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Magnetocaloric Cooling Near Room Temperature – A Status Quo with Respect to Household Refrigeration

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ABSTRACT

Magnetocaloric cooling is currently a prospering field of scientific investigations. Especially in the last decades a significant increase in research activities took place, mainly with the aim to find a competitive substitution for conventional cooling techniques – primarily with a special focus to vapor compression cycles. At least from a theoretical standpoint magnetocaloric cooling has the potential to exceed efficiencies of conventional cycles. However, there are still a number of challenges that need to be overcome.

This paper is intended to give a basic overview on the status quo of magnetocaloric cooling near room temperature with respect to household refrigeration. Basic data regarding materials and magnet field generation are discussed. The most powerful demonstrators so far published in literature are analyzed and compared to performance requirements for standard household refrigerating appliances. Several comparisons are carried out to emphasize the crucial points that will be decisive on whether magnetocaloric is a future option for household refrigeration or not.

1. INTRODUCTION

Basically, the magnetocaloric effect describes the alignment of elementary magnets in a certain material and the accompanied entropy change. As a consequence, the temperature within the material changes. Materials with positive magnetocaloric effect show a temperature increase when exposed to a magnetic field. Accordingly, materials with negative magnetocaloric effect show a temperature decrease. Reasons for this behavior can be found in interaction of electron motion and external magnet field which was fundamentally described by Maxwell's equations. Depending on the material, this apparently easy-to-explain effect can be indeed very complex and is therefore an individual subject in physics or material science, respectively. However, for engineering applications the macroscopic characterization is sufficient.

The generation of cooling out of the magnetocaloric effect has been well known since a long time. The discovery goes back to Warburg in the year 1881. Later Debye and Giauque proceeded Warburg's work independently in 1926 with the aim to produce very deep temperatures near absolute zero (Mendelsohn, 1977).

Since this, cryogenics and the production of cold in cryogenics is clearly the main field of application for the magnetocaloric effect – with great success. The recently published multi-stage ADR (adiabatic demagnetization refrigerator) for sub-Kelvin temperature applications developed by Peter Shirron from NASA achieved the world's best mass related efficiency (Shirron, 2007). In other words, magnetocaloric cooling is a well-established technique in deep temperature cryogenics and can compete with all other available cooling methods. There are two reasons for this. Firstly, the very low temperature differences to overcome and secondly, the availability of very high magnetic fields due to superconductivity.

Since the investigations of Brown (1976) and the discovery of the "Giant Magnetocaloric Effect Materials" by Pecharsky and Gschneider (1997), the research activities at near room temperature have been increased exponentially. The main driver for this is the theoretical potential of magnetocaloric cooling to be competitive or even better than conventional vapor compression cycles (see e.g. Sari and Balli, 2014). The establishment of an individual conference “THERMAG” exclusively for magnetocaloric topics and a permanently rising number of publications in this field demonstrate the continuous interest. Two representative review articles of Yu *et al.* (2010) and Nielsen *et al.* (2011) prove the impressive progress of the last two decades. However, all published cooling machines are still on a laboratory level with a certain potential to probably step into the market in a future stage. In contrast, a number of press releases (see e.g. Achrnews, 2013) promote magnetocaloric cooling machines to be almost market-ready – also with respect to household refrigerating appliances.

Obviously, a contradiction exists with a laboratory level on the one hand and market maturity on the other hand. In According to our assessment, this contradiction leads to certain confusion in industry – at least in Germany. Hence, the motivation for this paper is to assess the status quo of magnetocaloric cooling on a more scientific basis. Further, the paper may help to highlight the main challenges of magnetocaloric cooling application with a special respect to household refrigerating appliances.

2. REQUIREMENTS FOR HOUSEHOLD REFRIGERATING APPLIANCES

2.1 Thermodynamic Requirements

2.1.1 Standards:

The thermodynamic requirements for household refrigerating appliances are clearly defined by standards. As widely used examples the following standards should be mentioned:

- EN ISO 15502
- AHAM HRF-1-2008
- AS/NZS 4474

In addition, for worldwide standardization IEC 62552 part 1-3 is in final preparation but not yet published.

2.1.2 Temperatures and Differences:

It is not an intention of this paper to compare given temperatures within the standards deeply, but all standards give similar temperature levels for different compartment types in the appliance (see Table 1).

Table 1: Comparison of selected temperature conditions within the standards EN ISO 15502, AHAM HRF-1-2008 and AS/NZS 4474

Compartment	DIN EN ISO 15502	AHAM HRF-1-2008	AS / NZS 4474
Ambient temperature	25°C (32°C) ± 0.5°C	32.3°C ± 0.6°C	32°C ± 0.5°C
Fresh food compartment	5°C	3.3 - 7.22°C	3°C
Freezer ***	-18°C	-15 / -17.8°C	-15°C

In Table 1 only the fresh food compartment and the freezer temperatures are listed, although a number of other compartment type definitions can be found within the standards. We have chosen both in order to show representative values for a standard household refrigerator and/or a freezer.

Deviating ambient temperature levels within the standards primarily take local climate differences (climate zones) into account. In the past also a general ambient temperature of 43°C has been discussed, but with respect to valid standards 32°C may be seen as best fit.

With these very strict temperature requirements out of the standards we can derive two temperature differences for further consideration in this paper (see Table 2).

Table 2: Simplified cases for temperatures and differences in household refrigerating appliances.

Case	T_0	T_U	ΔT
1 – Standard household refrigerator	5	32	27
2 – Standard household refrigerator with freezer	-18	32	50

Out of this very easy calculation we can see that a simple household refrigerator has to maintain at least temperature differences of 27..50 K to comply with international standards. In a future case with possible ambient temperature of 43°C this difference would increase to even 61 K.

2.1.3 Cooling Power and Efficiency:
The specific cooling power is not defined explicitly within the standards. The actual cooling demand to maintain the required temperatures in the compartments is mainly depending on size, loading conditions, insulation and duty cycle of the appliance and is therefore more an implicit result for a specific design. At a rough estimate, typical household refrigerating appliances show cooling power between 50..150 W in average.

In order to achieve this cooling power, manufacturers usually aim for reduced costs and therefore power saving operation. On the basis of own measurements modern household refrigerating appliances can achieve exergetic efficiencies COP/COP_{Carnot} of up to 43 % under standard test conditions with 35°C ambient temperatures. Sari and Balli (2014) even indicate up to 50 % exergetic efficiency with modern compressors. Further improvements of the efficiency currently might be prevented due to corresponding cost increase of the appliance. Although this fact seems to be absurd, the current costs for electricity do not necessarily justify further comprehensive system optimization except of the typical gradual improvements of every market product.

2.1.4 Method of Cold Generation:
The standards do not require or recommend a specific method for the generation of cold. Hence, all requirements within the standards have to be maintained for possible magnetocaloric cooling appliances as well.

2.2 Additional Requirements

Beside the thermodynamic requirements market-standard appliances usually do underlie additional requirements for customer-friendly appearance, e.g.:

- reasonable price
- attractive design
- adequate compartment size and position
- acoustically balanced
- maintenance-free operation (e.g. no-frost technology)

Most of these additional requirements involve further restrictions to the manufacturer in terms of package or intelligent component installation, respectively.

3. MAGNETOCALORIC HOUSEHOLD REFRIGERATORS – STATUS QUO

3.1 Materials

A core component for magnetocalorics is an appropriate magnetocaloric material. Main intention is therefore to use materials with a magnetocaloric effect as big as possible under given boundary conditions. Typical materials which show such a significant effect near room temperature are mainly chemical compounds made of rare earth elements or metals belonging to the iron group. The individual composition of suitable materials is an individual subject and therefore more located in material science. A comprehensive discussion of all currently investigated material groups can be found at Shen *et al.* (2009) and Franco *et al.* (2012). In order to give at least 2 examples we want to mention firstly pure Gadolinium, which is a very prominent candidate and still a widely used magnetocaloric material also for benchmarking purposes. Secondly, we want to point out Lanthanum-Iron-alloys which can show adequate performance as gadolinium but with much less amount of cost intensive rare earth metals.

The largest magnetocaloric effect can be observed near the Curie-point or Curie-temperature T_c, respectively, where the transition between ferromagnetic and paramagnetic properties takes place. This transition involves a certain impact to the material. Two separate phase changes can be distinguished:

- 1st order phase change: narrow but peaky magnetocaloric effect near T_c, irreversible magnetization, internal changes within material structure including macroscopic volume change effects, elevated thermal and magnetic hysteresis, apparently latent heat like behaviour with comparably high Δs
- 2nd order phase change: wide magnetocaloric effect near T_c, reversible magnetization, very low thermal and magnetic hysteresis, negligible changes within material structure, comparably low Δs

For performance reasons materials with a 1st order phase change usually are preferred because of comparably high Δs. However, 1st order materials involve further – quite crucial – problems such as possible macroscopic volume changes which might end in material destruction over number of cycles.

In general, the optimization of magnetocaloric materials therefore focusses on three main objectives:

- increasing of the adiabatic temperature change ΔT_{ad} at defined magnetic field changes
- increasing of the specific difference in magnetic entropy Δs between defined magnetic field conditions
- adaption of the Curie-temperature T_c of the material

The adaption of Curie-temperature is a well-established technique in material science and can be provided for many types of alloys near room temperature. With respect to ΔT_{ad} and Δs Table 3 gives an overview what typical magnetocaloric materials can achieve at near room temperature conditions and a magnetic field change of 2 T. For comparison reasons we also added in Table 3 some data for a light expansion of nitrogen (2 to 1 bar) and the vaporization of isobutane (R-600a) as a standard refrigerant in household refrigerating appliances. We can observe a significant difference of one to two orders of magnitude with respect to ΔT_{ad} and Δs between currently discussed magnetocaloric materials and conventional substances and processes. This tremendous difference has to be compensated by process design or further optimizations of magnetocaloric materials.

Table 3: Approximate values for ΔT_{ad} and Δs of different materials near room temperature in comparison to conventional fluids and processes.

Property	Condition	Values
ΔT_{ad}	MCM 1st order, 0-2 T	3..7 K
	MCM 2nd order, 0-2 T	1..6 K
	Expansion N_2, 2 to 1 bar, 20°C	53 K
Δs	MCM 1st order, 0-2 T	15..40 J/kg K
	MCM 2nd order, 0-2 T	1..10 J/kg K
	Expansion N_2, 2 to 1 bar, 20°C	210 J/kg K
	Vaporization R-600a, 273 K	1300 J/kg K

3.2 Magnet Field Generation

Another relevant factor for achieving large magnetocaloric effects is the application of strong magnetic fields. Near room temperature only the use of permanent magnets seems to be feasible which results in further constraints for recent considerations.

Current permanent magnets based on the combination of neodymium, iron, boron will enable highest magnetic fields. The largest magnetic flux densities reachable are in a typical range of 1 to 1.5 T with respect to the chosen configuration. If a complex arrangement of magnets (e.g. Halbach configuration) is applied higher magnetic flux densities of approximately 2 T can be provided.

For technical realization a number of design proposals have been published which combine an optimal magnetic field and minimal amount of necessary material (Björk et al., 2010, 2011). The focus of research lies on enabling instantaneous transition between high and zero magnetic field, the homogenous distribution of magnetic flux density, and synchronized force and momentum characteristics of the interaction when magnetocaloric material is being guided in and out of the permanent magnets field.

In particular for first estimations of the necessary magnet size for a given amount of magnetocaloric material the theoretical approach of Jensen and Abele (1996) can be applied. For optimal conditions the volumes of the magnet and the gap in between are related like the following:

- $V_{mag}/V_{gap} = 8/1$ for single use of magnetic field
- $V_{mag}/V_{gap} = 4/1$ for double use of magnetic field

With this theoretical lower boundary reasonable calculations can be made even if most of published demonstrators show significantly higher values (Rowe, 2011).

3.3 Principle Process Steps and Cycle Design Issues

In order to provide certain cooling power out of a magnetocaloric material several process steps are needed. These are as follows:

- Exposure of magnetocaloric material into a magnetic field (temperature increase by ΔT_{ad})

- Heat removal to ambient or adjacent temperature level
- Removal of the magnetic field (temperature drop by ΔT_{ad})
- Heat absorption and therefore provision of certain cooling power

A seperation of local heat removal and absorption plus a cycling mode will lead to a more or less quasi-continious cooling cycle depending on the frequency. In order to schematize this cycle behaviour three basic cycles are commonly used and transferred to a conventional T-s diagram with isomagnetic field lines (see examples in Figure 1):

- Carnot cycle (2 isentropic and 2 isothermal sections)
- Ericsson cycle (2 isomagnetic and 2 isothermal sections)
- Brayton cycle (2 isentropic and 2 isomagnetic sections)

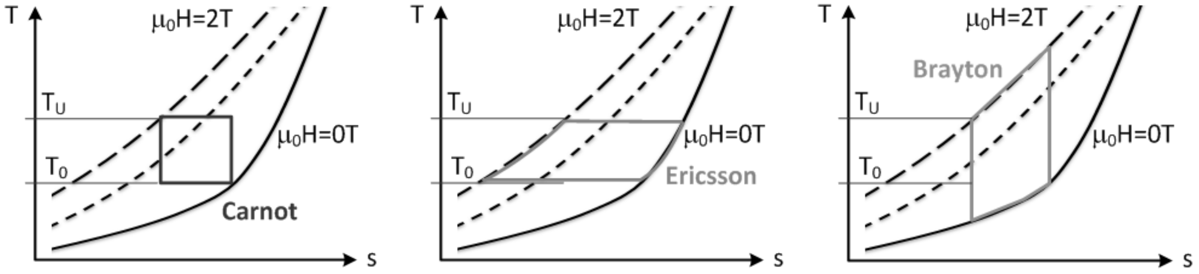

Figure 1: Basic cycle options for magnetocaloric devices, transformed to a T-s diagram with isomagnetic lines.

The Carnot cycle serves only for benchmarking and efficiency comparison. However, under certain boundary conditions half of Carnot-cycle was used for cooling near absolute zero (Mendelsohn, 1977). For application near room temperature usually a combination of Ericsson and Brayton cycle is used.

The ΔT_{ad} of the latest materials is still too small to achieve considerable temperature differences such as for household refrigerators. Therefore, regenerators directly filled with magnetocaloric material (active magnetic regenerator) are applied. With this technique – well known from Stirling coolers – a much higher temperature difference can be maintained. So far all published demonstrators for room temperature application apply an active magnetic regenerator. The regenerator is perfused by a heat transfer fluid, usually without any phase change. Both ends of the regenerator are coupled to warm and cold heat exchanger.

The internal design and optimization of the active magnetic regenerator and the coupled fluid flow are one of the main challenges for a efficient cycle operation. From Stirling cooler research a number of papers are available that intensively discuss the problematics of heat transfer to pressure drop in regenerators (e.g. Rühlich, 1999). Further, several different techniques are discussed in literature comprising continuous and discontinuous flow options as well as varying approaches for magnetic field and active magnetic regenerator configuration (Yu et al., 2010, Scarpa, 2012). Presumably, the most promising approach so far is a continuous flow through the regenerator, controlled by several valves, and a rotating magnet field mechanism.

3.4 Performance Data of Published Demonstrators in Literature

In literature a number of demonstrators are published which are operated near room temperature. In order to get an insight to which cooling power and which temperature differences can be achieved so far, we carried out a literature survey.

Performance determination usually comprises the following points:

- Determination of maximum cooling power at zero temperature span: Indicates the maximum power of the device without any temperature span along the regenerator ($T_0 = T_U$).
- Determination of maximum temperature span: Indicates the maximum temperature span without provision of external cooling.
- Determination af characteristic points in between: Indicates the cooling power to temperature span line.

Unfortunately, not all publications clearly indicate the above mentioned data. For benchmarking all devices with respect to household application we plotted the maximum temperature span and the maximum cooling power against the mass of the magnetocaloric material in Figure 2. Out of this data we can conclude the three best devices in both disciplines which are shown in Table 4.

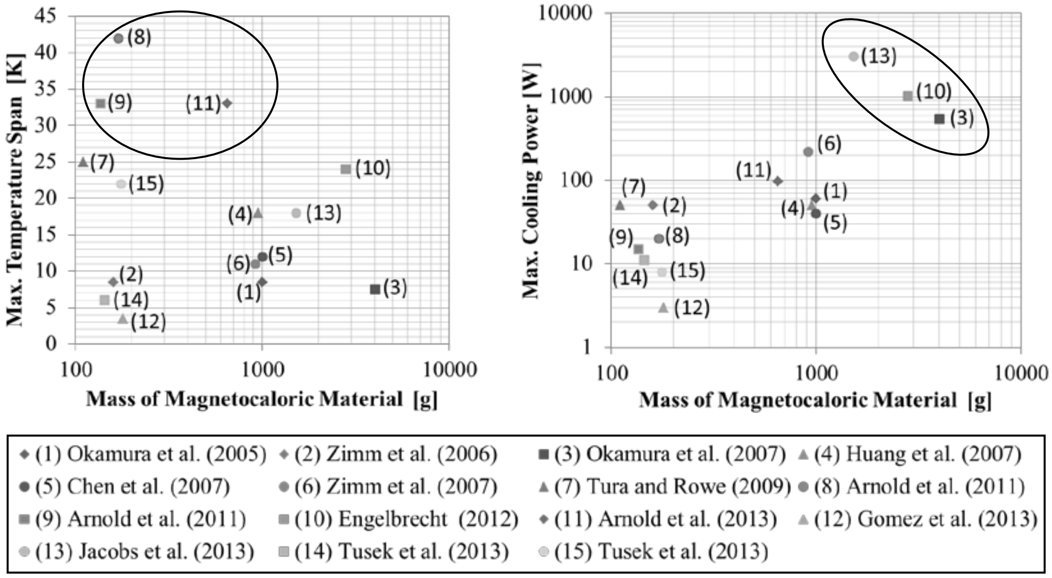

Figure 2: Maximum temperature span (left) and maximum cooling power (right) of published demonstrators over the mass of magnetocaloric material used.

Table 4: Collection of the three best demonstrators for maximum cooling power and maximum temperature span.

Demonstrator	Max. cooling power	Mass of material	Max. temperature span
Max. cooling Power			
Okamura et al. (2007)	**540 W**	4000 g	8 K
Engelbrecht et al. (2012)	**1010 W**	2800 g	19 K
Jacobs et al. (2013)	**3042 W**	1520 g	20 K
Max. temperature span			
Arnold et al. (2011)	31 W	136 g	**30 K**
Arnold et al. (2013)	96 W	650 g	**33 K**
Arnold et al. (2011)	42 W	170 g	**42 K**

Some additional comments are necessary in order to evaluate the performance of all demonstrators.

Firstly, the common way for cooling power determination is to apply an electrical resistor for cooling power compensation. The results therefore reflect an ideal way of using the gained cooling power. Under normal conditions at least two additional heat transfer barriers have to be crossed which involves additional ΔT and entropy losses. Secondly, the ambient temperature level of all demonstrators varies in a certain range. Some of them work at approximately room temperature, others slightly elevated. This might shift the total performance results slightly because of Curie-Temperature adjustment. In other words, Gadolinium based regenerators will loose a certain amount of performance at higher ambient temperatures since the Curie-temperature is about 294 K.

The following general results can be concluded:

- The most three powerful devices do not show the largest temperature spans, likewise.
- So far, only three devices can achieve the necessary temperature span for refrigerating appliances (Table 2, Case 1) when only magnetic field strength of less than 2 T is taken into account.
- No device is suitable to achieve the necessary temperature span for freezers compartments at all (Table 2, Case 2).

Therefore, we have to state that no demonstrator published in literature is able to satisfy the thermodynamic requirements of a standard houshold refrigerating appliance in compliance to international standards. However, we can only refer to published articles. It is likely that hidden activities are carried out by individual research groups or companies. Those activities might shed another light on the results above.

3.5 Required Components and Cost Estimation

Another significant aspect is the comparison of relevant components which are basically needed for cycle operation. Since the components can be seen as major cost driver during the manufacturing process, we want to compare very roughly the approximated costs for a magnetocaloric cycle and a vapor compression cycle.

For magnetocaloric cycle operation at first a certain amount of magnetocaloric material is needed which will be perfused by the heat transfer fluid. For continuous or discontinuous pumping of the heat transfer fluid at least one pump or displacement unit is needed. The permanent magnets have to be incorporated to a movement mechanism in order to realize the prescribed path for high / low magnetic field generation and absorbing upcoming forces. In order to drive the mechanical components a motor (usually electrically powered) is needed additionally. In case of continuous pumping of the heat transfer fluid at least two valves (usually more) have to be included to the cycle in order to control the fluid flow through the regenerator bed. Additionally required are the cold and warm heat exchanger, some piping and the control system including necessary sensors.

For operating a vapour compression cycle the following – well known – components are needed: compressor, condenser, expansion device (usually a capillary tube) and evaporator. Additionally, we need to take into account the refrigerant and various small positions such a s compressor oil and the piping.

Table 5 shows the comparison of all mentioned components. When comparing both principles and the necessary components we cannot obtain an obvious advantage for the magnetocaloric machine. The number of components is most likely higher as for a conventional vapor compression machine.

Another point is the complexity of the components. In case of the magnetocaloric machine the most complex issue lies on designing the interaction of all moving parts and the optimized heat transfer and magnet field generation. The most complex component in a vapour compression cycle is the compressor with all its well-known weak points.

With respect to the costs of all necessary components the following comparison will be carried out on a basis of 500 g magnetocaloric material. In comparison to the best published demonstrators (see Table 4) this amount of magnetocaloric material seem to be very low. In other words, this amount would presumably not be enough to maintain a cooling power of some Watts at a temperature span of at least 27 K (Table 2, Case 1) under the current technical level. However, from a theoretical standpoint 500 g might be sufficient and other publications, such as Bjork *et al.* (2010), show similar amounts as well. We therefore we assume 500 g as a kind of perspective amount for future appliances.

The price for magnetocaloric material is mainly driven by the chemical substances included. The primarily used Gadolinium is quite expensive with approximately 500 $/kg (large price differences possible) and is therefore no realistic option for later household refrigerating appliances at all. Nevertheless, recently investigated alternatives, such as La-Fe-compounds might reduce this costs to roughly 20 $/kg (Rowe 2011).

Based on the amount of 500 g and an assumed porosity of 40 % we can derive an approximate volume for the material bed of 105 ml. Applying the rule of Jensen and Abele (1996) this would lead to a magnet volume of 422 ml at minimum. Permanent magnets made of NdFeB are also quite expensive due to rare earth material application (app. 40 $/kg, Rowe, 2011). As a consequence, the magnets are even more cost driving than the magnetocaloric material due to the coupled volume increase.

The prices for all other necessary components in the magnetocaloric device are assumed to be almost equivalent to a conventional vapor compression system. Therefore, cost advantages of series production are included in a certain way.

The component costs for a conventional vapor compressions appliance might be estimated fairly good, since the manufacturing process is well established and several experts out of this field could be consulted.

Table 5 shows the allocated price span for each component and a total sum range. The given costs just assume the basic components for cold production and do not include any peripherical components, auch as casing or inner compartment arrangement.

If we compare the very rough costs for a magnetocaloric and a vapour compression cycle, we can obtain a certain difference. The magnetocaloric machine will presumably be more expensive – at least under the current technical point of view. This is mainly because of two points – firstly the higher number of components and secondly the cost intensive magnet material.

Table 5: Comparison of necessary components for a magnetocaloric cycle and a conventional vapour compression cycle including rough cost estimation.

Magnetocaloric cycle	Cost estimation [US-$]	Vapour compression cycle	Cost estimation [US-$]
Pump / Displacement device	7..20	Compressor	30..60
Movement mechanics (Magnets, AMR)	5		
Permanent magnets (3.3 kg, 40 $/kg)	132		
Motor	12		
Regenerator with material (500 g, 20-500 $/kg)	10..250	Refrigerant	0.5
Heat transfer fluid	1	Oil	1
Valves	24	Capillary tube / Expansion valve	0.5..7
Warm heat exchanger	2..6	Condenser	2..6
Cold heat exchanger	2..6	Evaporator	3..15
Piping	2	Piping	2
Control system / Electronics / Small components	25..50	Control system / Electronics / Small components	25..50
	= 222..508		= 64..142

3.6 Short Comment on the Environmental Impact and Life Cycle Assessment

It is often mentioned that magnetocaloric cooling might be a future alternative for conventional refrigeration techniques. Higher COP and therefore lower energy consumption are typically the main arguments for this. However, for realistic evaluation a life cycle assessment is needed which comprises production, usage and end of life of a certain product. Monfared *et al.* (2014) recently published the first study on life cycle assessment dedicated to the comparison of magnetocalorics to conventional vapour compression technique with respect to household appliances. They concluded that possibly higher efficiencies of magnetocaloric refrigerators cannot compensate all extra impacts to environment. A major contribution to this extra environmental impact comes from mining and production of rare earth magnets (NdFeB). It is undisputed that rare earth materials will significantly contribute to the environmental impact of magnetocaloric refrigerating appliances. Therefore, a valuable future work might be to carry out an extended study similar to Monfared *et al.* (2014). This would substantially help to obtain perspective requirements for at least environmentally neutral behaviour in comparison to conventional refrigeration.

4. CONCLUSIONS

The technology of magnetocaloric cooling near room temperature experienced an enormous increase of development and remarkable progress in performance. Even if a practical confirmation has not yet been shown near room temperature, a number of theoretical considerations allow the conclusion that magnetocaloric cooling offers the potential to eventually be superior upon conventional cooling technology (e.g. vapor compression) in terms of efficiency. A proof of already feasibly employed magnetocaloric cooling can be found in the earlier presented example of cryocoolers.

Due to a number of recent press reports the apparent state of the art of magnetic cooling especially with respect to household refrigeration has been critically questioned. The announcement to launch competitive devices based on magnetic technology stirs an uncertainty in the cooling industry about the actual status of the development.

This publication therefore concentrates on the issue whether and to which extent magnetocaloric cooling near room temperature can be competitive to modern household refrigerators based on conventional technology.

In a first step effectual requirements following DIN EN ISO 15502, AHAM HRF-1-2008, and AS/NZS 4474 have been presented.

In the following survey of recent developments in magnetocaloric cooling with respect to materials and magnetic field generation an informative basis has been gathered to enable subsequent comparisons.

A thorough investigation on published demonstrators revealed, despite the notable development of recent years, that no experimental setup was able so far to achieve the required temperature span in combination with the cooling power for a commonly used household refrigerating appliance. However, there are examples available which can achieve at least one of both necessary requirements. Consequently, a future machine might be suitable for demonstrating both.

Focusing on the number of necessary components of a prospective magnetocaloric fridge no clear advantage for magnetocaloric cooling technology can be identified if compared to conventional cooling technology. In contrast the components complexity and number will most probably increase.

Also, a very rough estimation of the components costs for a magnetocaloric cooling device does not indicate obvious advantages. Mostly the future prize for the magnetocaloric material and suitable permanent magnets will determine whether this new technology will be feasible cost wise.

With respect to environmental issues at least one critical paper was shortly discussed that reveals magnetocaloric devices to be more environmentally impacting as conventional vapor compression devices – primarily due to the application of rare earth materials.

Magnetocaloric cooling is beyond doubt a fascinating technology with large potentials. However the announcement of to launch feasible and competitive household refrigerators based on magnetic cooling in the near future seems to be speculative and not realistic.

With respect to other cooling applications e.g. with a significantly smaller temperature span the authors propose to conduct a separate assessment regarding readiness for marketing.

NOMENCLATURE

COP	coefficient of performance	(..)
COP_{Carnot}	Carnot efficiency (COP of Carnot cycle)	(..)
$\mu_0 H$	magnetic flux density of an air filled gap	(T)
s	entropy difference	(J/kg-K)
Δs	specific entropy difference	(J/kg-K)
T	temperature	(°C)
T	absolute temperature	(K)
T_c	Curie-temperature	(K)
ΔT_{ad}	adiabatic temperature change	(K)
ΔT	temperature difference	(K)
V_{mag}	volume of the magnet material	(m^3)
V_{gap}	volume of the air gap within the magnets	(m^3)

Subscript

0	cold
U	warm, ambient

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