Practical Refrigerated Appliance Design and the Problems Posed To Magnetocaloric Machines

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A consumer product in the modern marketplace is defined by a myriad of requirements, some regulatory, some safety, some consumer constraints and some environmental. The regulatory environment is well understood by original equipment manufacturers (OEM's) in any of the product categories of refrigerated appliances. An example is the energy performance required by the Department of Energy (DOE).

The product must maintain 5^{O}F in the freezer compartment and 41^{O}F in the fresh food compartment with no door openings (NDO). Generally an interpolated performance from the mid-mid and warm-warm control settings is used since exact settings are not possible. The test was derived as a surrogate of performance at normal indoor temperatures and normal usage. NDO is much more reproducible than an actual door opening schedule. The test result is the standardized annual energy consumption for comparison to other products in its size class.

Another element of the specification of a product is the requirements of the brand. That is, each company has its own standards, or what the brand stands for. One stands for "value and quality", another, "simply the best". Other brand images are: "Functionality with Style and Economy; "Substance, Style and Reputation."; and, "Quality of Life". Each of these images introduces differences into the specifications that drive testing and evaluation.

In addition to this each company has a complement of tests they perform to meet internal standards or external performance ratings such as the space stars that are awarded in Europe or Energy Star® in the United States.

The Specification Challenge

In order to build a refrigerator for commercial distribution the governing document of design is the technical specification. The specification consists of all the environmental factors, food storage factors and human factors within which the product must successfully function

Table 1 provides a summary of typical environmental and performance settings under various usage conditions for the market in the United States (US). Some are mandatory tests required by a regulation or rating agency while some are simply voluntarily imposed performance unique to a brand or company. The latter have to do with brand image or company risk management.

The real import of these requirements to scientific inquiry is that determine the thermodynamic performance envelopes of the components that provide the desired consumer effect, "Cold".

As can be seen from Table 1 each of the performance requirements in the specification whether regulatory or voluntary imposes a unique set of source and sink temperature along with differing performance expectations.

They also describe the competitive environment of any potential disruptive technology. That is, it is not likely that the specification will change simply because a "green" or "greener" technology has been created; source and sink temperature must remain the same. Heat exchanger technology may improve so that delta T's are reduced by half but that will have no impact on the source or sink temperature, only the required lift.

Summary Thermal Specification

requirement	condition	Test parameters	purpose	consequences of deviation
Interior environment for safe food storage "Normal Range"	Fresh 1 > 5°C Frozen -18 > -12°C	all	for safe shelf life of food; meat, poultry, dairy, fruits and vegetables Long term keeping of meat, vegetables, processed fruits, bread and other food stuffs	Dairy ½ life for each 1°C above 5°C Softening, skinning Bread stales rapidly with cycling above -7°C
Target interior temperatures for DOE energy test	Fresh 4.5 °C Frozen -15 °C	32°C NDO	Simulates normal household temperatures but with usage. Removes ambiguity of schedule.	
Holding Hot ambient	Within normal	32°C NDO	Simulates normal household temperatures but with usage Verifies operation in outdoor or unconditioned space as is often encountered in tropics or lower income housing	Unit is incapable of performing basic purpose.
Holding Normal ambient	Within normal	21°C NDO	This is the normal kitchen environment and low usage keeping condition	Expectation is perfect holding with long shelf life anything else is product failure.
Holding Cold ambient	Within normal	10°C NDO	This is the outdoor, garage or set-back vacation ambient condition for holding load	Two week holding is to be expected Humidity can be a factor
Heavy Usage (Door openings with high temperature and high humidity)	Within normal 5°C Maximum rise in frozen section	32°C 80% RH with door openings * (32°C/90% RH w/door opening) Most extreme test condition observed	This is a maximum test of all systems. Air flow, frost management, reserve capacity, load stability, stratification, door seals, etc	This gets to consumer satisfaction When will the unit fail to "work fine"?
External Sweat	Dry	30°C 80% RH *	Standing water on the unit is destructive	Early failure of finishes and onset of corrosion. Potential safety issues.
Dust	Within normal	32°C or another temperature at company's discretion	Demonstrate successful operation in unseen unclean environment Verify compressor protection	Compressor tripping damages the windings of the compressor and degrades life of the unit. Food spoilage increases
Maximum pull-down	Within normal temperatures from ambient in less than a specified time	32°C or another temperature at company's discretion	Impress the consumer that the unit is powerful When installed the unit is pulled down ready to use within an acceptable time.	Indicates insufficient refrigerating capacity, A psychological or real issue.
Excess Capacity	Minimum temperatures reached	43°C	Verify unit has sufficient capacity to provide effective refrigeration for load while accepting a new warm load, for instance, from the market.	Internal temperatures drift high and cause spoilage.

* Temperatures, schedules and durations are company dependent since these kinds of tests are optional and have to do with the company's standards for brand.

Table 1: Design conditions for domestic refrigerator. Though not all the individual specifications are included these are some of the anticipated or boundary conditions within which an appliance must operate effectively. In Europe similar tests are run to establish badges or ratings for storage quality as part of the product certification.

If the goal is to reduce energy consumption while the product specification remains the same then any disruption in the marketplace for energy consumption must greatly improve the performance of the device while meeting all the other performance requirements.

How much better the efficiency of electrical utilization must be is a matter of risk and reward. The benchmark will always be the incumbent technology. The disruptor will need to exceed the incumbent's performance sufficiently to mitigate risk. Risk will be discussed later in some depth.

Carnot Entitlement and Actual Performance

The mathematics of the Carnot cycle is well understood. The basic relationship depends on the observation that the best such a system can perform is to have heat exchangers that can exchange the heat with zero temperature difference and isentropic compression and expansion. Imposing such a condition reduces the COP for Carnot refrigeration (COP_R) to:

$$COP_R = \frac{1}{\frac{T_H}{T_C} - 1} \qquad \text{Eq 1}$$

Where T_C and T_H are source and sink temperature respectively, Equation 1 is easily plotted for all combinations of source and sink. Figure 1 below shows COP_R plotted for source temperature and some of the most common sink temperatures in cardinal values. One of the most common sink temperatures for all home appliances and space conditioning testing is the $32^{O}C$ ($90^{O}F$). We will approximate that temperature with the $30^{O}C$ ($86^{O}F$) line below and plot some common appliance operating points on the chart. The alternate definition of COP is, "desired effect divided by the cost to produce the effect."

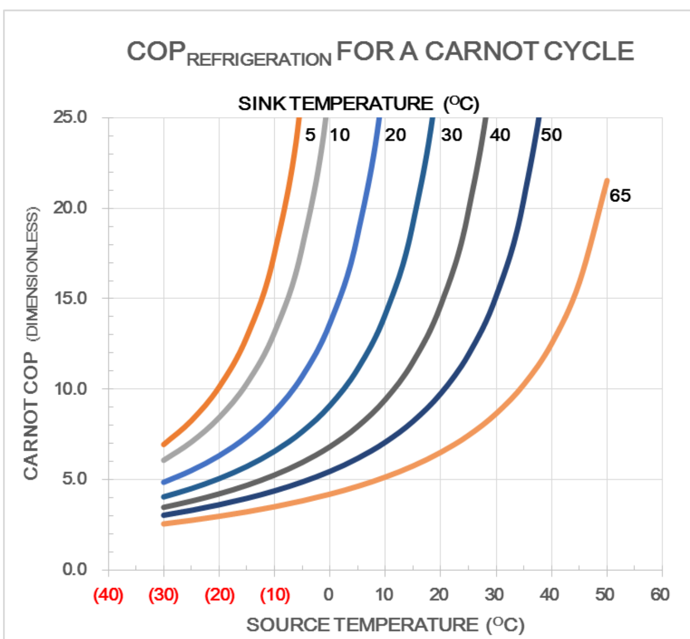

Figure 1: Design space for a refrigerator operating between a source and a sink. A parametric plot of $COP_{REFRIGERATOR}$ using the Carnot cycle as the ideal cycle

Some Observed Coefficients of Performance

	COP observed			Carnot COP			
	Bene effect Watts	Cost in energy Watts	COP	T_H °C	T_C °C	COP_C	Φ % of Carnot
Compressor on test	219.7	100.0	2.2	32.2	(17.8)	5.1	**43%**
Refrigerator in use	131.8	79.8	1.7	21.1	(17.8)	6.6	**25%**
Beverage Cooler	65.9	12.1	5.5	21.1	7.2	20.2	**27%**
Air Conditioner	3,516	750	4.7	43.3	15.6	10.4	**45%**
Commercial Freezer	14,064	8,000	1.8	32.2	(23.3)	4.5	**39%**

Table 2: COP's of various residential appliances using vapor compression refrigeration. "Bene" above is an abbeviation for Beneficial.

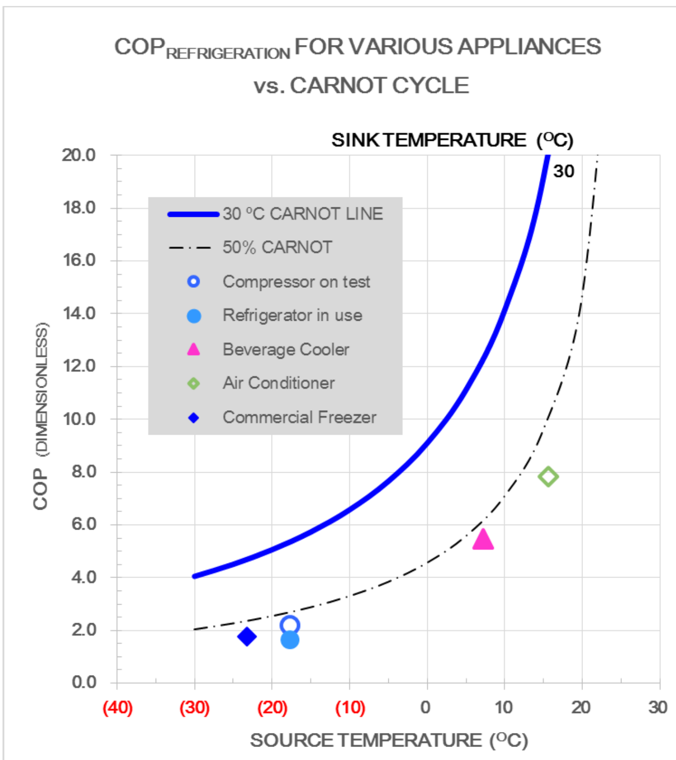

Figure 2: plotting actual performance vs the Carnot entitlement line of various household appliances. Notice that vapor compression appliances run less than 50% of Carnot as shown above and in Table 2. Especially note the derating of a refrigerator-freezer COP from its compressor COP in calorimeter testing.

By measuring the beneficial effect produced by these appliances and measuring all the energy that enters the product Table 2 can be constructed and the resulting data points plotted on a Figure 2, similar to Figure 1.

The right most column of Table 2 is the ratio of observed COP to Carnot COP at the same source and sink temperatures. This ratio is called the normalized COP symbolized by the Greek phi, "Φ".

Reducing the plotted sink temperature lines on Figure 1 and plotting the actual COP's for the above appliances on the COP chart it can be seen that vapor compression (VC) operates at about 33-45% of Carnot generally as shown in Table 2 and plotted in Figure 2. Over the last 40 years VC systems have come from 20-25% Φ to their present level.

Today, high efficiency VC systems for home appliances perform in the 40-45% range of Carnot regardless of the source temperature. It is also generally true that higher COP's are observed with larger compressors and system capacity though all. Depending on compressor selection, beverage coolers seem to have the widest range in performance since they involve low loads and small, inefficient compressors.

If heating is the desired effect of the refrigeration cycle the COP shifts 1 unit larger. In the source and sink range employed by household appliances that shift can range from 25 to 5% depending on the source or cold temperature.

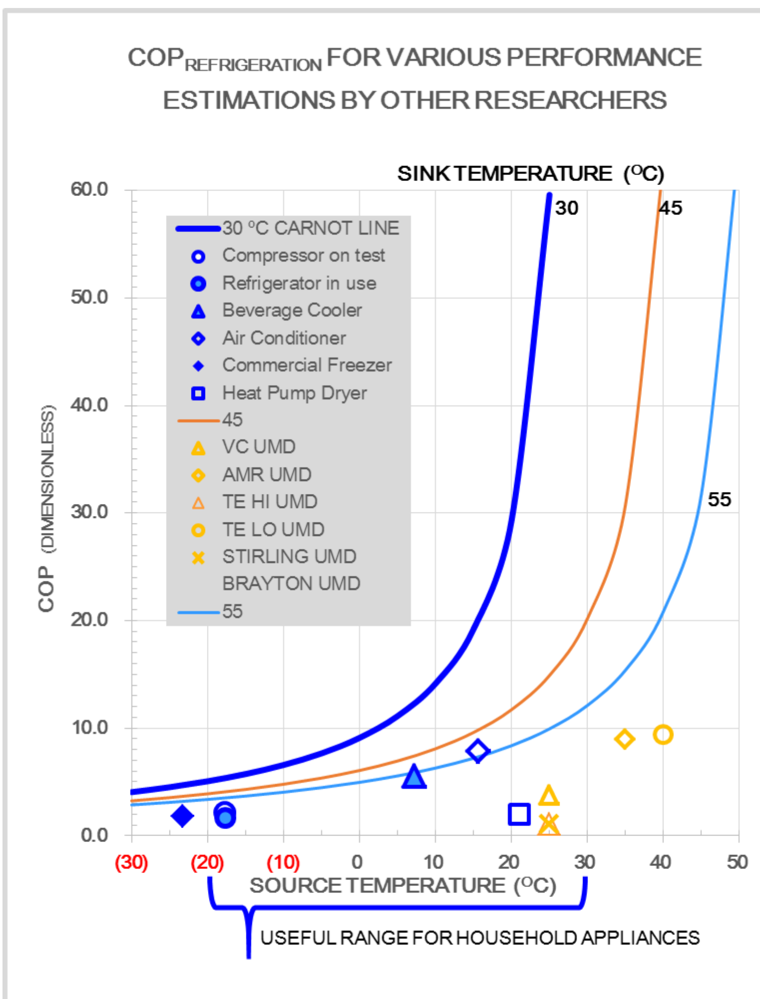

Figure 3: COPs reported by various researchers and for various appliances in the retail marketplace.

Recently Qian et.al. calculated exergetic energy for a number of potential cycles factoring in losses and reached similar conclusions. Their work is illustrated in Figure 3. Their results are supported by calculations performed by Abdellaziz, O. at Oak Ridge National Laboratory (ORNL)..

Ratio to Carnot as a Universal Expression of Performance

As can be seen from figure 3 the expression of COP as the performance indicator can have myriad values and meanings. In casual conversation or formal presentation it is obscure at best, misleading at worst and distracting if not stated in context of its hot and cold temperatures. A better approach is to state the performance in terms of percent of Carnot efficiency. The calculation of Carnot or ideal efficiency across so many ideal cycles makes it a universal expression of both performance and losses.

Since for refrigeration most cycles are grounded on their source temperature the improvement of the performance of the device tends to follow a vertical line. The ratio of the actual or present COP to the ideal or Carnot COP shows the progress toward the ideal. Improvements in friction, heat exchangers, motor efficiency, etc. all simply raise the ratio on the same source line.

Interestingly, from figure 3, for all but the heat pump dryer, most existing household vapor compression refrigerated appliances group around the 45% of Carnot value regardless of source temperature.

The alternate definition of COP is the ratio of desired benefit (or beneficial effect) to the power consumed to create that benefit. Since the application of the refrigeration system is to a characteristic source temperature and the desired benefit is a product of the heat load the byproduct of operation of the thermodynamic machine is the power consumed. Therefore, the device with the highest COP or Φ is the most efficient. Where the driving energy form is electricity, then the highest Φ has the lowest electrical consumption.

The Basic Elements of Magnetocaloric Design

Span

The community has been at the room temperature magnetocaloric task for nearly 20 years now. It started with Gadolinium. We have found several other materials that seem to work. We have been working them to improve basic response. For first order materials the general response is limited to approximately $2^{O}C$ at 2 Tesla yielding about $6^{O}C$ span for a single material. Gadolinium has a slightly higher ΔT response but over a very broad span approximating $20^{O}C$. The top of the gadolinium response is about $27^{O}C$ or $300^{O}K$.

The most useful cold chain product of the refrigerated appliances is the combination refrigerator-freezer. It is possible to make refrigerator only appliances. However, they only serve to stage "fresh" foods for consumption and provide no real buffer for convenience to supply. Separate products merely double the cost or more and do not alleviate the span issue. From table 1, using the worst case maximum pull down sink temperature (T_H) is $43^{O}C$ and source temperature (T_C) is observed to be $-18^{O}C$ giving an approximate span of $60^{O}C$.

However, the difference between source and sink is not the reality. Source and sink are the T_C and T_H for calculation of Carnot efficiency, but an appliance is not an ideal machine. It has real heat exchangers that also need a temperature difference to work. Since heat flows downhill figure 4 shows the impact of heat exchangers on span.

As can be seen from figure 4 the temperature difference at the heat exchangers extends the ideal cycle span from source and sink to rejection to absorption temperatures.

In today's plate fin technology, air to refrigerant heat exchangers require 7-10^{O}C of temperature difference to transfer the heat to air. But those have two phase refrigerant flow where most magnetocaloric machines are single phase liquids, normally water based. Adding these approach temperatures to the previous span means that an actual span of 80^{O}C may be necessary to meet the most extreme test conditions.

The conclusion to be reached from all this study is that staging is necessary to cover a practical span. Little is presently known about staged spans. We are just now beginning to learn about them. We know that for a single material a span of nearly 6^{O}C can be observed. But when placed in a cascade the effective span of a single stage may be only 2^{O}C or less in order for power to flow from one stage to another.

In a session keynote of Thermag IV Dr. Andrew Rowe demonstrated the challenging conditions for effective stage interaction.

For normal operation in a conditioned kitchen the span would be 62^{O}C. This compared to a seldom seen 80^{O}C span of the most extreme test condition. But the stages for the worst must be there. That is a 33% overhead in both pumping power and magnetization power. Will all that regenerator energy be wasted? Certainly the pumping power will be. And then there is the heat transfer and how we prevent adverse effects of large span.

Few researchers have actually explored freezing temperatures for these machines. For water based coolants a significant power problem is presented.

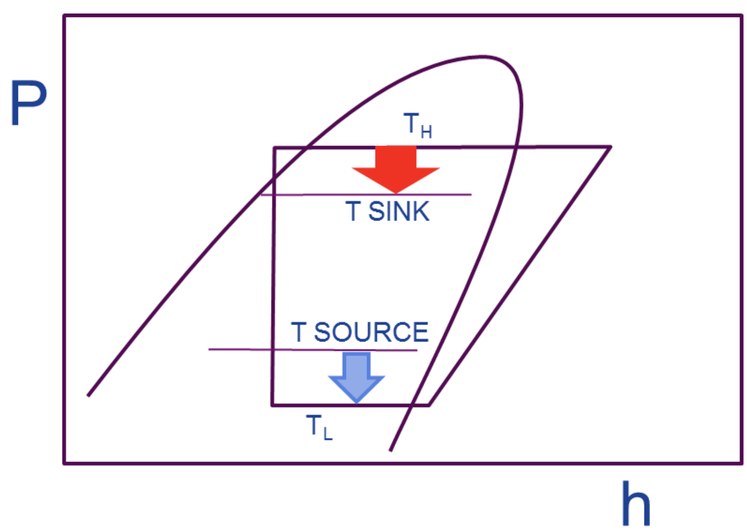

Figure 4: The relationship of rejection temperature or the true T_H to the sink temperature and the absorption temperature or T_L to the source temperature for a vapor compression cycle.

All this simply illustrates that we still have a long way to go to understand the interaction of specification with regeneration and the magnetocaloric machine.

Capacity

Power or capacity of the magnetocaloric machine is determined by two factors, the amount of magnetocaloric material and strength of the magnetocaloric effect. A unique property of a magnetocaloric machine is that its highest power is at zero span and no power at maximum span. The best operating point is somewhere in between.

So to design to deliver cooling power one must consider the regenerator span to support capacity at the design span. There must be more span in the regenerator than the design span of the system. So considering the example span above, 80^{O}C, the true regenerator span may need to be 100^{O}C.

More span means more material. To prevent the addition of material, which also adds pressure drop, the amount of material is designed short causing attempts to run more span to "stall" the machine and break down the cascade. It is simply unable to reject enough heat to sustain the cycle as shown in the line labeled "BD" or "breakdown" span in figure 5.

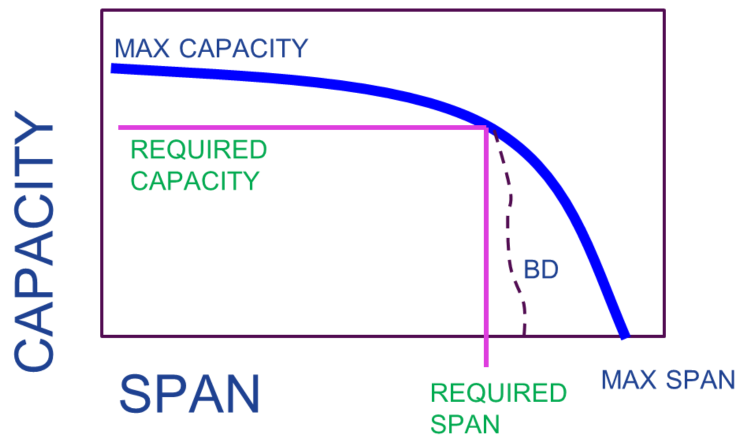

Figure 5: Typical capacity-span curve for magnetocaloric machine. Note that max span must exceed design span and that max capacity must exceed design capacity.

The required capacity is determined by the construction of the refrigerated enclosure. For instance, a large capacity bottom freezer unit may have 620 liters and have a 125 Watts load in a 32^{O}C ambient. Now the designer may choose to design for the 125 watts. This would mean 100% runtime. If the owner opened the door the load would immediately exceed the capacity of the machine. The unit would never catch up. There are two strategies to solve this: more capacity and cycle the unit in normal mode, or variable capacity made possible by speed control or plumbing features or a combination of the two.

For instance if the designer provided a 150 or 175 watt capacity allowing a run time of 80—70% there is enough excess capacity to allow occasional perturbations of load. This extra capacity can be provided by either more material or more speed and be used to manage surges of load such as a large load of warm food or pulling down after a setback or off period.

Efficiency

Span proves the device can do a practical job. Capacity proves that you can have a product. Finally the product must be made competitive. To be disruptive, the product must be more efficient than any other competing technology. If it intends to displace vapor compression, it must be more efficient than vapor compression.

Magnetocaloric inefficiencies

In the design of vapor compression compressors an early technique employed was to categorize and quantify the losses experienced by the compressor in application. The categories of losses such as Coulomb losses were further broken down into piston friction, rocker pin friction, etc. until all the identifiable loss sources could be named and quantified. Then, using Pareto prioritization as shown in figure 6 system the losses were attacked in order of priority by magnitude.

These techniques have been used for over 40 years in the best compressor engineering groups. The result is compressor efficiencies approaching 70% with motor and power conditioning approaching 95% each. There is less room to improve the system today than even 10 years ago. And the cost to compressor production is getting higher for each additional percent of performance improvement.

In Figure 6 note especially the valve losses between the two devices. One being much smaller than the other, they do however never go away. Likewise in magnetocaloric machines valves play a key role in machine operation. Though magnetocaloric does not have the same types of viscous and compressibility losses, it nevertheless has viscous losses which must be considered. Depending on choices of tubing elastic losses may replace compressibility losses.

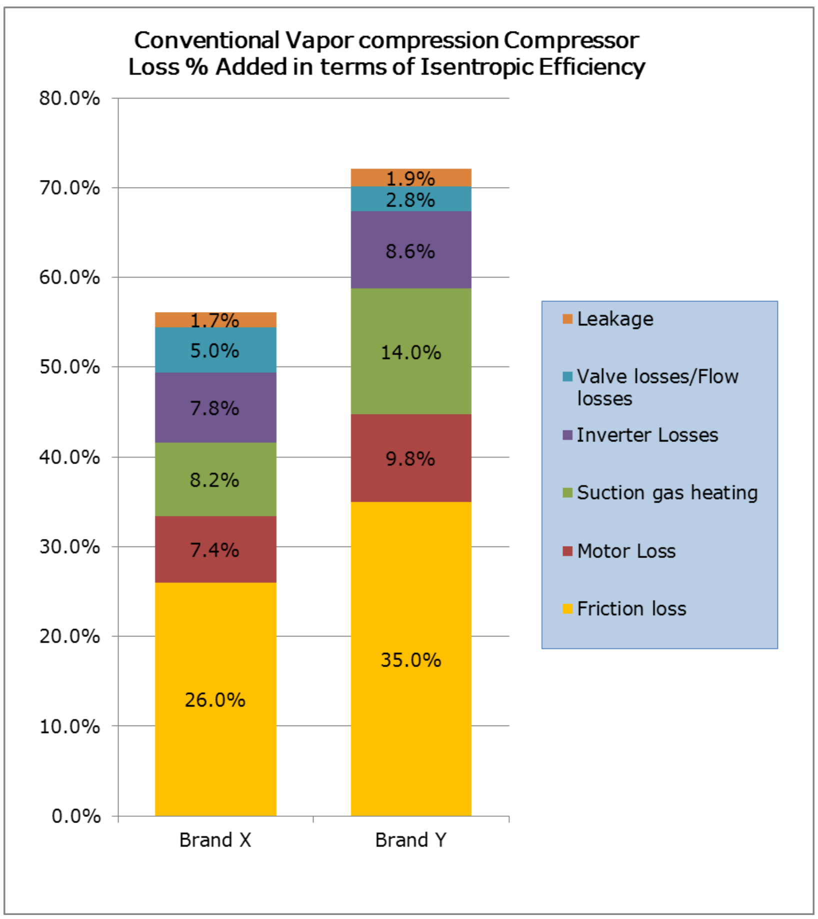

Figure 6: The ranked effects of various losses in two vapor compression compressors plotted with respect to Isentropic efficiency. The ranking allows prioritization for work in improvement. Source: Internal work of Heat Engines Design Team.

The promise of magnetocaloric refrigeration was that the basic magnetocaloric effect was large for the energy to produce it. Early expectations were 50% improvement of COP. The question that needs to be asked is: “By only subtracting losses which are VC losses without adding back in magnetocaloric losses what are we overlooking?" In most 1-D simulation efforts the collateral effects of space and mechanism are neglected. In many pumping power, pump and motor efficiencies are neglected. Many early papers completely disregarded temperature lift to affect heat exchange. Because in most cases single phase heat exchange is required additional lift to account for temperature glide of single phase heat transfer is completely overlooked.

Qian et.al, have developed presentation of losses similar to figure 6 in terms of decrements to Carnot COP. They use a normalized COP or ratio of residual COP to COP_{CARNOT}, or Φ. The results should be quite sobering to the magnetocaloric community. Illustrated below in Figure 7 is a typical of buildup of losses for Magnetocaloric refrigerator by their method. Their result for an Active Magnetic Refrigeration (AMR) system is shown in figure 7 below:

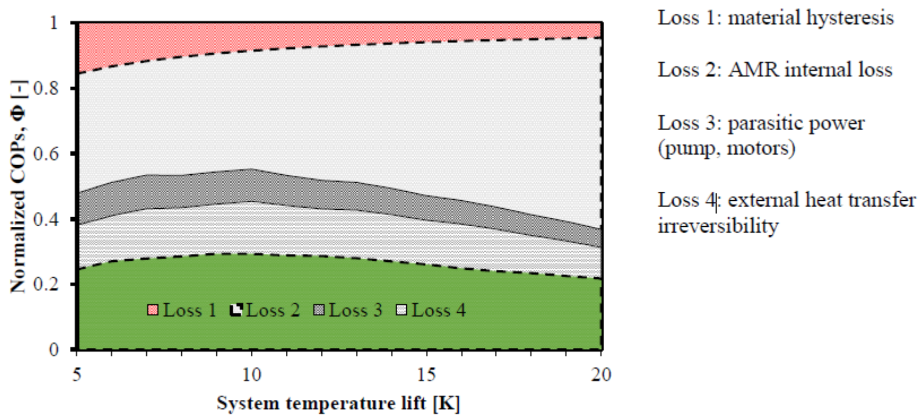

Figure 7: Loss chart from Carnot for an AMR system by the method of Qian et.al. The green region boundary represents the residual fraction of Carnot after the losses presented in the text. Losses and residual are plotted vs. temperature lift or "span".

As an example, consider variation of amplitude of response vs. field strength. Each material compound has an expected performance based on the intrinsic properties of the material and its

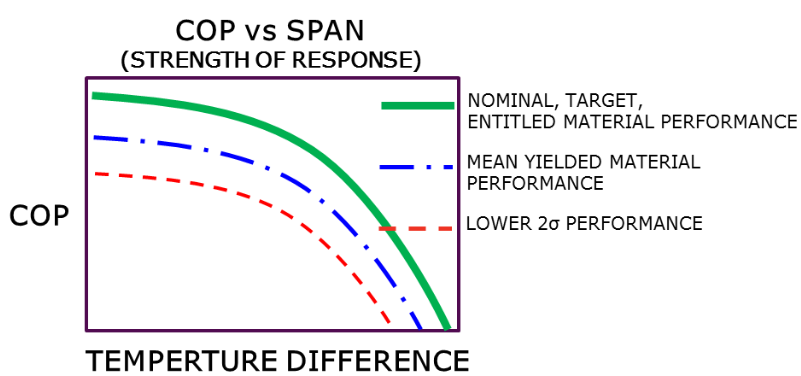

Figure 8: Characteristic response of a magnetocaloric system based on the statistical properties of the manufacturing yielded material. The green "NOMINAL" line represents the entitlement line or the upper limit of performance. The other lines represent the mean and lower bounds of performance.

constituents. It is common that the compound actually created, is sometimes off. The result is either a different temperature or lower amplitude response. Considering just the effect, the characteristic performance variation curve of Figure 8 is observed from simulation:

The problem with this variation in performance is that for design purposes, the lower 2 or 3 sigma of performance must be what is designed for and with. The degradation in both span and COP means that more material will be used, and more field will be called for. The resulting design will be overdesigned.

In order to properly understand this inefficiency and provide the most efficient design there really needs to be process research in how to yield tighter and tighter distributions; likewise, more precise centering of response. There can be statistical, material and process research in looking for ways to manage the probabilistic mixing to get the correct span management and regenerator performance. There are many more possible research topics in this work.

There are massive opportunities in machine design. The realization of moving elements with complex thermal and mechanical details requires sophistication and profound knowledge. Clearance management, and speed management all work together to make a magnetocaloric system complex.

Qian et.al, posited that the cause of failure in general success of Stirling cycle engines was "…the complicated mechanical-thermal coupling design they required." There may be reasonable suspicion that the same holds true in magnetocaloric refrigeration.

Table 3 below lists some of the inefficiencies that must be accounted for.

The impressive nature of Table 3 is the plethora of research and engineering opportunities available. Like vapor compression and Stirling Cycle, the research for a promising technology is endless. Especially if one is willing to work any and all the issues for success.

Cost inefficiencies

While there are many technical challenges yet to overcome, they are matched in severity by the cost inefficiencies. Any time a technology is allowed 100 years to improve and mature, it will inherently hold a cost advantage over a newly proposed technology. It will simply be stated here that the minimum competitive economies of scale for such machine devices is 1,000,000 units per year. Some maintain for compressors, the minimum economic annual production is rather 3,000,000 units per year. Production far short of that number multiplies per unit cost.

The whole competitive challenge

To effectively disrupt technology three things are necessary

1. Performance covers the specification envelope including anticipated off design conditions.
2. Technical and Commercial Risk is mitigated at or below present technology
3. Cost is at or below present technology plus any credit for performance or risk mitigation

Conclusions

The first conclusion to be reached is that in most all cases the spans assumed in magnetocaloric benchmarking and development are inadequate to address the demands of real product specifications. It is recognized that starting small with perhaps a niche product with limited

Inefficiencies in a Magnetocaloric Machine

inefficiency	description	Engineering problem	Scientific work needed
Motor efficiency	Efficiency of power conversion in the motor	Improvements	
Pump efficiency	Efficiency of power conversion of pump to fluid power	Improvements	
Pumping losses	Resistance to flow in regenerator due to variability in bed configuration		Pressure drop with generation CFD modeling
Mechanical friction	Friction in the moving parts of the magnetocaloric machine	Experimentally discovered and improved	
Heat gain to cold flow	This is the principle thermodynamic loss in a magnetocaloric machine Directly robs cooling capacity		
Heat loss from hot flow	Impacts the starting temperature on hot flow. Introduces inefficiencies in the regenerator		
Dead volume	In a pulse flow system this is a direct loss as unutilized effect In a circulating system this gives risk of heat transfer loss		Effects and recovery CFD
Heat exchanger loss	irreversibility of temperature difference to effect heat flow	Design	R&D to reduce ΔT
Field loss	Magnet gap size due to relative motion and manufacturing tolerances	Design	FEA and field modeling
Flux loss	Proximity of erroneous ferrous flux path to magnetic circuit		FEA and field modeling
Idle cycle			
Material variation	Design must perform with worst material. Multiplies material amount and number of stages	Manufacturing and engineering in concurrent design	Compounding robustness and precision
Reliability	Material degradation in effect or structure with use	Increasing material density	
Power	Maximize MCE and cooling power		
Accuracy and precision	Proper composition to multi-stage regenerators		Power continuity Stage to stage heat flux
Basic magnetic strength	Variation in unit-to-unit and lot-to-lot magnetic strength		
Effective field strength	Degradation of field strength from magnet strength by the magnetic circuit design	Magnetic circuit design	Magnetic field creation Magnetic configuration FEA Stronger PM's
Effective field profile	Deviation of actual field profile from ideal square wave		

Table 3: Inefficiencies in a magnetocaloric heat pump. All the items above represent opportunities for loss or failure to deliver full anticipated cooling power to the system. Some are well understood or the engineering to control or reduce them well known. Several however, still require significant material, thermodynamic or physical research.

Note: The table is incomplete and can serve as a framework for future workshops span is advised to break into the market. However, all products in those classes already enjoy mature, highly competitive and cheap economies of scale. Enough so, that there is little opportunity for advantageous pricing. People may need to be paid to take such products.

COP's still lag significantly below vapor compression with much work yet to do. Some are advocating relief from the established performance standards for domestic refrigeration. Sale of large enough numbers to establish economies of scale would be counterproductive to the objectives of environmental regulation. Sufficient sales to gain needed experience in the marketplace would benefit only the manufacturer since the price would be outrageous to the consumer. Consequently the community must continue to invest in breakthrough efficiency and improving COP while simultaneously improving cost of production. Innovation and development directed by such maps as shown in Table 3, continuously improved through community workshops.

Percent of Carnot COP has emerged as a desirable figure of merit for magnetocaloric systems for several reasons. It removes the ambiguity of source and sink temperature inherent in a naked COP calculation. Every manufacturer knows the range of their devices and the ratio to Carnot expresses unambiguously the state of progress of any machine. It provides a consistent means of comparison with other technologies.

In order to make the improvements necessary for disruption significant broadening of research efforts into the inefficiencies associated with magnetocaloric machines will be needed. Though the vapor compression compressor has been in service for over 100 years and the hermetically sealed compressor for over 60 years there is still much research and engineering being performed to make them more efficient, more economical and smaller in size. This must be the case with magnetocaloric as well. We know the upper ends of entitlement. We must now push from the bottom to approach that entitlement.

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