A STANDARDIZATION OF THE COEFFICIENT OF PERFORMANCE FOR MAGNETIC REFRIGERATORS, HEAT PUMPS AND ENERGY CONVERSION MACHINES

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ABSTRACT

Publications on magnetocaloric materials, magnetic refrigerators, magnetic heat pumps and magnetic power conversion machines contain experimental results as well as solutions obtained by physical modeling, analytical and numerical calculations. Whereas material scientists usually aim for physical property data, thermal and electrical engineers are interested in the efficiency of the operation and economists in both, production and operation costs of a machine. However, without exact data of the magnetocaloric and magnetic materials, no precise determination of the energy consumption of a magnetic refrigerator can be achieved. Magnetic and thermodynamic measurement techniques must be reviewed and discussed. In the article a method for an accurate determination of a global *COP* of a magnetic refrigerator, heat pump, respectively energy conversion machine is proposed, taking all possible losses of the machines into consideration. Only a full account in a machine characterization gives the possibility to estimate correctly its final energy consumption. For a fair comparison of different magnetic refrigerators, a standardization of the *COP* and cost determination is very much required. The Working Party for Magnetic Refrigeration of the International Institute of Refrigeration IIF-IIR aims to coordinate such an activity. This article is a first proposal and recommendation in this direction and shall serve as a basis for further discussions and improvements.

1. INTRODUCTION

The thermodynamic analysis of magnetocaloric systems and devices serves not just for their evaluation or comparison. It also helps to learn and understand how a large number of different variables influence some characteristics of machines. This is especially important in a process of optimization, where efficient, compact, and low-cost machines are the objective. The large number of variables (in our present work at minimum sixteen occur) requires a very systematic approach to the problem.

Following the magnetocaloric material and machine developments, it is realized that there exists no general agreements to apply which definitions, physical quantities and physical units. This is the case in the materials science sector, in thermodynamics and (mechanical) engineering. Furthermore, a certain lack of coordination on the evaluation of data of magnetocaloric materials leads to somehow incomplete information for the applied scientists and machine designers.

The main goal of optimization processes is to reduce irreversibility's in magnetic refrigerators. Thus, the development of magnetocaloric machines is not only dependent on good magnetocaloric materials and strong magnets. A machine design depends also on the fluid chosen, fluid dynamics behavior and heat transfer properties, which belongs to the engineering sector. Research on magnetocaloric materials and machines is still some distance from its maturity, and there is a remaining large potential for improvements. However, to proceed successfully, a good basis for the determination and presentation of theoretical, numerical and experimental results is demanded. Certain standardization in the material developments sector, the magneto-thermodynamic machine design and even by studying some economic aspects could accelerate and improve the process of magnetic refrigeration approaching some suitable refrigeration markets. For such activities a programme is proposed to the IIR Working Party on Magnetic Refrigeration.

2. THE COP, ENERGY EFFICIENCY AND EXERGY EFICIENCY

The most important characteristic's of a magnetocaloric device is its efficiency. It is usually defined by the Coefficient Of Performance (*COP*). The *COP* presents a ratio between the refrigeration energy and the total electric energy input. Because theses energy fluxes are usually continuous and steady instead of energies the related powers can be determined. The refrigeration energy is measured by monitoring the difference of the energy fluxes into and out of a machine by convective fluid flows. Eq. (1a) represents this fact. For a heat pump it presents a ratio between the heating power (also measured in the fluid flows) and the total electric power input (see Eq.1b):

$$COP_R = \frac{\dot{Q}_R}{P_{el}}, \qquad COP_H = \frac{\dot{Q}_H}{P_{el}}. \tag{1a,b}$$

If the power is only the one related to the energy of movning magnetocaloric sample(s) into magnetic field(s) – against the occurring magnetic forces – than one obtains the *COP*, which describes the efficiency of the thermodynamic cycle. As a rule, this value is the highest obtainable *COP*. If the total electric power of a system, including pumps, fans, regulation, motors, etc., is taken into consideration the powers in Eq.'s (1a) and (1b) increase in the denominators and by this the *COP* values decrease. Numerous published experimental and theoretical results on magnetocaloric machines do not include all these power data. That makes a comparison between different systems rather difficult, or – especially when not scientifically educated persons are involved – sometimes even slightly unfair.

The thermodynamic efficiency presents the ratio of the electric power output and the heat power input to the device (measured on the fluid sides):

$$\eta = \frac{P_{el}}{\dot{Q}}. \tag{2}$$

The ideal *COP* is the COP_C of a Carnot cycle. These values and the thermodynamic efficiencies of a refrigerator, heat pump and a energy conversion machine are given by the following equations:

$$COP_{CR} = \frac{T_R}{T_H - T_R}, \quad COP_{CH} = \frac{T_H}{T_H - T_R}, \quad \eta_C = \frac{T_H - T_R}{T_H} \Rightarrow \eta_C = \frac{1}{COP_{CH}}. \tag{3a-d}$$

By Eq. (3d) one sees that the energy conversion machine is somehow the inverse machine to the heat pump. A characterization of a machine by the *COP* is not complete (e.g. see the article by A. Rowe in these proceedings). Therefore, it is very important to define also some additional operation characteristics. Such are the heat source and heat sink temperature. In engineering usually, the power of a machine is defined at the very beginning. Thus, it is also important to have knowledge about the frequency of operation of a machine. This frequency defines also the number of thermodynamic cycles that a sample of magnetocaloric material performs per unit of time:

$$\upsilon = \frac{N}{\tau}. \tag{4}$$

As soon as the total mass of magnetocaloric material and the frequency of a machine have been determined, one obtains a apparent mass flow of magnetocaloric material through the machine:

$$\dot{m}_{app} = m_{mc}\upsilon. \tag{5}$$

The term «apparent» is applied, because some devices operate discontinuously. Reciprocate machines usually follow such a principle. It means that the process of magnetization/demagnetization is stopped for a certain period in order to allow a fluid flow to transport heat in or out of a machine compartment containing magnetocaloric material. Then an appropriate integration calculus must be applied to determine $\dot{m}_{app}$.

The apparent mass flow is very useful information about the performance of a machine. With a known refrigeration or heating power, it gives information on the real specific cooling capacity (Eq. 6a) of the magnetocaloric material, the real heating capacity (Eq. 6b) and the real specific work (Eq. 6c), respectively:

$$q_R = \frac{\dot{Q}_R}{\dot{m}_{app}}, \qquad q_H = \frac{\dot{Q}_H}{\dot{m}_{app}}, \qquad w = \frac{P_{el}}{\dot{m}_{app}}. \qquad \text{(6a-c)}$$

In a *COP* or a thermodynamic efficiency determination the following losses should be incorporated:

- Hysteresis effect in the magnetocaloric material (frequency dependent)
- Heat gains related to the hysteresis effect
- Eddy currents
- Heat gains because of eddy currents
- Loss given by the motor efficiency
- Motor heat gains (if heat is not evacuated out of the machine)
- Losses defined by the fluid pump or ventilator efficiency
- Fluid pump or ventilator heat gains (if heat is not evacuated out of the machine)
- Fluid friction losses
- Heat gains because of the fluid friction
- Friction losses in bearings and seals or other transmission elements
- Heat gains caused by friction in bearings, seals or other transmission elements
- Irreversible losses by heat transfer between the fluid and the magnetocaloric material
- Heat transfer losses in external heat exchangers (may be of the secondary circuit)
- Power consumption of the regulation system and armatures
- Heat losses or gains because of non-ideal insulation
- Losses caused by fluid leakage (rather seldom).

As one has noticed, certain losses appear twice, at first as a transformation of mechanical work or electricity into generated heat; and then also as losses, which are caused by the rejection of the heat gains. Such losses occur in a motor, pump, because of fluid friction losses, because of friction in seals, bearings and other transmission elements. Furthermore, they occur as result of hysteresis effects and eddy currents and lead to a heating and waste valuable electricity in the device. Here an important remark must be made. In a refrigerator these heat sources caused by losses must be additionally removed. On the other hand in a energy conversion machine they may again contribute to the inflowing heat. Least problematic they are in a heat pump, because there they even may add up to the out flowing thermal energy of the machine.

For all three types of machines in this article under consideration, namely the magnetic refrigerator, heat pump and power conversion machine, sometimes also named somehow incorrect «power generator» another very useful approach exists. It is a concept more applied in engineering than in physics. It is the concept of exergy, which is widely used in conventional thermodynamics. The word “exergy” goes back to 1953 when Rant (see in Baehr (1965)) proposed the words “exergy” and “anergy” as two complementary parts of the energy. Exergy is the part that is fully transformable into other kinds of energy, whereas anergy is the other non-transformable part.

In magnetocaloric devices, beside mechanical and magnetic work, heat transfer processes are playing a crucial role. Heat is the energy, which is only partly transformable into other kinds of energy. Therefore, it is very meaningful to perform exergy analyses of magnetocaloric devices. Furthermore, an exergy analysis can give the most appropriate definitions of efficiencies of machines. It can also define a good basis for fair comparisons of different machines. This article does not deal with the theory of exergy. However, it may be a good repetition to emphasize that some energies, which present pure exergy, are fully transformable to all kinds of other energies. Such are potential energy, kinetic energy, electric energy, mechanical energy, etc. The most important representative of energy, which contains a mixture of exergy and anergy is the thermal energy “heat”. Be aware that one Joule of electric energy is more valuable than one Joule of heat. This is more and more the case the lower the temperature of the considered heat is. In the case that its temperature is identical to the one of the ambient environment, its potential to be transformed to other kinds of energy becomes zero.

This is especially the case when dealing with refrigerators and heat pumps. Exergy of heat is defined as follows:

$$dE_Q = dQ - dB_Q = \left(1 - \frac{T_{amb}}{T}\right) dQ \ . \qquad (7a,b)$$

Expressed by time derivatives this becomes:

$$d\dot{E}_Q = d\dot{Q} - d\dot{B}_Q = \left(1 - \frac{T_{amb}}{T}\right) d\dot{Q} \ . \qquad (8a,b)$$

In the case of a refrigerator or a heat pump the exergy of cooling or heating is defined by:

$$d\dot{E}_R = \left(1 - \frac{T_{amb}}{T}\right) d\dot{Q}_R \ , \qquad d\dot{E}_H = \left(1 - \frac{T_{amb}}{T}\right) d\dot{Q}_H \ . \qquad (9a,b)$$

Equations (9a,b) show that only a part of the cooling power or heating power, respectively, presents exergy. And as already explained, a heat source at ambient temperature $T=T_{amb}$ in Eq.'s (9a,b) doesn't at all contribute to exergy production.

For an energy conversion process the electric power output equals to pure exergy. This follows because electrical energy is exergy. However, the heat inflow into such a device has a limited exergy value, as shown by Eqs.(7a)-(9b). One concludes that for an ideal Carnot cycle the ratio between the exergy input and exergy output of a device equals to one. This means that all the exergy potential, e.g. mechanical or electric energy, is transformed into useful exergy of cooling energy in a refrigerator or to useful heating energy in a heat pump. It also follows that in such an ideal case all the exergy of the inflowing heat into a energy conversion machine is transformed to exergy, which in this case is mechanical or electrical energy. The exergy efficiencies for all three kinds of devices are given in the following equations:

$$\xi_R = \frac{\dot{E}_R}{P_{el}} = \frac{COP_R}{COP_{CR}} \ , \qquad \xi_H = \frac{\dot{E}_H}{P_{el}} = \frac{COP_H}{COP_{CH}} \ , \qquad \xi_g = \frac{P_{el}}{\dot{E}_Q} = \frac{\eta}{\eta_C} \ . \qquad (10a\text{-}f)$$

3. DEFINITION OF DIFFERENT EXERGY LOSSES

Losses, which occur in a magnetocaloric device, are listed in Chapt. 2. In this chapter these are now expressed by their exergies. For a motor or an energy converter with a certain efficiency, the exergy loss is:

$$\dot{E}_m = (1 - \eta_m) P_{el} \ , \qquad \dot{E}_g = (1 - \eta_g) P_{el} \ . \qquad (11a,b)$$

If the heat created by the irreversible power loss of a motor or a "generator" occurs directly in the device under consideration, then additional exergy losses occur. The reason is that the generated heat has to be evacuated out of the machine's body. It is clear that the quantities are identical to those shown in Eq.'s (11a,b):

$$\dot{E}_{hm} = (1 - \eta_m) P_{el} \ , \qquad \dot{E}_{hg} = (1 - \eta_g) P_{el} \ . \qquad (12a,b)$$

For a fluid pump or a ventilator, with efficiency η_p, the exergy losses are:

$$\dot{E}_p = P_{elp} = \frac{P_{ffr}}{\eta_p} \ . \qquad (13a,b)$$

And for the heat generated by friction in the fluid flowing along the material boundaries:

$$\dot{E}_{hffr} = P_{ffr} \ . \qquad (14)$$

If heat, generated by the irreversible losses of a pump or a ventilator, is transferred into the device, then similar as in the case of a motor, additional exergy losses have to be taken into consideration:

$$\dot{E}_{hp} = (1 - \eta_p) P_{elp} \,. \tag{15}$$

In the case of friction losses in bearings, seals or other transmission elements two equivalent losses occur. The first is a reduction of the mechanical work, which is expressed by:

$$\dot{E}_{fr} = P_{fr} \,, \tag{16}$$

and the second is related to a heat generation:

$$\dot{E}_{hfr} = P_{fr} \,. \tag{17}$$

Eddy currents lead to a power consumption, because the electricity is generated inside the machine. Since this is related also to heating, again two kinds of losses occur:

$$\dot{E}_{eddy} = P_{eddy} \,, \tag{18}$$

and

$$\dot{E}_{heddy} = P_{eddy} \,. \tag{19}$$

The hysteresis of the magnetocaloric material acts in a similar manner as eddy currents. A portion useful work is consumed, because of the hysteresis effect. This leads again to an undesired heat production:

$$\dot{E}_{hys} = P_{hys} \,, \tag{20}$$

and

$$\dot{E}_{hhys} = P_{hhys} \,. \tag{21}$$

Heat transfer processes are irreversible and always accompanied by exergy losses. These losses are caused by temperature differences between the fluid and the magnetocaloric material. We assume that all the heat transfers from the fluid directly to the magnetocaloric material and that a variation of temperature occurs. Then it follows that:

$$d\dot{E}_{Qf} = \left(1 - \frac{T_{amb}}{T_f}\right) d\dot{Q}_f \,, \tag{22}$$

and also:

$$d\dot{E}_{Qm} = \left(1 - \frac{T_{amb}}{T_m}\right) d\dot{Q}_m = \left(1 - \frac{T_{amb}}{T_m}\right) d\dot{Q}_f \,. \tag{23a,b}$$

The irreversible heat transfer between the fluid and material is equal to the difference of the exergy flows of the fluid and the material (solid boundary):

$$d\dot{E}_{htf-m} = d\dot{E}_{Qf} - d\dot{E}_{Qm} = T_{amb}\left(\frac{T_f - T_m}{T_f T_m}\right) d\dot{Q}_f \quad \Rightarrow \quad \dot{E}_{htf-m} = \int T_{amb}\left(\frac{T_f - T_m}{T_f T_m}\right) d\dot{Q}_f \,. \tag{24a-c}$$

Irreversibility’s are given for heat fluxes between the fluid and magnetized or demagnetized magnetocaloric material and in ordinary external heat exchangers. Finally, the heat transfer between a primary and secondary working fluid via heat exchangers and certain surfaces is studied. For the three cases, heat transfer irreversible losses in a magnetized part, heat transfer losses in hot heat exchangers and heat transfer losses in cold heat exchangers, the symbols applied are the following:

$$\dot{E}_{htlm-f} \quad \dot{E}_{hthhex} \quad \dot{E}_{htchex} . \tag{25a-c}$$

Exergy losses occur also due to heat losses or heat gains. An important example occurs, because of heat losses caused by an imperfect insulation of a magneto-thermodynamic machine. For this case the exergy loss is defined as in Eq. (8a,b):

$$\sum_{1}^{n} \dot{E}_Q = \sum_{1}^{n} \int \left(1 - \frac{T_{amb}}{T}\right) d\dot{Q} . \tag{26}$$

Because heat losses or heat gains may occur in different parts of a device and at different temperature levels, it makes sense to introduce a sum of all heat fluxes over the present surfaces. It is also necessary to consider losses caused by fluid leakages. This usually does not occur, but may be possible, e.g. in machines with air as working fluid. Usually small losses of electric power are due to a control or regulation system.

The overall exergy efficiencies of the three types of machines are presented in Eq. (10a-f). To give an example for a refrigerator, we summarize all the losses, which have been discussed in this chapter:

$$\begin{aligned} \dot{E}_{tot} &= \dot{E}_m + \dot{E}_{hm} + \dot{E}_p + \dot{E}_{hffr} + \dot{E}_{hp} + \dot{E}_{fr} + \dot{E}_{hfr} + \dot{E}_{eddy} + \dot{E}_{heddy} + \dot{E}_{hys} + \dot{E}_{hhys} \\ &+ \dot{E}_{htf-m} + \dot{E}_{htm-f} + \dot{E}_{hthhex} + \dot{E}_{htchex} + \sum_{1}^{n} \dot{E}_Q . \end{aligned} \tag{27}$$

With this thermodynamic quantity the exergy efficiency of the refrigerator is then:

$$\xi_R = \frac{P_{el} - \dot{E}_{tot}}{P_{el}} = \frac{\dot{E}_R}{P_{el}} = \frac{COP_R}{COP_{CR}} . \tag{28a-c}$$

With the *COP* of the Carnot cycle, which with Eq. (3a) is simple to determine, and by the application of Eq.'s (27)-(28c) the real *COP* of a refrigerator is determined. In an analog manner the exergy efficiencies of a magnetic heat pump or a magnetic energy conversion machine is determined.

4. EXERGY CONSIDERATIONS

The magnetocaloric material Gadolinium is considered as reference material, similar as the ideal gas in conventional thermodynamics. Analogies between the conventional thermodynamics of an ideal gas and the thermodynamics of magnetocaloric systems exist. Our studies have shown (Kitanovski and Egolf, 2007) that this is especially the case when the external force on the system, which in a conventional system is the pressure (stress parameter), in magnetic refrigeration is described by the external magnetic field. On the other hand the corresponding order parameters are in the conventional system the specific volume and in the magnetic system the magnetization of the material. A deeper analysis reveals that also the specific exergy is analogously defined. The specific exergy is sometimes also named the exergy of the enthalpy. It is given by:

$$de = dh - T_{amb}\, ds . \tag{29}$$

A reference state, sometimes named dead state, is usually defined by ambient conditions. Then the specific exergy is known to be as follows:

$$e = \int_{h_{amb}}^{h} dh - T_{amb} \int_{s_{amb}}^{s} ds = h - h_{amb} - T_{amb}\left(s - s_{amb}\right) . \tag{30a,b}$$

The entropy and the enthalpy of a magnetocaloric material at ambient conditions are taken at zero external magnetic field, ambient pressure and ambient temperature. By the application of theoretical work or experimental data, it is possible to create exergy diagrams which are analogue to conventional thermodynamics. Our work in this paper may be referred to the thermodynamics described by Kitanovski and Egolf (2006) and Rosensweig *et al.* (2009).

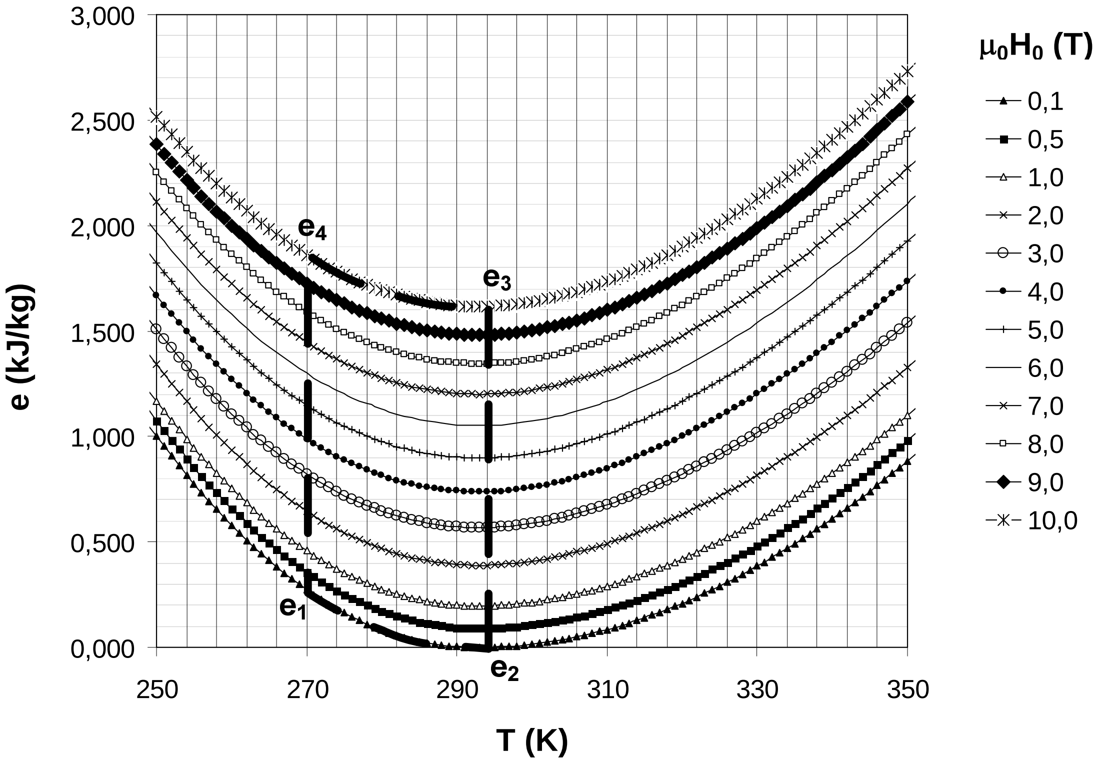

Figure 2: The specific exergy diagram for Gadolinium at different constant external magnetic fields. The dotted line in the graphics presents an example of a magnetic Ericsson cycle. The dead state was defined at ϑ=20°C and $\mu_0 H_0$=0.1 Tesla. The small value approximates a zero magnetic field.

The basic data for the enthalpy and entropy is defined through a theoretical model, described in detail in Rosensweig *et al.* (2009). It can be proven by a calculation of specific exergies that – even if all ireversibility's, caused by the losses listed in Chapt. 2 are neglected – the exergy efficiency of the magnetocaloric cycle cannot reach the Carnot value. The reason are irreversible losses occurring due to «non-balanced» properties of magnetocaloric material. A discussion of this problem is found in Chen *et al.*, (1992).

5. OTHER IMPORTANT CHARACTERISTICS

A most important part of a magnetocaloric machine is its permanent magnet assembly. It usually contains magnets and soft ferromagnetic material. The magnet assembly is designed to magnetize a space domain which is occupied by magnetocaloric material and a working fluid. A high competence and much experience in designing such magnet assemblies lead to higher magnetic flux densities. Or on the other hand, by the same amount of magnetic and high permeable material a larger volume of magnetocaloric material is magnetized. In order to compare different magnetocaloric systems containing permanent magnets, it is useful to introduce the ratio of magnets mass and magnetocaloric material mass obtained for a given magnetic field strength (usually given as an induction in Tesla):

$$\xi = \frac{m_{mag}}{m_{mc}} . \qquad (31)$$

For a given magnetocaloric material mass the smaller this ratio is, the better the machine was designed. As magnets are rather expensive, this value has also an economic importance!

A further measure is the ratio between the total mass of the magnet assembly and the cooling power (heating power, generator power, respectively) given at well-defined operating conditions:

$$\eta_{mag} = \frac{m_{mag}}{\dot{Q}_R}, \tag{32}$$

with the disadvantage that this measure is not non-dimensional.

Very similar conventions have also been introduced in conventional refrigeration technology. Eq. (31) and (32) are only a starting point for further discussions and work. The objective is to get some good standards, which can easily be applied, in a reasonable time.

6. CONCLUSIONS

In this paper a standardization of magnetocaloric machines is proposed, and it gives first valuable information on the thermodynamics part of the posed problem. Other important sectors for such work are the materials domain including magnets and magnetocaloric materials. Furthermore, such a study could be extended also to an economic evaluation of magnetic refrigerators, heat pumps and energy conversion machines.

If scientific domains overlap, the first problem that occurs concerns the applied units. For example, for a certain part of scientists of the IIR Working Party on Magnetic Refrigeration the quantity H is a magnetic field, where for the other it denotes the enthalpy H of a substance. There are other such examples. It could be valuable to start with clearing such confusing situations. In magnetism numerous conventional units, different from SI standards, are applied. It could be very helpful for the thermodynamics specialists to obtain transformation rules and tables.

A standardization of magnetocaloric materials properties mainly asks for unique definitions; such are e.g. the specific cooling capacity, the specific heating capacity and the specific power capacity. It has to deal also with the hysteresis effect and its dependence on the frequency of operation of a machine . Dynamic magnetocaloric effect measurements should be explained and proposed. Furthermore, the internal «unbalanced» ireversibility (addressed in Chapt. 4) is important.

A domain that will become more important is the domain of mechanical material properties. Brittleness, ductility, pliability, flexibility, machinability, etc. of magnetocaloric materials are to be studied, avoided or improved and will call for specially adapted measures and standards specially prepared for magnetic refrigeration appliances.

The thermodynamics part also needs large efforts to make scientific and testing work of different groups comparable. The exergy analysis outlined in this article could be a cornerstone of such considerations. The presented theory should be further developed and graphical methods should be worked out and applied to make the complex energy and exergy fluxes more visible.

Models how to quantify energy production costs for different numbers of units per year and the energy demand of a magnetic refrigerator, heat pump and energy conversion machine are in the competence of economists working together with machine designers. Valuable contributions to a future IIR booklet could also come form this sector.

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NOMENCLATURE

Standard

B	Anergy (J)
$\dot{B}$	Anergy flux (W)
COP	Coefficient of performance (-)
E	Exergy (J)
$\dot{E}$	Exergy flux (W)
h	Specific enthalpy (J kg^{-1})
H	Magnetic field strength (A m^{-1})
m	Mass (kg)
$\dot{m}$	Mass flow (kg s^{-1})
N	Number of thermodynamic cycles
p	Pressure (Pa)
P	Power (W)
q	Specific heat (J kg^{-1})
Q	Heat (J)
$\dot{q}$	Specific heat flow (W kg^{-1})
$\dot{Q}$	Heat flow (W)
s	Specific entropy (J $kg^{-1}K^{-1}$)
S	Entropy (J K^{-1})
$\dot{S}$	Entropy flux (W K^{-1})
T	Temperature (K, °C)
w	Specific work (J kg^{-1})

Greek

η	efficiency (-)
ϑ	Tempertaure (°C)
μ	magn. perm. (Web, $A^{-1}m^{-1}$, NA^{-2}, H m^{-1})
ν	Frequency (Hz, s^{-1})
ξ	Exergy efficiency (-)
τ	Time (s)

Indices

amb	Ambient
app	Apparent
C	Carnot
CR	Carnot refrigeration
CH	Carnot heating
dyn	Dynamic
eddy	Eddy currents
el	Electric
elp	Electric pump
f	Fluid
fr	Mechanic friction losses
ffr	Fluid friction losses
g	Generator, generator losses
H	Heating
heddy	Heat gains from eddy currents
hg	Generator heat gains
hm	Motor heat gains
hp	Pump heat gains
hfr	Heat gains from mechanic friction
hffr	Heat gains from fluid friction
htf-m	Heat transfer fluid to material
htchex	Heat transfer cold heat exchanger
hthhex	Heat transfer hot heat exchanger
htm-f	Heat transfer material to fluid
hys	Hysteresis
hhys	Heat gains from hysteresis effect
tot	Total losses
m	Motor, motor losses, material
mag	Magnet
mc	Magnetocaloric material
p	Pump losses, pump
Q	Heat
R	Refrigeration
0	External, vacuum

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