refrigerators
- Locally cooled display cabinets (refrigerators only) and glass-door or chest-types refrigerators.

b) *Larger magnetic refrigeration units*

- Walk in rooms (refrigeration, no freezing; for medicine, marine transport, warehouses, supermarkets, etc).
- Food production:
 - Refrigerated silos, vessels or blenders, e.g. in dairy industry
 - Wine and beer fermenters
 - Beverage carbonation.
- Food processing for storage:
 - Hydro cooling of vegetables and fruits (by immersing)
 - Forced air cooling of vegetables and flowers
 - Spray chilling or brine cooling of meat
 - Dry air coolers for meat.
- Food storage:
 - Cold storage of fruits, vegetables and flowers
 - Short term storage of meat products
 - Refrigerated walk in rooms
 - Cold storage rooms with temperatures above freezing.
- Refrigeration of food or other goods in transportation:
 - Refrigeration of vegetables or cut flowers in truck trailers, refrigerated mechanical rail cars, ship containers
 - Centralized or decentralized magnetic refrigeration units in ships.
- Central refrigeration systems for display cabinets and glass-door or chest-types refrigerators.

c) *Smaller magnetic cooling and air-conditioning units (buildings, marine)*

- Magnetic RAC (RAC – Room Air Conditioning unit): window, wall or ceiling mounted
- Magnetic split system (e.g. single outside heat rejection unit, multiple inner cooling units).

d) *Large (central) magnetic cooling and air conditioning units (e.g. buildings, marine, district cooling, supermarkets)*

- Magnetic water cooled water or brine chiller (water/water, brine/brine)
- Magnetic air cooled water or brine chiller (water/air, brine/air).

10.1. Smaller magnetic refrigeration units

Figures 51 to 54 show the COP and exergy efficiency, total mass and total volume depending on different operating conditions. The equivalent temperature denoted by the star means that the condensing temperature of gas refrigerant in the conventional device is equal to the temperature of the solid magnetocaloric refrigerant in the magnetic refrigerator. In such a way the external air temperature is not taken into account and the analysis is rather focused on the core of the device.

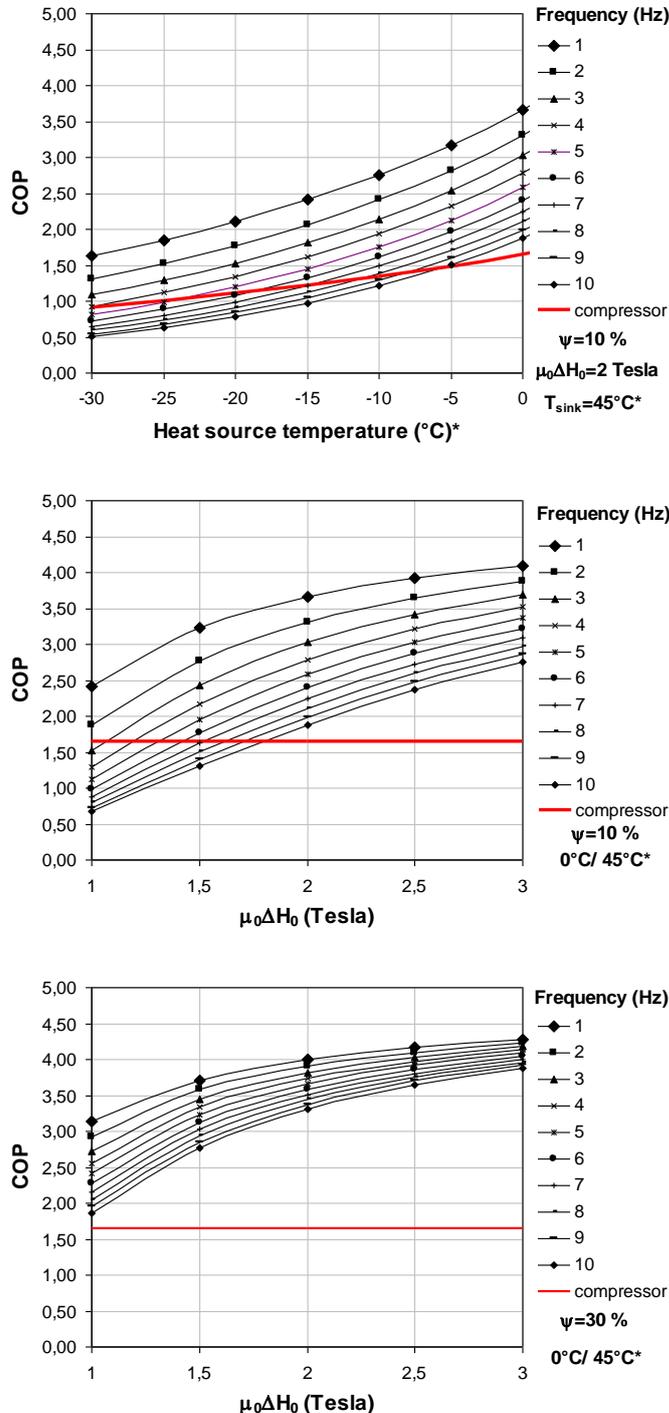


Figure 51: The COP's of rotary magnetic refrigerators depending on different operation characteristics such as heat source temperature, frequency of operation, magnetic flux densities and volume fraction of the magnetocaloric porous structure. The frequency of operation strongly influences the characteristics of a magnetic refrigerator. The reason is that a higher velocity of the working fluid leads to a higher pressure drop and therefore also to larger irreversibilities. The red thicker lines correspond to the COP of Danfoss hermetic compressors (LBP/MBP and MBP/HBP, R404a/R507, type FR 6CL, condensing temperature 45°C). As it may be seen, the magnetic refrigerator with frequencies up to 10 Hz and volume fractions of magnetocaloric porous structure of 10 % becomes competitive with magnetic flux densities around 1.5 Tesla. If the volume fraction is increased and the mass flow rate and the pressure drop of the fluid are kept almost constant (thicker structure, slight increase of hydraulic diameter) the efficiency may be substantially improved. That is due to the reduction of specific losses since the specific cooling power of the device is increased. The third diagram also shows that the increase of volume fraction enables (at least theoretically) higher frequencies of operation, e.g. beyond 10 Hz. Our investigations on fluid dynamics and heat transfer had shown that such frequencies could be feasible in future machines, allowing higher efficiencies than conventional technologies. One should also note that at the present stage of development of magnetic refrigerators, the magnetic flux density of 3 T is rather an upper limit, so one may expect that in the near future machines between 1.5 and 2.5 Tesla will be built.

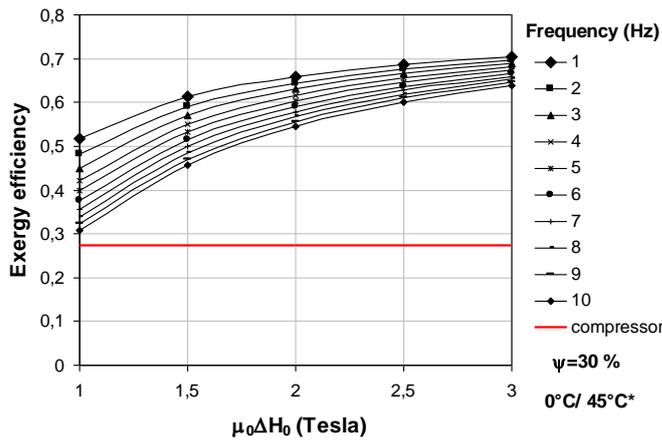
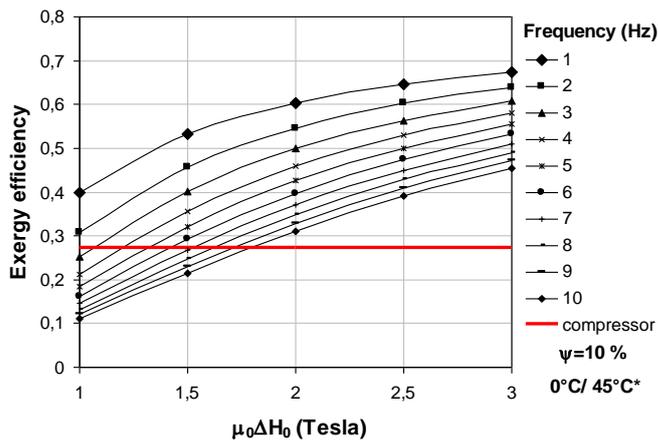
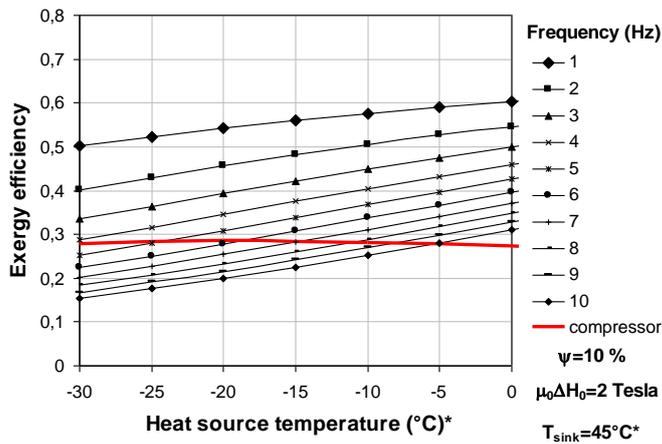


Figure 52: The exergy efficiency of rotary magnetic refrigerators depending on different operation characteristics as heat source temperature, frequency of operation, magnetic flux density and volume fraction of the magnetocaloric porous structure. The thick red lines correspond to the exergy efficiency of Danfoss hermetic compressors (LBP/ MBP and MBP/HBP, R404a/R507, type FR 6CL, condensing temperature 45 °C). This was calculated as the ratio between the real COP and the COP of a Carnot cycle operating at the same temperature levels. The results were extracted from data already leading to Figure 51.

A 50 W magnetic refrigerator was selected for the analysis of the total mass and total volume of the device. Figures 53 and 54 show the corresponding results.

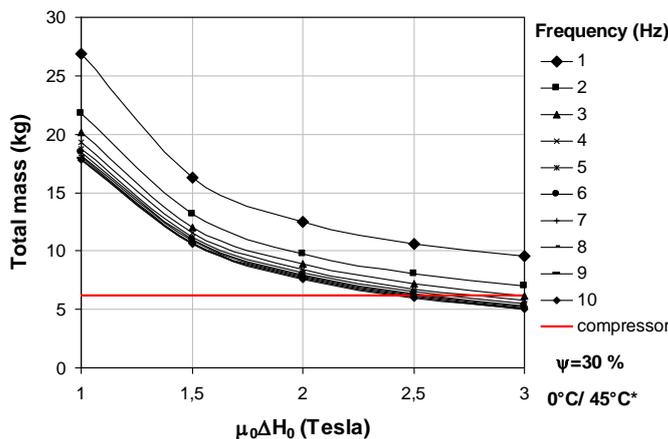
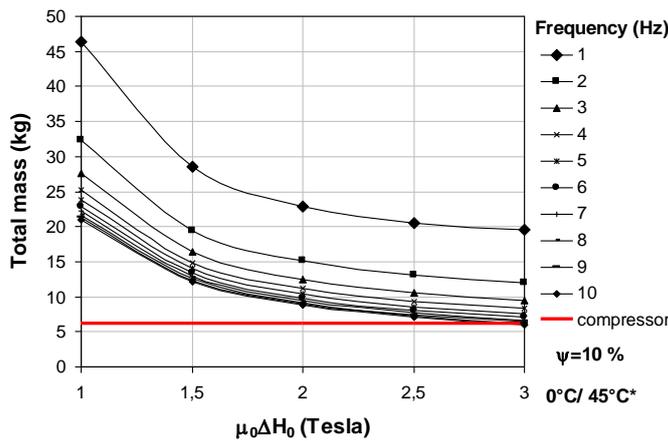
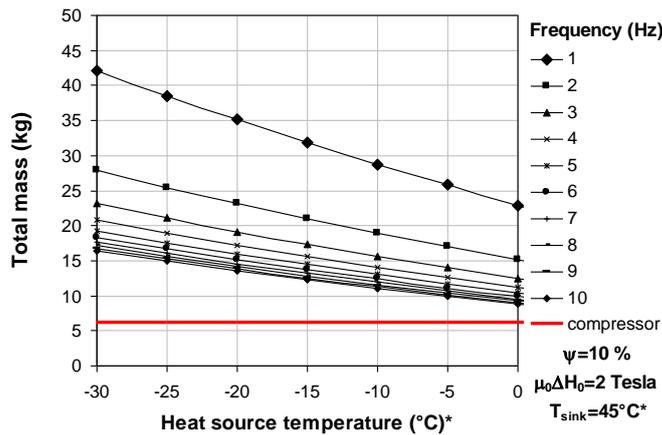


Figure 53: The total mass of a 50 W cooling-power rotary magnetic refrigerator depending on different operation characteristics such as heat source temperature, frequency of operation, magnetic flux density and volume fraction of the magnetocaloric porous structure. The red thick line shows the approximate mass of a hermetic compressor of the same power.

The total mass strongly depends on the magnetic flux density, frequency of operation as well as on the volume fraction of the magnetocaloric material. As one can see, volume fractions of 10 % of the porous magnetocaloric structure lead to a quite large total mass. The total mass of the magnetic refrigerator may reach the one of a hermetic compressor if the magnetic flux density is around 3 T and if the frequencies are rather high. Since 3 T is at present a limit for commercial possible solutions, improvements to reduce the total mass are to increase the volume fraction of the magnetocaloric material. This is shown in the last diagram. There one can observe that increasing the volume fraction up to 30 % may substantially reduce the total mass and increases the efficiency, since by this the losses per power are substantially reduced. Combining the results from Figures 51, 52 and 53 shows that a higher volume fraction would enable frequencies beyond 10 Hz. Such frequencies may then enable that a 2 T magnetic flux density becomes sufficient to have a comparable mass to the conventional compressor technology.

In general the mass of a magnetic refrigerator presents a drawback compared to the conventional technology. However, there still exist large opportunities for improvements as noted above.

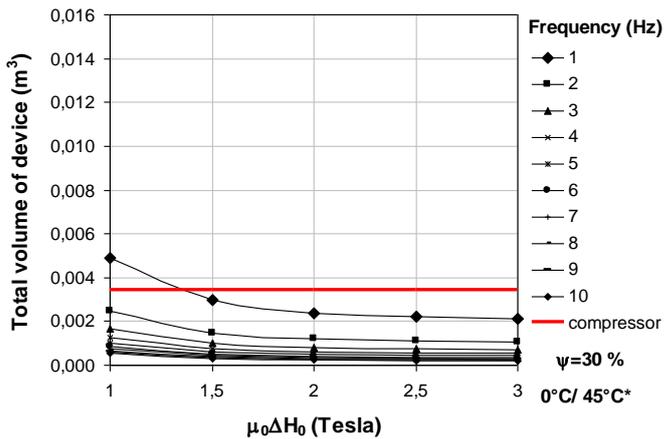
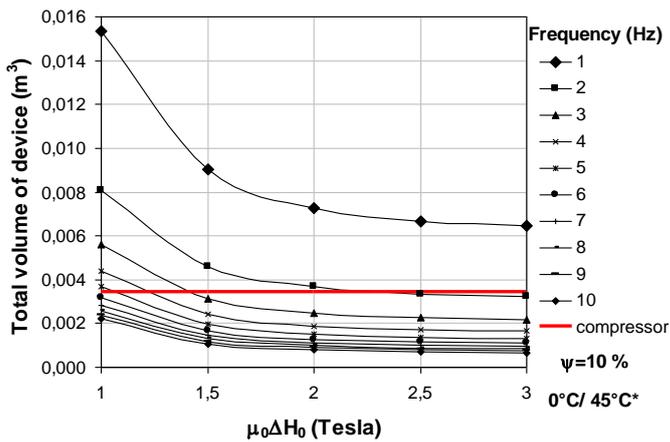
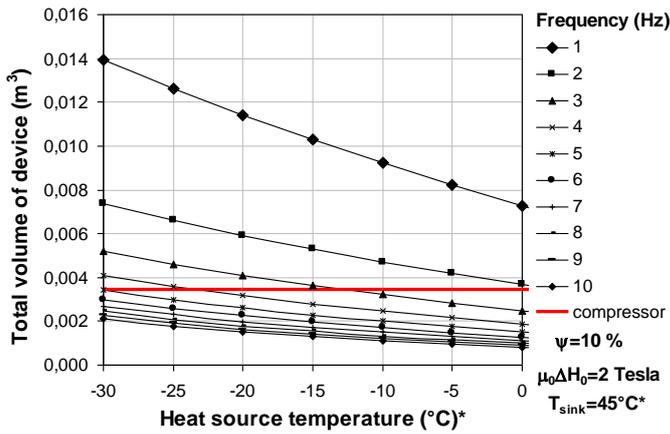


Figure 54: The total volume of a 50 W cooling power rotary magnetic refrigerator depending on different operation characteristics, such as heat source temperature, frequency of operation, magnetic flux density and volume fraction of the magnetocaloric porous structure are presented in this figure. The red thick line shows the approximate volume of a hermetic compressor of the same power.

The total volume, similar as the mass, strongly depends on the magnetic flux density, frequency of operation as well as on the volume fraction of the magnetocaloric material. However the compactness of the magnetic refrigerator does not present such a large obstacle than the total mass. One should note that a large contribution to the total mass is given by the permanent-magnet assembly, where its density has to be taken into account.

One observes that a refrigerator with even 10 % volume fraction of magnetocaloric material presents a volume comparable with the one of a classical refrigerator. When the volume fraction increases the cooling power increases, but the gap in the permanent magnet assembly does not need to be changed. The result is thus a much smaller volume at a higher fraction of the magnetocaloric material in the porous structure. At such volume fraction the magnetic flux density may be low (e.g. above 1 T).

10.2. Larger magnetic (industrial) refrigeration units

A variety of applications refers to industrial refrigeration, where different temperature levels are applied. The analysis was performed for the COP and exergy efficiency of industrial magnetic refrigerators.

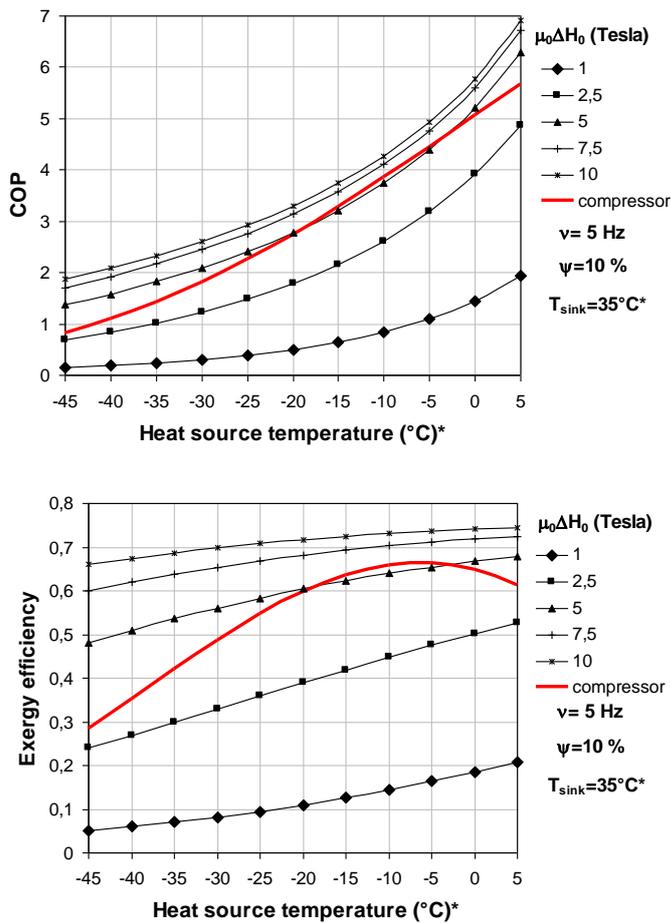


Figure 55: The COP and exergy efficiency of a large scale industrial magnetic refrigerator depending on the magnetic flux density (which considers a use of permanent magnets as well as superconducting magnets) and depending on the equivalent temperature of heat source and heat sink for the frequency of operation of 5 Hz are shown. The comparison is made with the data of a MY-COM screw compressor (Ammonia as refrigerant). As one may notice the larger temperature span between the heat source and the heat sink requires magnetic flux densities around or beyond 5 T. This implies the use of superconducting magnets. However, the use of such magnet systems calls for large scale applications, in order to minimize the additional energy losses due to the special cryogenic cooling systems, as well as due to the costs of such a special system. For large-scale applications one may assume that the total mass, as well as the total volume of a magnetic industrial refrigerator, would be smaller than one of the conventional technology.

10.3. Smaller magnetic cooling and air-conditioning units (buildings, marine)

Individual small units, as window, wall or ceiling-mounted devices as well as split systems are in most cases mounted in buildings, houses and transport means (buses, rail cars and marine transportation).

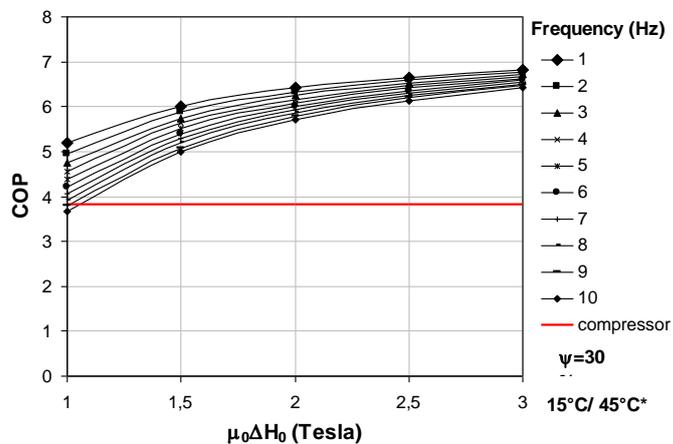
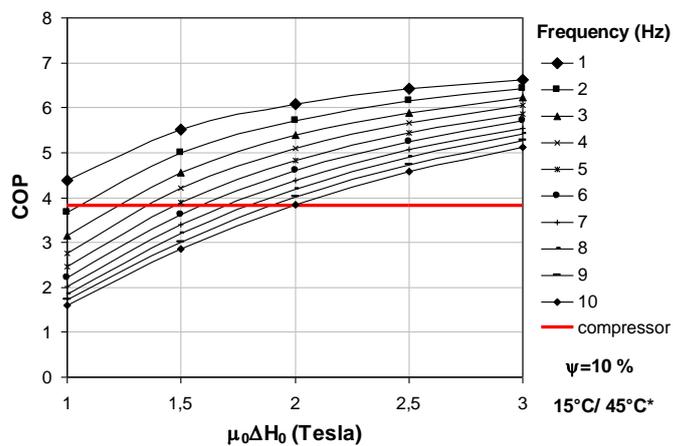
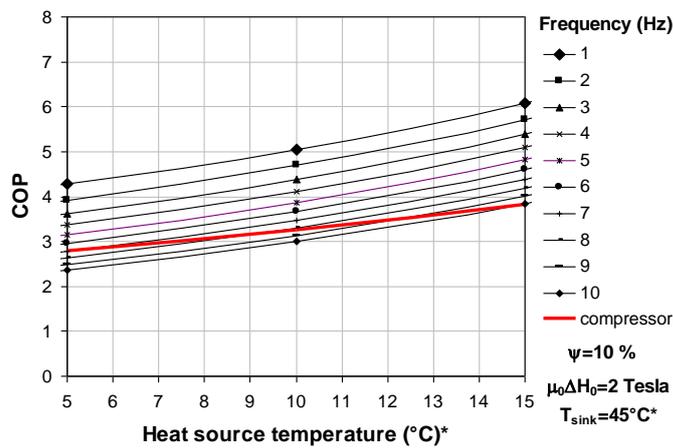


Figure 56: The COP of a small magnetic cooling unit as a function of the heat source temperature, frequency of operation, magnetic flux density change and volume fraction is shown. The red thicker line corresponds to the COP of a Danfoss hermetic compressor (MBP/HBP, R407c, type SC15DL, condensing temperature 45 °C). With volume fractions of 10 %, small magnetic cooling devices become feasible already with a small magnetic flux density of 1 T, but at low frequency. Since the frequency is very important when compactness is required, the increase of volume fraction substantially improves not only the dimensions, but also the efficiency, because it lowers the specific losses. This enables an operation of a magnetic cooling device with a magnetic flux density between 1.5 and 2.5 T with frequencies beyond 10 Hz, what will with a high probability be a characteristic value in future magnetic cooler developments .

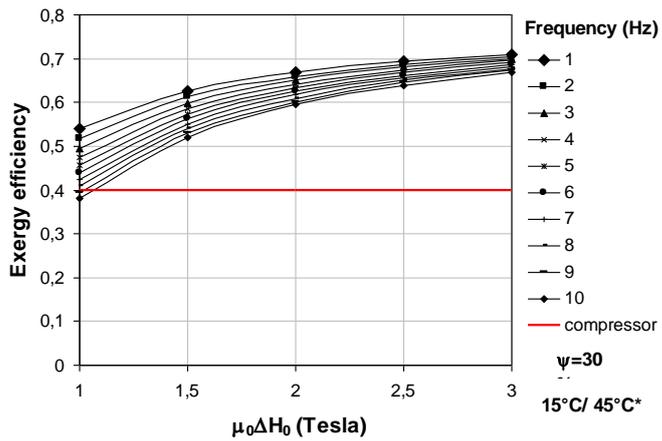
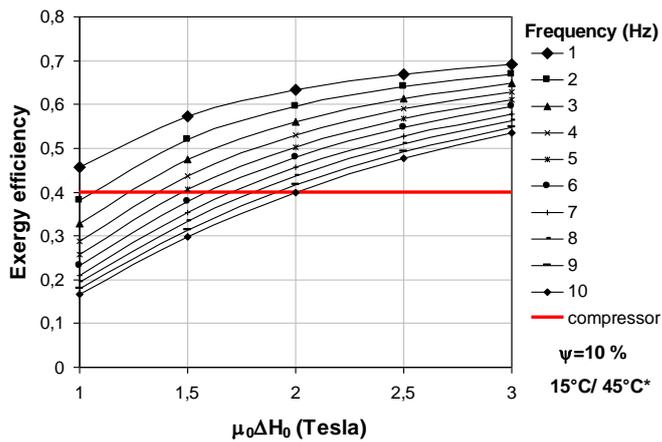
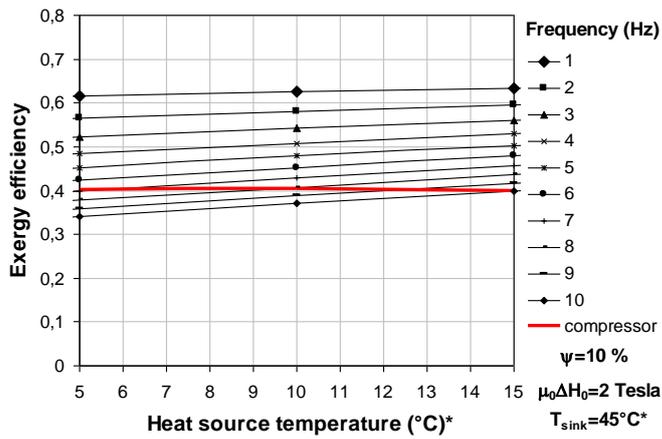


Figure 57: The exergy efficiency of a small magnetic cooling unit as a function of the heat source temperature, the frequency of operation, the magnetic flux density change and volume fraction. The red thick line corresponds to the COP of a Danfoss hermetic compressor (MBP/HBP, R407c, type SC15DL, condensing temperature 45 °C). One observes that the exergy efficiency follows the characteristics of the COP: small magnetic cooling devices are feasible even with small magnetic flux densities and high efficiencies may be achieved even with high operating frequencies. That will lead to compact and light devices. This can be seen in Figures 58-59.

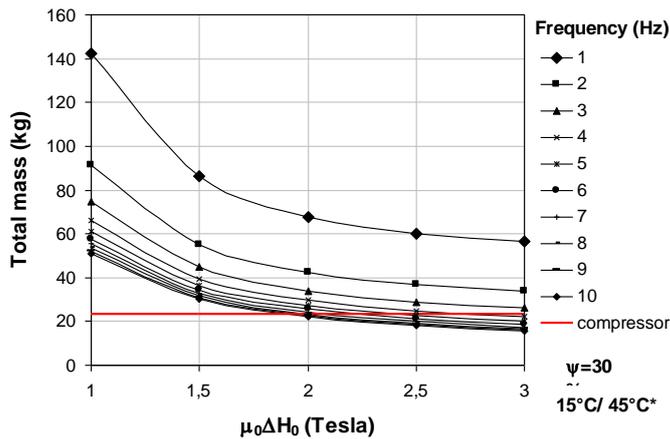
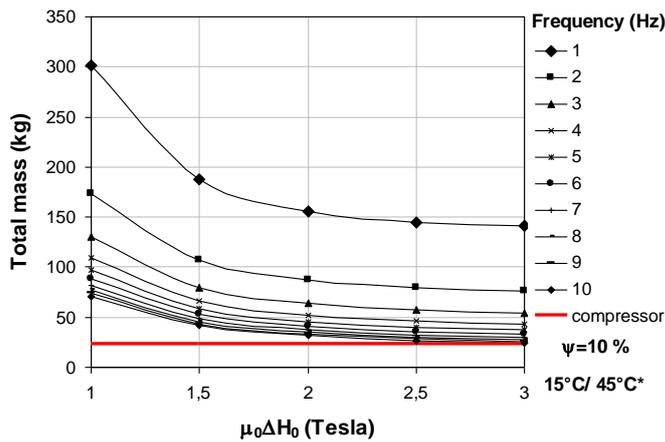
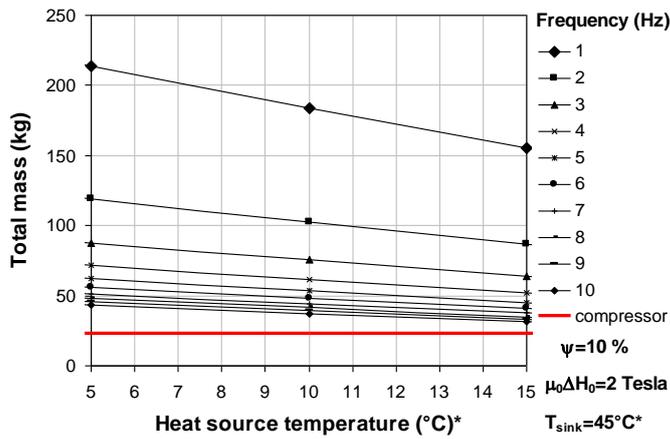


Figure 58: The total mass of a 2 kW magnetic cooling unit as a function of the magnetic flux density, frequency of operation for given temperatures of heat source and heat sink is shown. The red thick line corresponds to the approximate total mass of a Danfoss hermetic compressor having the same cooling power. When considering a volume fraction of magnetocaloric material of 10 %, the total mass of the device presents a drawback for the magnetic cooling technology. However, since this depends on many other parameters, possibilities of improvement still exist. One is the increase of the magnetic flux density, but this is rather difficult, especially when considering permanent magnets. A much easier improvement is the increase of the volume fraction of the magnetocaloric material in a porous structure. For instance a volume fraction of 30 % enables weights comparable with the conventional technology already at some 2 T flux density. Considering also the efficiency data contained in Figures 56-57, the frequency of operation at a so high flux density may be also increased beyond 10 Hz. The conclusion is that the mass of a magnetic cooling device is an obstacle, but different solutions may lead to substantial improvements and thus in the extreme case even to so light-weight machines than the conventional ones.

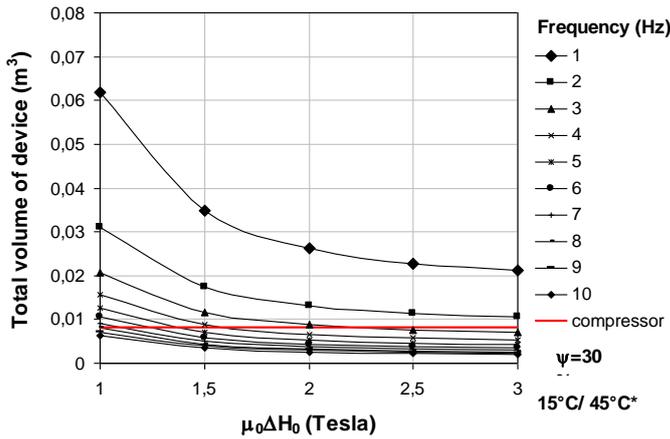
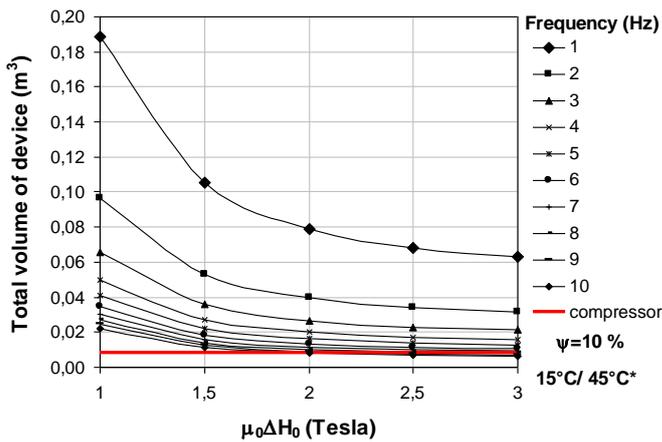
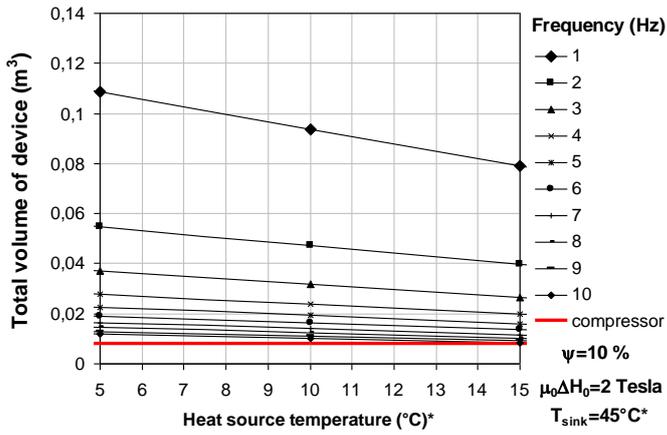


Figure 59: The total volume of a 2 kW magnetic cooling unit as a function of the magnetic flux density, frequency of operation for given temperatures of heat source and heat sink is shown. The red thick line corresponds to the approximate total volume of a Danfoss hermetic compressor having the same cooling power. According to the figure, it is obvious that the volume of a small magnetic cooling device doesn't present a so large obstacle as the mass does. Increasing the volume fraction of the magnetocaloric material to 30 % also drastically changes the dimensions. One may observe a comparable volume of a magnetic cooling device at magnetic flux densities already beyond 1 T and also when higher frequencies (e.g. beyond 10 Hz) are considered.

10.4. Large (central) magnetic cooling and air-conditioning units

This kind of domain contains a large number of different applications. Because of the variety of such applications, the goal in this analysis is to divide them into medium and large scale applications. The medium size applications corresponds to a usual chiller with a cooling power of about 500 kW. Such chillers are applied individually or in groups in many buildings or similar applications and also other means such as marine transport. Large-scale units are usually associated with a central cooling system driven by turbo compressors or sorption chillers. The application of those are found in large building centres as well as in district cooling systems. Therefore, the analysis is made for the following types of chillers: medium-scale air-cooled liquid chillers, medium-scale water-cooled liquid chillers, large-scale water-cooled liquid chillers.

Medium-scale air cooled liquid chillers

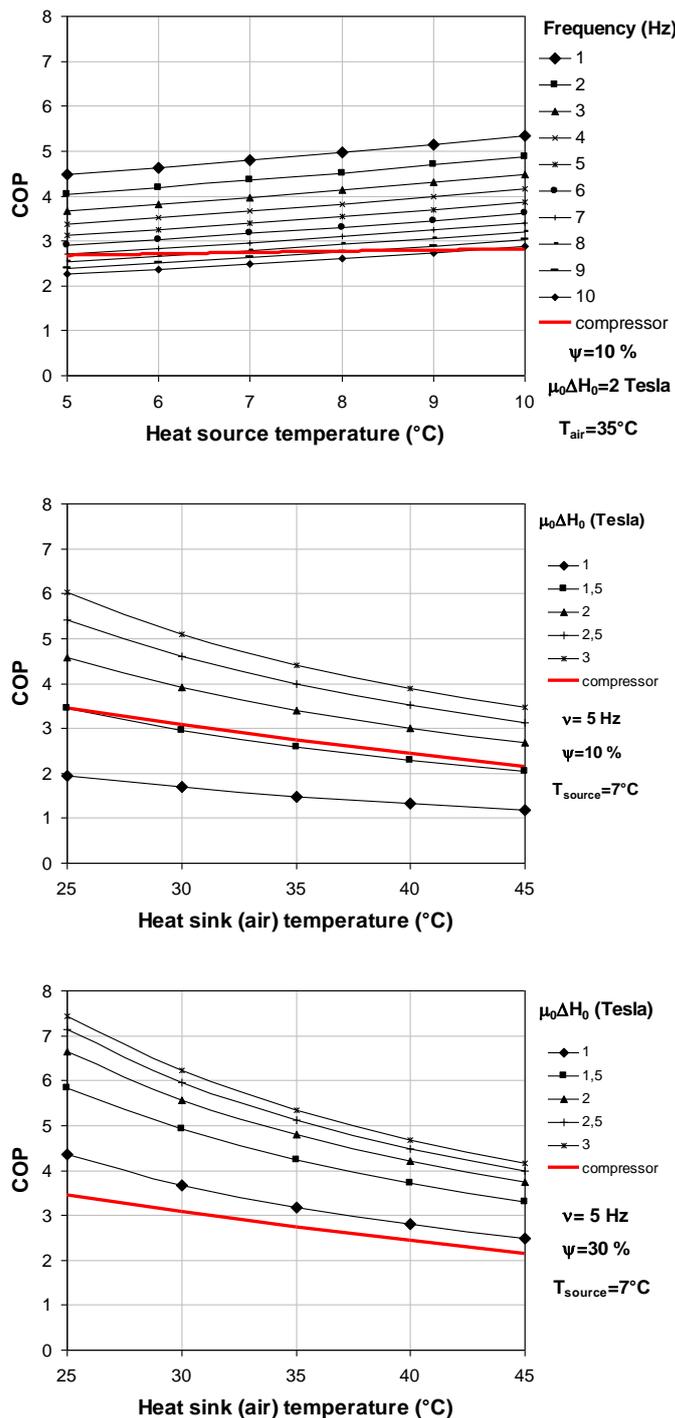


Figure 60: The COP of an air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of the operation of the machine, the temperature of heat source and of the magnetic flux density. Furthermore, the graphic contains typical values of COP's of a screw compressor chiller operating under the same conditions (Carrier 30 GK). The magnetic flux density 2 T enables much higher COP's than those of the conventional technology already at volume fractions of 10 %. This means that the frequency of operation could be applied beyond 10 Hz, what strongly influences positively the compactness of a device. One may also notice that the minimum required magnetic flux density with 10 % of volume fraction is around 1.5 T. When the volume fraction is increased, this enables the use of magnetic air-cooled chillers with rather high frequencies and at moderate magnetic flux densities.

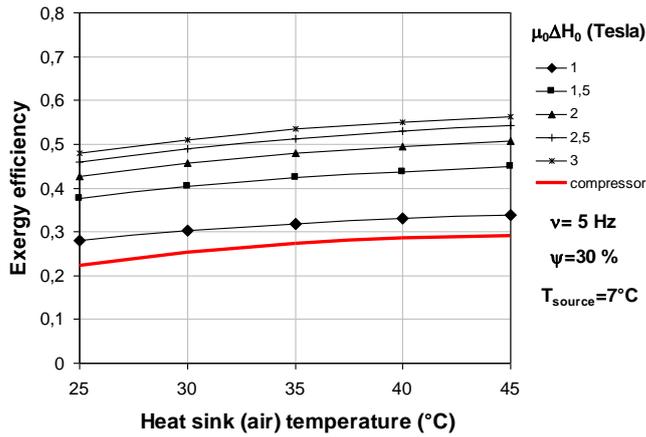
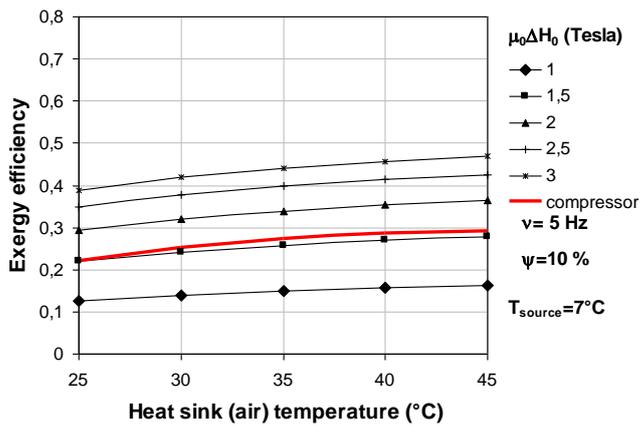
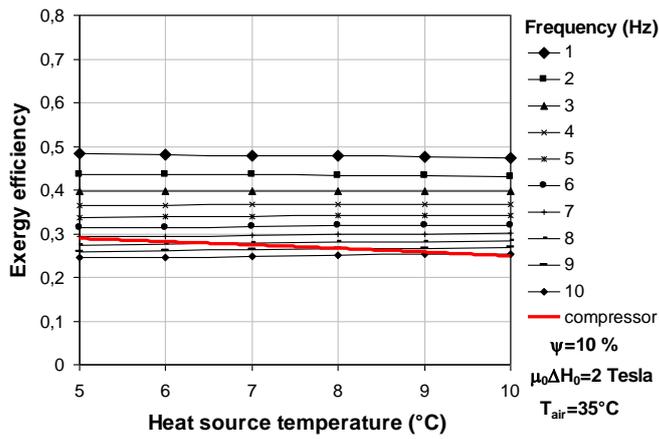


Figure 61: The exergy efficiency of an air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of operation of the machine, the temperature of the heat source and different magnetic flux densities. Furthermore, the graphic contains typical values of exergy efficiency of screw compressor chillers operating under the same conditions (Carrier 30 GK). One observes that the exergy efficiency of commercial conventional chillers is very low. An improvement may be the use of air-cooled magnetic chillers, which are sometimes twice more exergy efficient than conventional chillers. The increase of volume fraction, high magnetic flux density and high frequencies of operation also leads to very compact devices. All this is shown in Figures 62 and 63.

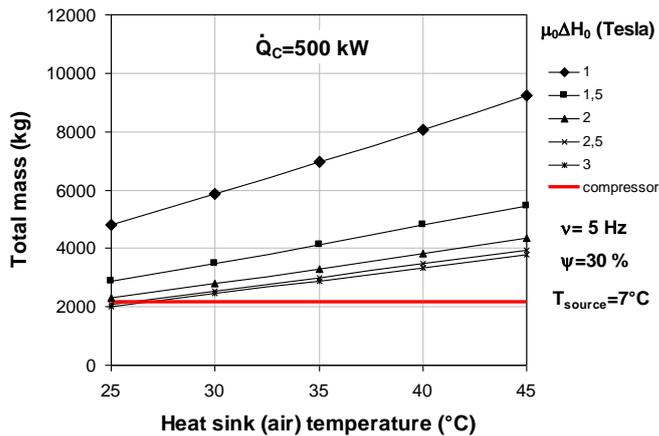
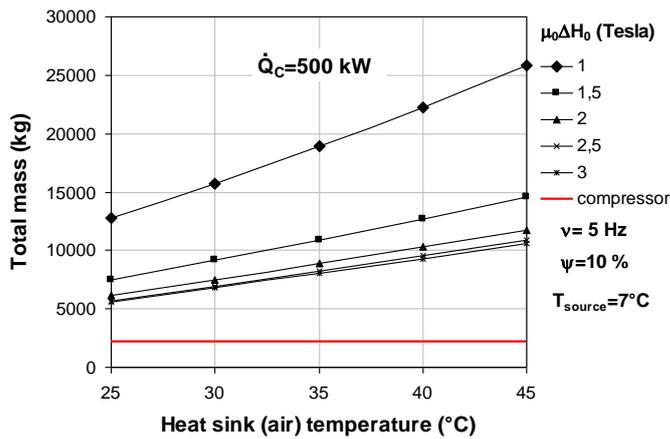
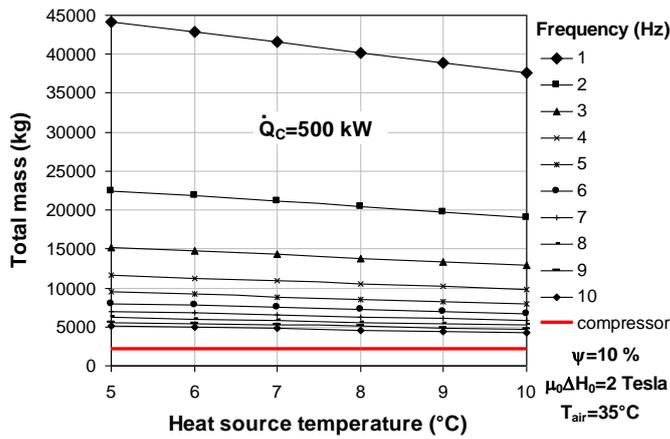


Figure 62: The total mass of a 500 kW air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of operation of the machine, the temperature of heat source, magnetic flux density as well as the volume fraction of the magnetocaloric material structure. Furthermore, the graphic contains typical values of mass of a screw compressor (without condenser and evaporator) operating under the same conditions (Carrier 30 GK). The total mass of a magnetic central air-cooled chiller is expected to be much larger than the one of a conventional chiller, a fact that naturally presents a drawback in some cases. However, one should note that the data corresponding to such results are for a chiller with 10 % volume fraction of magnetocaloric material. This of course influences the total mass of the device. When studying for instance 30 % of volume fraction, the total mass of a magnetic chiller is very close to the one of a conventional chiller. When the temperature of the heat sink is not too high (small temperature spans between the temperatures of the heat source and the heat sink) this would mean that the total mass of air cooled by the magnetic refrigerator with 30 % of volume fraction is comparable to the one of a conventional chiller, especially when higher frequencies (around 10 Hz and beyond) are applied.

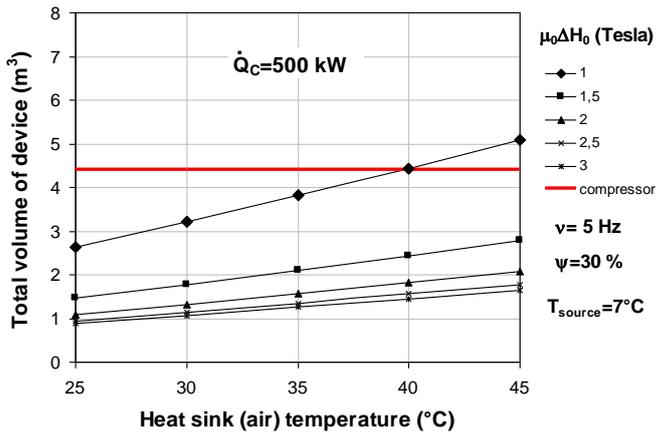
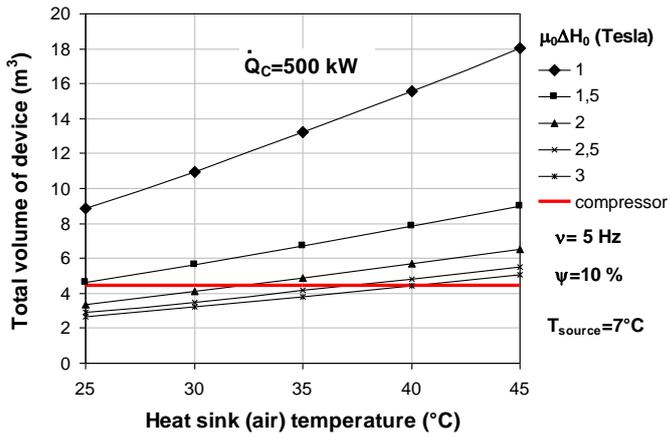
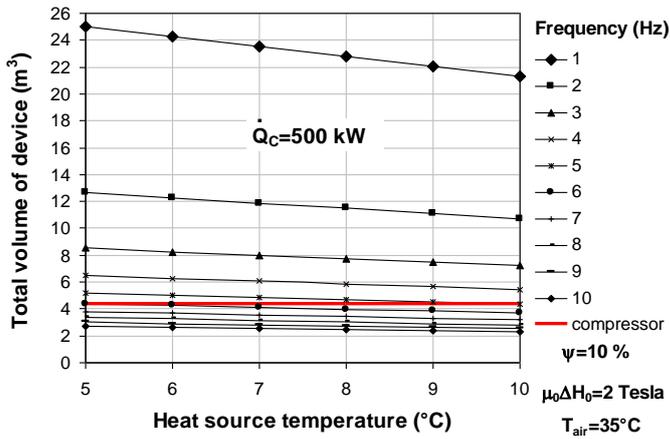


Figure 63: The total volume of a 500 kW air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of operation of the machine, the temperature of heat source, magnetic flux density as well as the volume fraction of the magnetocaloric material structure. Furthermore, the graphic contains typical values of volume of a screw compressor (without condenser and evaporator) operating under the same conditions (Carrier 30 GK).

Medium-scale water-cooled liquid chillers

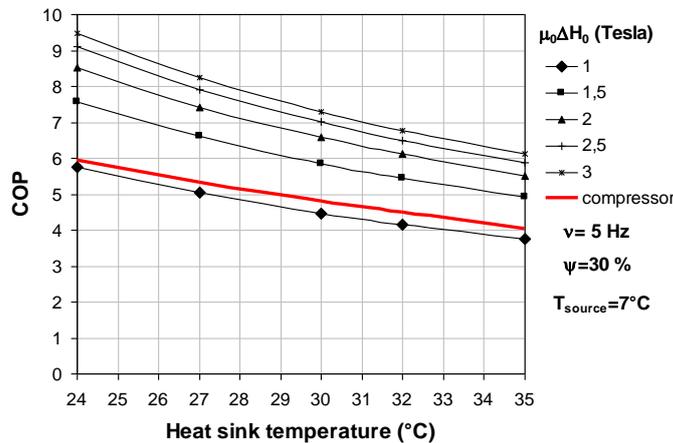
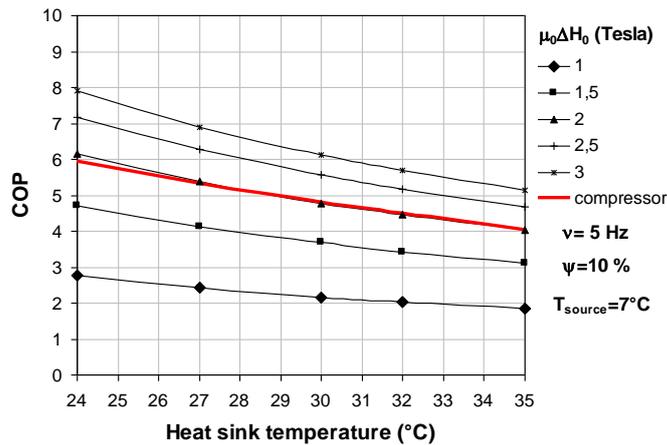
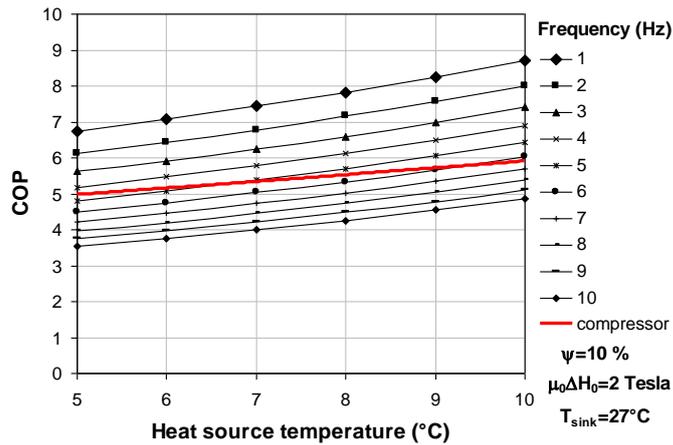


Figure 64: The COP of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source and heat sink temperatures (water), the frequency of operation as well as the magnetic flux density (corresponding to the use of permanent magnets). Furthermore the graphic contains typical values of COP's of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a).

The COP of a magnetic refrigerator with a magnetic flux density of 2 T and 10 % volume fraction of magnetocaloric material requires rather a low frequency of operation in order to compete with machines of the conventional technology. However, the increase of volume fraction from 10 to 30 % will affect not only the mass and volume, but also the efficiency, since the specific cooling power of magnetocaloric material becomes higher and thus the relative losses become smaller. At 30 % volume fraction of magnetocaloric porous structure the conventional compressor technology may be beaten by the magnetic one, when magnetic flux densities around 1.5 T are applied. Lowering the frequency of operation enables a higher efficiency, but it leads to a smaller cooling power and thus the mass and volume of a device becomes too large. At moderate magnetic flux densities a higher volume fraction enables a substantial increase of the frequency of operation.

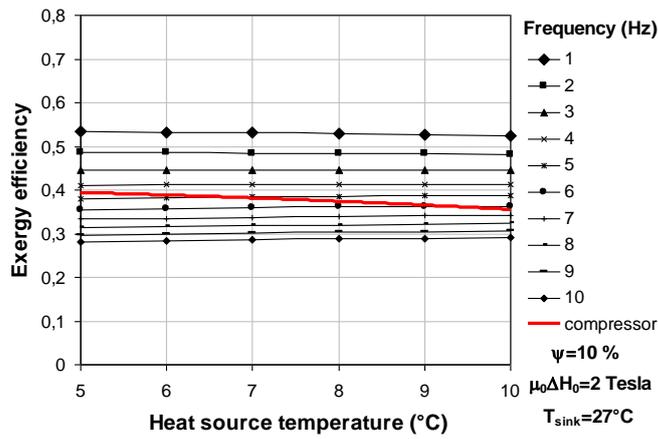
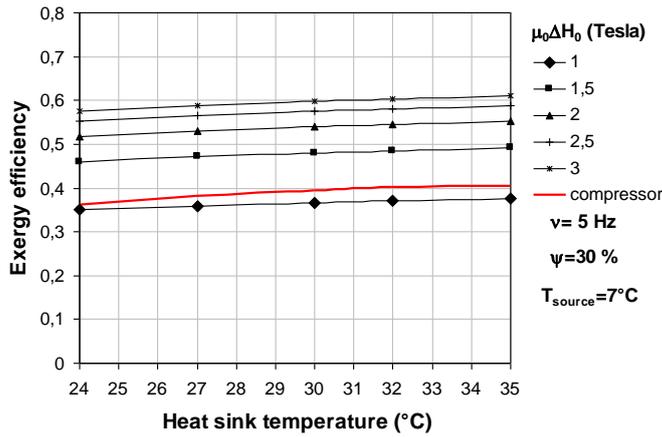
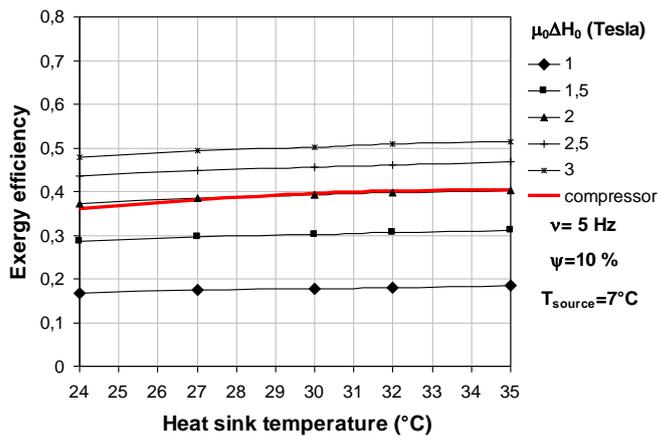


Figure 65: The exergy efficiency of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source and heat sink temperatures (water), the frequency of operation as well as on different magnetic flux densities (corresponding to the use of permanent magnets). Furthermore, the graphic contains typical values of exergy efficiencies of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a).



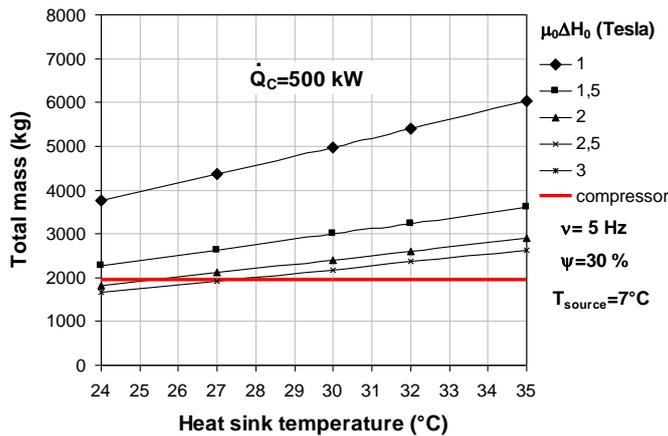
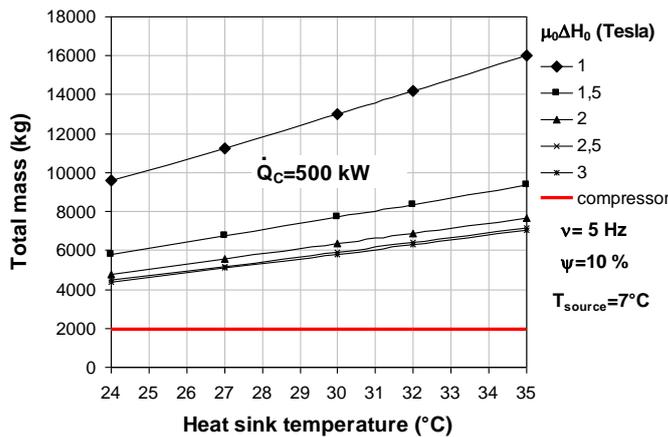
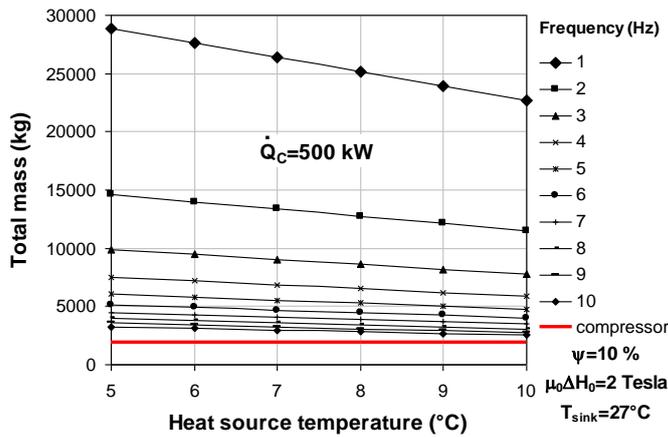


Figure 66: The total mass of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source and heat sink temperatures (water), the frequency of operation and the magnetic flux density. Furthermore, the graphic contains typical values of the total mass of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a). With a volume fraction of 10 %, the total mass of a water cooled magnetic chiller is much higher than the one of a conventional chiller. This drawback cannot be bridged even when the frequency of operation is increased up to 10 Hz (despite it is approaching the mass of a conventional chiller) or when the magnetic flux density of the permanent magnets is reaching its limits. However, the increase of the volume fraction of the magnetocaloric porous structure substantially lowers the mass. An assumption can be made that 30 % of volume fraction, coupled with a magnetic flux densities above or near 2 T and frequencies near or beyond 10 Hz, would lead to lighter devices than the corresponding ones of the conventional technology.

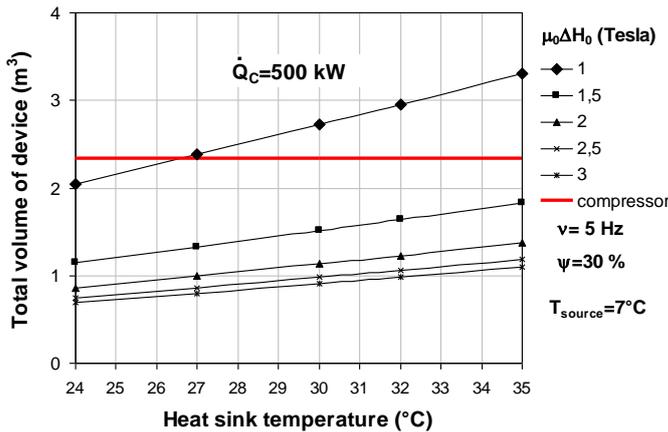
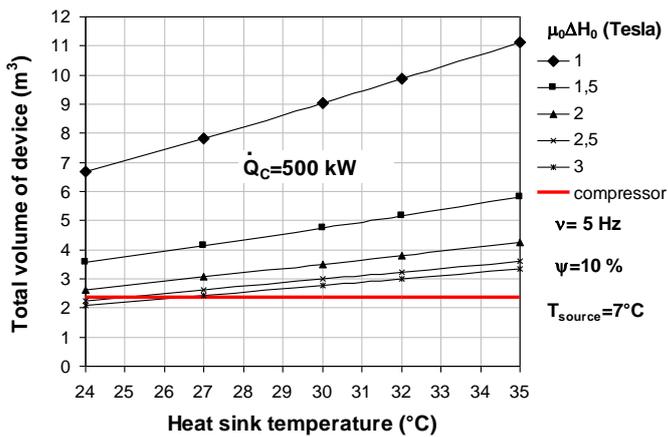
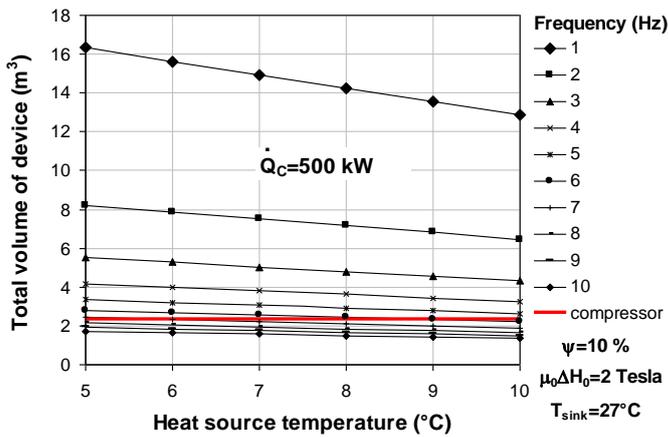


Figure 67: The total volume of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source and heat sink temperatures (water), the frequency of operation and the magnetic flux density. Furthermore, the graphic contains typical values of the total volume of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a). Similar as for other types of chillers and refrigerators, the total volume does not present such a challenge for developers in the magnetic cooling technology as the total mass. With 10 % volume fraction, a magnetic flux density around 2 T and frequencies of operation beyond 5 Hz, a water cooled magnetic chiller will have a total volume comparable to the one of a conventional chiller. Increasing the volume fraction up to 30 % allows lowering the magnetic flux density applied to the magnetocaloric material beyond 1.5 T. The frequency of operation in this particular case does not need to reach 10 Hz, but may also be lower, depending on the temperature of the heat source and heat sink.

Large-scale water-cooled liquid chillers

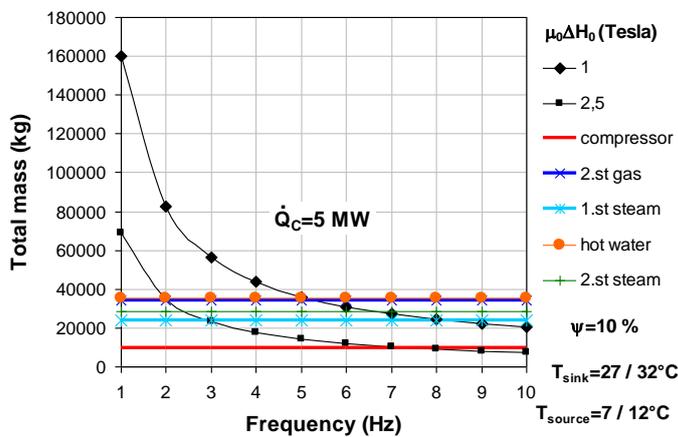
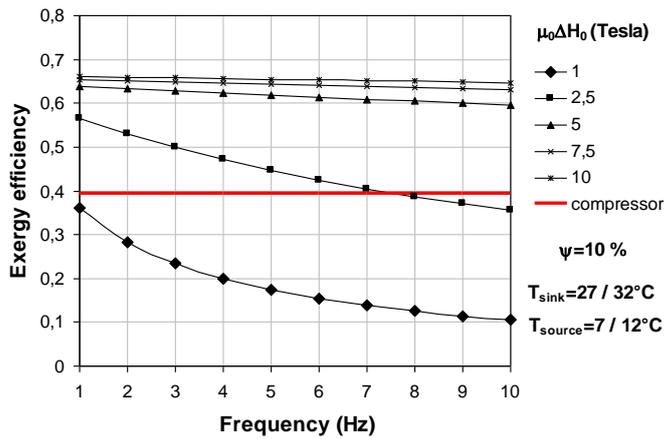
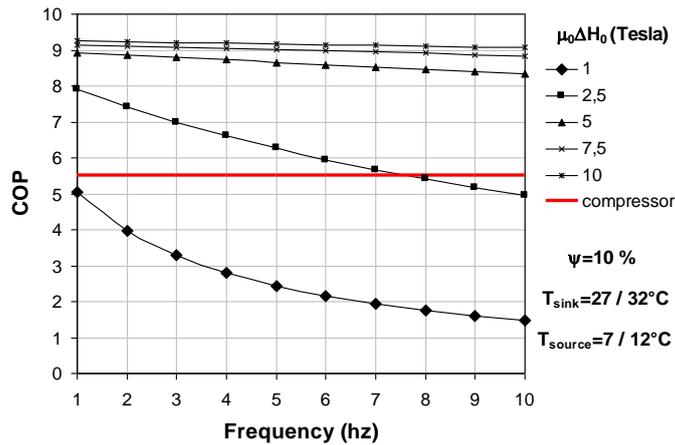
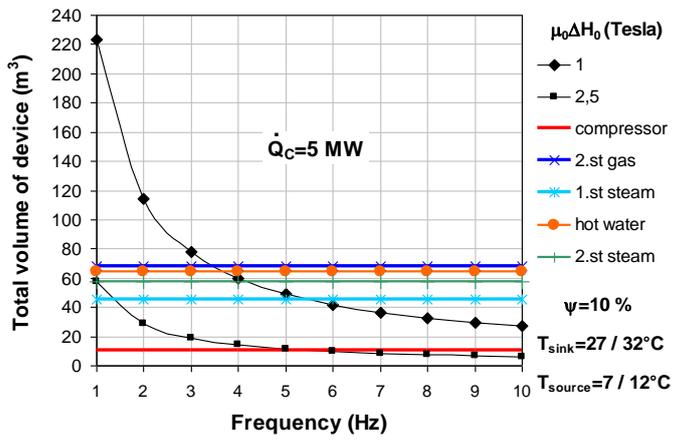


Figure 68: The COP of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the frequency of operation. Furthermore, the graphic contains the typical COP values of a centrifugal compressor chiller operating under the same conditions (Carrier XR/XRT). For the large-scale chillers operating at conditions given in the figure, the magnetic flux density should be around 1.5 T or higher, depending on the frequency of operation. On the other hand, lower frequencies lead to larger devices and larger masses. One may notice that the magnetic flux densities correspond to permanent magnets as well as superconducting ones. The reason is that large-scale applications may use superconducting magnets, because of their relatively low contribution to the energy efficiency and price. In such cases the frequency of operation may reach 10 Hz or beyond, even when the volume fraction of the magnetocaloric material is 10 %. Higher volume fractions lead to improved characteristics.

Figure 69: The total mass and volume of a 5 MW water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the frequency of operation. Furthermore the graphic contains the typical values of masses of centrifugal compressor chillers and different sorption chillers operating under the same conditions (Carrier).

Our assumption is that the use of superconducting magnets will lead to lowest possible mass and volume among all applications but only when considering large scale units.

The total mass of a large scale magnetic central chiller may reach the one of compressors if the frequency of operation is around 10 Hz and the magnetic flux density around 2.5 Tesla. This kind of magnetic flux density does not require superconducting coils. For absorption chillers it is known that they present a larger mass and volume.



The frequency of operation is in a strong correlation with the mass and volume. One should note that higher fractions of magnetocaloric material in the structures would lead even to more compact and lighter devices. A conclusion therefore is that large-scale magnetic cooling applications beat the conventional analogue technical devices not only in the sense of efficiency but also considering their mass and volume.

11. CONCLUSION

This Appendix contains a comprehensive list of the main cooling, refrigeration and air conditioning technologies and the possibilities of alternative technologies based on the magnetocaloric effect. The most feasible technologies are listed in Chapter 11 and are supported by the results of the analysis which was made for this project.

Briefly one can say that the applications with small temperature differences are much more favourable. Because of the limited adiabatic temperature difference of the magnetocaloric materials a high temperature difference implies the use of numerous cascading or regeneration stages. These lead to additional heat transfer losses and to a lower coefficient of performance. Furthermore, the restriction of operating around the Curie temperature of the magnetocaloric material makes the systems with steady operation conditions more favourable. If the temperature of the heat sources and sinks are wildly fluctuating an efficient operation of the machine is not guaranteed. These two restrictions are valid for all kind of magnetic machines: magnetic heat pumps, magnetic refrigerators and magnetic “power conversion” machines.

Furthermore the study reveals that for smaller magnetic fields high *COP* values are only possible, if the rotation frequency is low. This is necessary to keep the carry-over leakages small: only small velocities lead to small pressure losses in the porous structures of the rotary wheels, but if the velocities are small the angular velocity and the frequency must also be low.

At higher magnetic fields the dependence on the rotational frequency is smaller. If the magnetic field strength is high, a lower number of stages is needed, what leads to lower irreversibilities. And even more, because of fewer stages, fewer rotors in series occur, and also the pressure drop loss is smaller. That explains why high fields are very interesting for the magnetic/magnetocaloric machine design. Further, the increase of the volume fraction of the magnetocaloric porous structure has a substantial influence on all the characteristics. The reason is that in the same “gap” of permanent magnet assembly a higher concentration of magnetocaloric material leads to a much higher specific power. Our analysis has shown that it is possible to increase the volume fraction without having the problem of higher pressure losses if the structure is still allowing a good diffusion of heat and also a sufficient mass flow within the limits of the fluid carry-over leakage. The increase of the volume fraction therefore strongly improves the characteristics (note that there are limits of volume fraction so one may expect that 30 % of volume fraction is close to the optimal one), what leads to a large reduction of the specific losses. Furthermore, the Swiss team found solutions which theoretically enable very high frequencies of operation (beyond 10 Hz) without having the problem of the carry-over leakage. These solutions need now to be investigated also in practice. The mass and compactness of magnetic refrigeration and cooling devices is, beside temperature levels, strongly related to the magnetic flux density, the frequency of operation and the volume fraction of the magnetocaloric porous structure. It is seen in this report that achieving a small volume will not present such a challenge than a small total mass of a device. However, even the mass may be reduced to that of a machine belonging to the conventional technology with new future-oriented approaches. Furthermore, the use of high temperature superconducting magnets, most appropriate for large-scale magnetic cooling units, presents at present the best possible application of this green technology. Therefore, a special study related only to machines with superconducting magnets with large cooling powers would be a step forward towards the commercialization of this kind of technology. Beside this kind of technology, permanent magnet-based systems are very promising and at the present state of development even more feasible in the sense of a short term industrialization period. Based on the analysis of this project, as well as on possible improvements and modifications of the magnetic cooling and refrigeration technology, a comparison between the best possible applications was made in order to evaluate the most feasible technology and its fastest possible industrialization. These are listed in the final report of this project.

12. REFERENCES

- [1] World ACR compressors: rapid growth and shift towards regional hubs, Press release 24/04, BSRIA Limited, 2004.
- [2] www.liebherr.com
- [3] www.gorenje.si
- [4] www.air-conditioner-home.com
- [5] www.carrier.com
- [6] www.daviddarling.info
- [7] www.mcquay.com
- [8] S.A. Mumma, Ceiling Panel Cooling Systems, Ashrae Journal, Cooling systems, November, 2001, pp. 28-32.
- [9] www.hidria.si
- [10] www.rtfmanufacturing.com/healthcare/products/plus4degree/bloodbank.html
- [11] www.freezerlink.com/moderate_cold.htm
- [12] www.beerbrewer.co.uk
- [13] <http://morebeer.com/>
- [14] <http://pubs.logicalexpressions.com/pub0006/LPMArticle.asp?ID=42>
- [15] ASHRAE Handbook – Refrigeration, 2006, ASHRAE.- American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- [16] www.denso.com
- [17] www.konvekta.com
- [18] www.aitransit.com
- [19] www.grenco.nl
- [20] www.flickr.com/photos/hal_photos/533529027/
- [21] www.amsuper.com
- [22] <http://science.hq.nasa.gov/oceans/physical/SST.html>
- [23] J. Varun, P.W. Egolf, 2007, Application of magnetic refrigeration: A magnetic laboratory refrigerator. Scientific report of a summer internship at the University of applied Sciences of Western Switzerland.
- [24] R.D.Heap, The Refrigeration of Chilled Foods, Chilled Foods, 2nd edition, A comprehensive guide, Woodhead Publishing Limited, 2000, pp. 79-98.
- [25] www.refrigerated-containers.com
- [26] www.custombigrig.com/images2/hailetrailers.jpg
- [27] http://en.wikipedia.org/wiki/Refrigerator_car
- [28] www.trainweb.org
- [29] www.containerserviceco.com/refrigeration.html
- [30] www.mycomkl.com.my
- [31] www.linde-kaeltetechnik.de