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APPLICATIONS OF MAGNETIC «POWER PRODUCTION» AND ITS ASSESSMENT

A FEASIBILITY STUDY

Final Report

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INHALTSVERZEICHNIS

ZUSAMMENFASSUNG

Das Hauptziel dieses Projekts war es verschiedene Systeme der Wärmenutzung aufzuspüren in denen die magnetische Leistungsgenerierung - oder besser die «magnetische Energie-Konversion» - eine Alternative zu konventionellen Energie-Konversions-Technologien darstellen könnte. Magnetische Energie-Konverter-Systeme, basierend auf Permanentmagneten oder supraleitenden Magneten, wie sie in einem deponierten Patent der Universität für Angewandte Wissenschaften der Westschweiz (Abteilung HEIG-VD/IGT/SIT) beschrieben sind, werden vorgeschlagen und ihr Verhalten für verschiedene Temperaturen von Wärmequellen, magnetische Feldstärken und Frequenzen der rotierenden porösen Wärmetauscher untersucht. Eine spezielle numerische Analyse, beruhend auf einem thermodynamischen Modell, erlaubt es thermodynamische Wirkungsgrade, Exergie-Wirkungsgrade, totale Massen und totale Volumen von Maschinen zu bestimmen.

Resultate zeigen, dass die Wahl des Betriebsfluids einen merklichen Einfluss auf den Wirkungsgrad von magnetischen Energie-Konversions-Maschinen hat. Gute Exergie-Wirkungsgrade werden für Temperatur-Niveaux unterhalb 120°C beobachtet. In diesem unteren Bereich wird Wasser als Betriebsmedium eingesetzt. Der Exergie-Wirkungsgrad hat eine merkliche Abhängigkeit von der magnetischen Feldstärke. Die Resultate zeigen, dass magnetische Feldstärken von 1.5 Tesla oder höher angewendet werden sollten. Geringere magnetische Felder werden zu kleinen Exergie-Wirkungsgraden führen. Für hohe Temperaturen der Wärmequellen (z.B. von 120°C bis 350 °C) sollten andere Fluide als Wasser verwendet werden. Es wird betont, dass solche Fluide (üblicherweise verschiedene Sorten von Ölen) grösseren Druckabfall verursachen. Wenigstens ist es positiv, dass die Viskosität dieser Fluide als Funktion der Temperatur stark abnimmt. Über 350°C werden in Energie-Konverter-Maschinen normalerweise Gase verwendet. Solche Systeme zeigen nur dann sinnvolle Einsetzbarkeit, wenn supraleitende Magnete eingesetzt werden. In diesem Bereich ist es auch möglich spezielle Metalllegierungen anzuwenden (z.B. Bi-Pb-Legierungen). Diese verlangen spezielle Sicherheitseinrichtungen um Verfestigungen zu vermeiden. Supraleitende Magnete sollten eingesetzt werden, wenn sehr hohe Felder (über 2.5 Tesla) verlangt werden. Dies ist ökonomisch nur sinnvoll in grossen Systemeinheiten, wegen der reduzierten relativen Kosten und des Energieverbrauches des kryogenen magnetischen Quellsystems im Vergleich zu den totalen Kosten und dem totalen Energieverbrauch der kompletten Anlage. Die Resultate dieses Berichtes zeigen, dass der Anstieg des Wirkungsgrades, beeinflusst durch die magnetische Feldstärke, gegen grössere Felder hin konvergiert. Die Schlussfolgerung ist deshalb, dass supraleitende Magnet-Systeme auf magnetischen Feldstärken um 10 Tesla basiert werden sollten.

Eine hohe Betriebsfrequenz reduziert die totale Masse und das totale Volumen der Apparatur. Sie beeinflusst auch den Wirkungsgrad, welcher mit steigender Frequenz stark abnimmt. Dies gilt weitaus mehr für Systeme basierend auf Permanentmagneten als für solche mit supraleitenden. Bei hohen Temperaturen der Wärmequellen hängt der Wirkungsgrad weniger von der Rotationsfrequenz ab. Ein anderer wichtiger Einflussfaktor ist der Volumenanteil von magnetokalorischem Material der porösen Struktur der Wärmetauscher. Flüssig/Flüssig und Gas/Flüssig-Anlagen sollten mit Rädern, welche 30 % Volumenanteil haben, bestückt werden, währenddem für Gas/Gas-Systeme der Volumenanteil 10 % nicht wesentlich übersteigen sollte.

Zurzeit werden die meisten magnetokalorischen Materialien für Anwendungen in der magnetischen Kältetechnik um Raumtemperatur entwickelt. Es gibt nur wenige Forschungsaktivitäten, die der Anwendung von Materialien in magnetischen Energie-Konversions-Maschinen dienen sollen. Solche Materialien müssen eine hohe Curie-Temperatur aufweisen. Die Verfügbarkeit der Materialien ist der erste Grund warum diese Studie vor allem Anwendungen mit einem tiefen bis mittleren Temperatur-Niveaux gewidmet ist. Ein zweiter Grund ist, dass die Stoffwerte der Arbeitsfluide bei höheren Temperaturen als 350 °C zu einem eher komplexen Systemaufbau führen, vor allem im Falle dass flüssige Legierungen als Arbeitsmittel eingesetzt werden.

Das wohl wichtigste Resultat dieser theoretisch-numerischen Studie ist, dass die magnetische Energie-Konversion die konventionellen Technologien in mehreren Aspekten und in verschiedenen Bereichen schlagen kann. Dies ist speziell der Fall, wenn Wärmequellen mit tiefer Exergie auftreten. In solchen Fällen sind die konventionellen Systeme nicht wirksam genug um ökonomisch arbeiten zu können, wo hingegen die magnetische Energie-Konversions-Technologie zu einer höheren Exergie-Effizienz führen wird und daher zu günstigen Einsatzbedingungen für gewisse Anwendungen führen kann. Der Nachteil ist der geringe Carnot-Wirkungsgrad (obere Schranke der Wirkungsweise) der Maschinen, welche mit so tiefen Niedrig-Temperatur-Wärmequellen arbeiten. Dagegen ist der Vorteil, dass die Verfügbarkeit solcher thermischer Energie oftmals fast unbeschränkt gross ist. Ein anderer Vorteil von magnetischen Energie-Konversions-Maschinen ist, dass sie mit Temperaturdiffferenzen, eigentlich unabhängig von den beiden Temperatur-Niveaux der Quelle und Senke, arbeiten können.

Am Ende des Berichts, in einer Übersicht, werden verschiedene Systeme, die unter verschiedenen Bedingungen arbeiten, aufgelistet und bezüglich deren Potential für eine Anwendung der magnetischen Energie-Konversion bewertet. Best geeignet für eine erste Umsetzung in die Praxis ist ein System mit Permanentmagneten und einer Wärmequelle der Temperatur 120 °C.

RESUME

L'objectif principal de ce projet résidait dans la recherche de systèmes thermiques où la génération d'énergie par effet magnétique, plus communément nommé: « système de conversion d'énergie magnétique », offrent une alternative aux systèmes de conversion d'énergie conventionnels. Des générateurs d'énergie magnétiques basés sur l'utilisation d'aimants permanents ou supraconducteurs sont proposés et analysés. L'étude est réalisée pour de nombreuses températures de sources de chaleur, amplitudes de champs magnétiques et fréquences de rotation des échangeurs de chaleur poreux. Ces objets sont présentés dans une patente déposée par l'école d'ingénieur et de gestion du Nord-Ouest Vaudois, (HEIG-VD/IGT/SIT Division). Une analyse numérique spéciale basée sur l'utilisation d'un modèle thermodynamique permet la détermination de l'efficacité thermodynamique, l'exergie, la masse globale, ainsi que le volume d'une telle machine.

De nombreux résultats montrent que la sélection de fluides de travail possède un impacte sur l'efficacité des machines de puissances à effet magnétique. De bonnes efficacités exégétiques sont observées pour des températures en dessous de 120 °C. Dans cette fourchette d'utilisation, le fluide de travail est généralement caractérisé par de l'eau. L'efficacité exégétique présente alors une dépendance à l'amplitude du champ magnétique. Les résultats montrent que des champs d'induction de 1.5 Tesla ou supérieurs doivent être appliqués. Des valeurs plus faibles conduisent à une efficacité exégétique trop basse. Pour des températures de source de chaleurs élevées (c.à.d. 120 à 350°C) d'autres types de fluides doivent être utilisés. Il est souligné que des fluides, communément utilisés, à savoir des huiles, conduisent à d'importantes pertes de charge. Un aspect positif réside dans la décroissante rapide de leur viscosité avec l'augmentation de la température. Au-dessus des 350°C, les systèmes de conversion par effet magnétique emploient généralement des gaz. De telles configurations présentent une faisabilité uniquement couplées à l'utilisation d'aimants supraconducteurs. Dans cette gamme, l'utilisation d'alliages métalliques sous forme liquide devient envisageable, (alliages Bi-Pb). Un équipement spécial de sécurité empêchant la solidification devient nécessaire. L'emploi d'aimants supraconducteurs est préconisé pour des champs magnétiques de grande ampleur (>2,5 Tesla). Leur utilisation est économiquement viable pour des systèmes de grande dimension grâce à la réduction relative des coûts et à la consommation de la source cryogénique comparée au coût total et à la consommation de la machine dans son ensemble. Les résultats de ce rapport révèlent que l'efficacité croissante influencée par l'amplitude du champ d'induction converge pour de très hauts champs. En conséquence, une valeur avoisinant les 10 Tesla est préconisée pour des systèmes à aimants supraconducteurs.

Une haute fréquence de fonctionnement réduit la masse totale ainsi que le volume du dispositif. Cela influence également l'efficacité; fortement décroissante en fonction de l'augmentation de la fréquence. Ce comportement intervient de manière plus significative pour des systèmes à aimants permanents. Pour des températures de source de chaleur élevées, la dépendance de l'efficacité versus la fréquence devient moins importante.

Un autre facteur d'influence important réside dans la fraction volumique du matériau magnétocalorique dans la structure poreuse de l'échangeur de chaleur. Des stations d'énergie liquide/liquide et gaz/liquide peuvent employer des roues poreuses dont la fraction volumique est de l'ordre de 30%. Les systèmes gaz/gaz ne peuvent excéder les 10%.

Présentement, la plupart des matériaux magnétocaloriques sont développés pour le domaine de la réfrigération à température ambiante. Seul un faible pourcentage des recherches effectuées en laboratoire sont dédiées à la conversion d'énergie. De tels matériaux doivent présenter une température de Curie élevée. La disponibilité en de tels matériaux est la raison majeure pour laquelle ce rapport est dédié aux sources de chaleur à moyenne amplitude. Une raison secondaire est induite par le haut degré de complexité du design conduisant à l'utilisation de fluides de travail opérant avec des sources de chaleur à température supérieure à 350°C.

Le résultat le plus important de cette étude consiste à la capacité de cette technologie à supplanter par de nombreux aspects et domaines les techniques de conversion conventionnelles. C'est particulièrement le cas pour des sources de chaleurs à faible exergie. Pour un tel exemple, la conversion d'énergie par techniques conventionnelles offre une trop faible efficacité pour être économiquement rentable. A l'encontre de cet argument, la conversion par effet magnétique offre un rendement exégétique supérieur et atteint des conditions d'utilisation favorables. Le désavantage réside dans la faible efficacité de Carnot des machines opérant à des températures de sources si peu élevées. Cependant, la disponibilité de telles sources est presque illimitée. D'autre part, le fonctionnement de cette technologie ne repose que sur la différence de température entre sources et non sur leur niveau.

A la fin de ce rapport et en vue d'ensemble, différents systèmes travaillant sous diverses conditions sont listés et évalués dans le cadre d'utilisation de la conversion d'énergie par effet magnétique. Le plus adapté pour une première réalisation pratique est un système avec aimants permanents et une source de chaleur à une température de 120 °C.

SUMMARY

The main objective of this project was to search for different systems of heat utilization where magnetic «power generation systems» - or more accurately named «magnetic power conversion systems» - could present an alternative to conventional power conversion technologies. Magnetic «power generators», based on permanent or superconducting magnets, are proposed and are analyzed for numerous heat source temperatures, magnetic field strengths and frequencies of rotating porous heat exchanger machines as they were proposed in a patent deposited by the University of Applied Sciences of Western Switzerland (HEIG-VD/IGT/SIT division). A special numerical analysis takes advantage of a thermodynamic model, which permitted to determine the thermodynamic efficiency, the exergy efficiency, the total mass and the total volume of such magnetic power conversion machines.

Some results show that the selection of proper working fluids has an impact on the efficiency of magnetic power machines. Good exergy efficiencies are observed for temperature levels below 120°C. In this domain usually water is the working fluid. The exergy efficiency has a pronounced dependence on the magnetic field strength. The results show that magnetic fields with field inductions of 1.5 Tesla or higher should be applied. Lower magnetic fields will lead to too low exergy efficiencies. For high temperatures of the heat source (e.g. 120°C to 350°C) other kinds of fluids than water should be used. It is emphasized that such fluids (usually different kinds of oils) lead to high pressure losses. Positive is that the viscosity of these fluids rapidly decreases with increasing temperature. Beyond 350°C magnetic power conversion systems usually contain gases. Such systems will show a good feasibility only when superconducting magnets are applied. In this range it is also possible to apply special metallic alloys in their liquid state (e.g. Bi-Pb alloys). They require special safety equipment to prevent solidification. Superconducting magnets should be used in cases where very high magnetic fields (above 2.5 Tesla) are required. This is economically feasible only in large scale units due to a reduced relative cost and energy consumption of the cryogenic magnetic source system compared to the total cost and consumption of a complete machine. The results of this report reveal that the efficiency increase, influenced by the magnetic field strength, converges at very high magnetic fields. Therefore, the conclusion is that superconducting magnet systems should be based on magnetic field strengths around 10 Tesla.

A high frequency of operation reduces the total mass and total volume of a device. It influences also the efficiency, which is strongly decreasing with increasing frequency. This behavior is more occurring in permanent-magnet based systems than in superconducting ones. At high temperatures of the heat sources, the efficiency depends less on the frequency of rotation.

Another important factor of influence is the volume fraction of the magneto caloric material in the porous structure of the heat exchangers. Liquid/liquid and gas/liquid power stations should be mounted with wheels containing porous structures having a volume fraction of 30%, while for gas/gas systems the volumetric fraction should not much exceed 10%.

At present most of the magneto caloric materials are developed for an application in the magnetic refrigeration domain around room temperature. Only little research activities of material scientists are devoted to the application of materials in magnetic power generation systems. Such materials must show high Curie temperatures. The availability of materials is the first reason why this report is mainly dedicated to applications with low to medium temperature level heat sources. A second reason is that the properties of working fluids at higher temperatures than 350 °C will lead to a rather complex system design, especially in the case that liquid alloys will be applied as working fluids.

The most important result of this theoretical-numerical study is that magnetic power conversion may beat conventional technologies in many aspects and domains. This is especially the case if low exergy heat sources occur. In such cases conventional energy conversion technologies are not efficient enough to be economically operated, whereas the magnetic power generation technology leads to a higher exergy efficiency and, therefore, may reach conditions of favorable application. The disadvantage is the low Carnot efficiency (upper limit of efficiency) of machines operating with such low-temperature level sources. On the other hand the advantage is that the availability of thermal energy is very often nearly unlimited large. Another advantage of magnetic power generators is that they work favourably with a temperature difference actually independent of the height of the temperature levels of the source and sink.

At the end of the report, in an overview, different systems working under different operation conditions are listed and evaluated concerning the potential for an application of the magnetic power conversion technology. The best suited for a first realization in practice is a system with permanent magnets and a heat source with a temperature of 120 °C.

1. INTRODUCTION

1.1. State of the art

The basic phenomenon of magnetic power conversion is a temperature dependency of the magnetization. If a magnetic material is additionally magneto caloric, a more efficient thermodynamic cycle occurs. To see this, one has to study an adequate thermodynamic process in a *T-s* diagram. If for example a material is in its ferromagnetic state, it will be attracted toward the higher magnetic field. In the case that there is heat added to it, its magnetization decreases. By the heating-up the attracting force field is reduced. As a consequence high-temperature magnetic or magneto caloric material is less attracted by a spatial increasing magnetic field.

In an open thermodynamic system material is moving through a magnetic field. At its entrance it is attracted to the field and it moves in. If it is now heated in the magnetic field region its temperature is increased and its magnetization decreases toward the exit. Therefore, the repulsion force to push it out of the magnetic field is smaller than the corresponding attracting force at the entrance. If the attraction on one side of the magnetic field is higher than the repulsion on the other side, the magnetic material feels a resultant force field that moves the body. In a machine with rectilinear motion, if the resistance of the machine to a movement of the magneto caloric body is known, its velocity can be determined. The product of force times velocity determines the energy rejected per time unit, which is the obtained power of such a machine. In a rotary system the force field leads to a resultant moment. Resistance forces, which can be those of an electricity generator fixed to the axis of a magneto caloric wheel, will determine the equilibrium angular velocity. And here the product of moment with angular velocity is identical to the converted power.

The advantage of applying this method of power conversion is that such systems may also utilize heat of low temperature from many kinds of different heat sources. If the temperature of the source is low, the heat is of low exergy. The advantage of such systems is that it is possible to have a direct conversion of thermal energy into electrical energy without a necessity of additional mechanical devices.

The magnetic power generation is a research domain, which dates back to the late 19th century when the two famous scientists Tesla [3] and Edison [4] deposited their ideas in patents and named the related machines pyromagnetic generators. Their inventions were based on the discovery of Warburg [5], who observed an increase of temperature when he had brought an iron sample into a magnetic field and a decrease when the sample was removed out of it. At this ancient time the permanent magnets were not strong enough and the magneto caloric materials available not enough performing to build economical and practical devices.

There was not much research and development activities until to the 1950's when a large interest of scientists was created by the idea of performing magnetic power generators by applying magneto caloric suspensions as working fluids. Most of this pioneering work was performed by Resler and Rosensweig (see Ref.'s [6] and [7]). However, some single earlier publications than those may be found in the Ref.'s [8] to [11]. In that period ideas and publications were mainly related to the idea to consider magneto caloric suspensions as working substances. There is no evidence that any of these early ideas were transformed to real working prototypes.

Thirty years later most of the publications were related to studies of magneto caloric power generators with solid working materials (Ref. [12] to [14]). In the context of an exponentially growing research and development activity in the domain of magneto caloric materials and magnetic refrigeration the HEIG-VD group rediscovered the interesting idea of magnetic "power conversion". A scientist working on the Curie wheel [15] got into contact with experts of magnetic refrigeration (see Ref. [16] and [17]). The Curie wheel is a small device which contains the characteristic properties of such machines. The input of heat is given by light radiation absorption on the surface of the wheel. Because this surface is very small, the heat input is negligible. And even if the cylinder is held by levitation in its upright position and it shows hardly any friction, it cannot be applied to obtain a reasonable "power conversion". On the other hand it is an excellent device to study some basic phenomenon of this technology.

The development of permanent and superconducting magnets has been significantly improved compared to the time when first research activities in the domain of pyromagnetic generators occurred.

At present new developments in material science, concentrating on the creation of magneto caloric materials, exhibit the magneto caloric effect and "giant" magneto caloric effect, which occur at different temperature levels (also above the level of refrigeration) with improved physical properties.

A great advantage of magnetic power conversion machines is that their operation is mainly based on the temperature difference of the temperatures of a heat source and a heat sink and not so much on the height of these two temperatures. Furthermore, in this report it will be shown that this kind of systems present an excellent possibility of converting low exergy heat into mechanical work or even electricity and this with a good exergy efficiency.

Figure 1 shows an analogy between a conventional power production system on the left and a magneto caloric one on the right-hand side. If as a magnetic field source permanent magnets are applied, then the work - which is obtained from such a device - comes from the attraction of magneto caloric material into the magnetic field region. This attraction is stronger, if the magneto caloric material is in its ferromagnetic state, thus having a high magnetization. A high magnetization of magneto caloric material usually requires a low temperature. This is why cooling or heat rejection is required in the magneto caloric material before it enters the magnetic field region. Work input into the magneto caloric power machine may be due to the externally induced magnetic field (in permanent magnets this does not occur) or due to the force, which needs to be overcome in order to "pull" the magneto caloric material out of the magnetic field. This force is rather small if the magneto caloric material is in its paramagnetic state. Therefore, the material should be heated in the magnetic field in order to reduce its magnetization toward the exit. In an open system the difference between the two forces at the entrance and exit - with a certain "mass flow" of magneto caloric material over the two boundaries - leads to the magneto caloric power production.

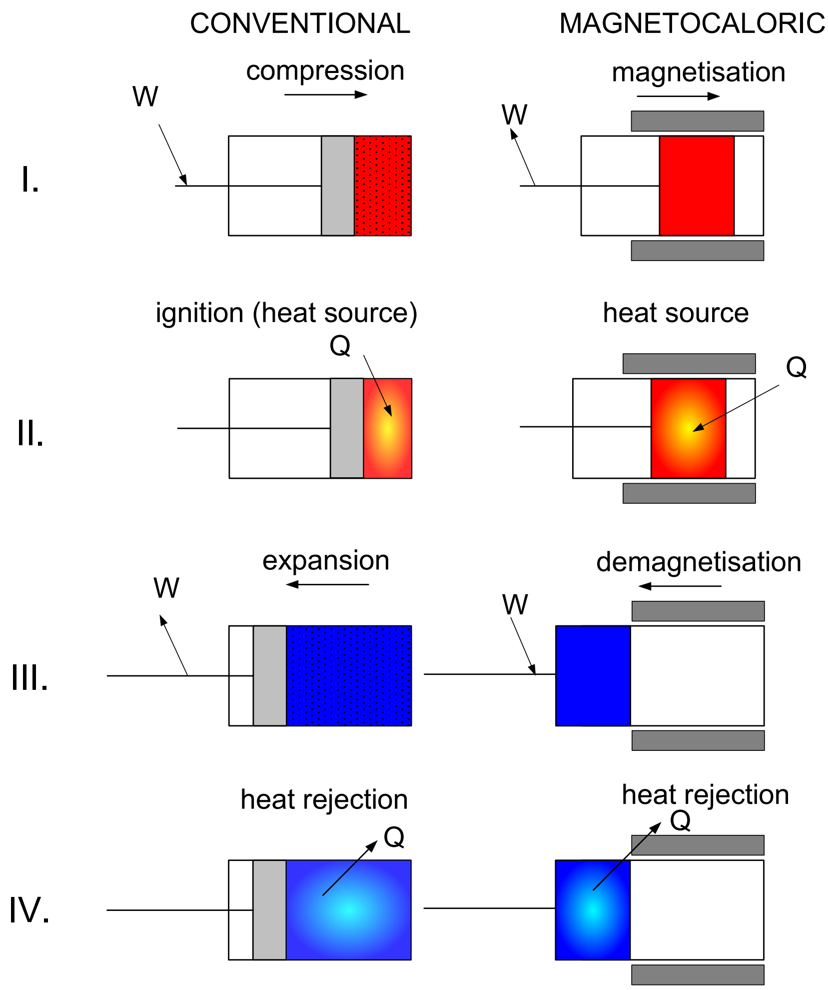


Figure 1: *Analogy between conventional (piston) and magnetic power production.*

1.2. Magneto caloric machines

At present there is no evidence of any existing prototype built to perform magneto caloric power conversion for a market application. The Curie and Palmy wheel are school demonstration devices, which cannot obtain large powers, because of too small heat absorbing surfaces. The major reason that no realistic prototypes exist is that only a small number of magneto caloric materials were known in the past, which are suitable for power conversion. And it is rather easy to demonstrate that the application of a single magneto caloric material cannot lead to machines with high temperature spans. However, numerous articles, patents, theories and new magneto caloric materials show that this technology should be further investigated, and that first operating prototypes with reasonable power conversion rates should be designed and realized. Developments of new materials for magnetic refrigeration with the highest Curie temperatures are also suitable for magneto caloric power conversion. One may distinguish between the following applications:

- Magnetic field sources (permanent magnets, electric magnets, superconducting magnets)
- Single stage devices, cascade devices, regenerative devices
- Magneto caloric materials as solid porous structures or as suspensions / close-to-nanofluids
- Rotary devices (rotation of magnets or rotation of magneto caloric material), linear devices (reciprocate movement of magnets or of magneto caloric material), and static devices (on/off operation of magnetic field source, or periodic guidance of magnetic flux between two different magneto caloric material beds by changing the permeability by applying a heat source and heat sink)
- Different kinds of thermodynamic cycles
- Heat transfer fluid being a gas, a liquid, a nanofluid or a suspension.

Figure 2 presents an example of a static magnetic power conversion machine based on electrically forced magnet coils by an application of an on/off operation. In order to perform a continuous operation, two such generators are assembled into one housing.

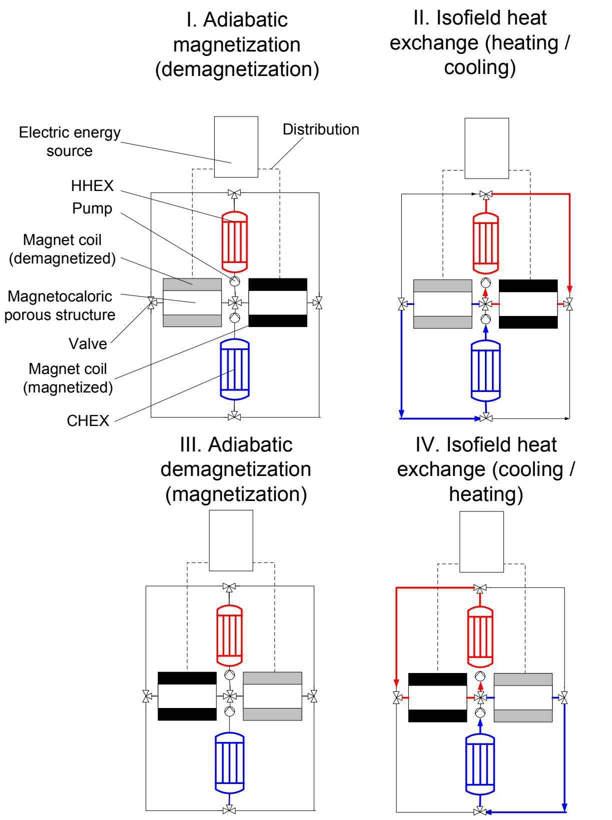


Figure 2: *Examples of the Brayton–type, continuous, static, single stage production cycle.*

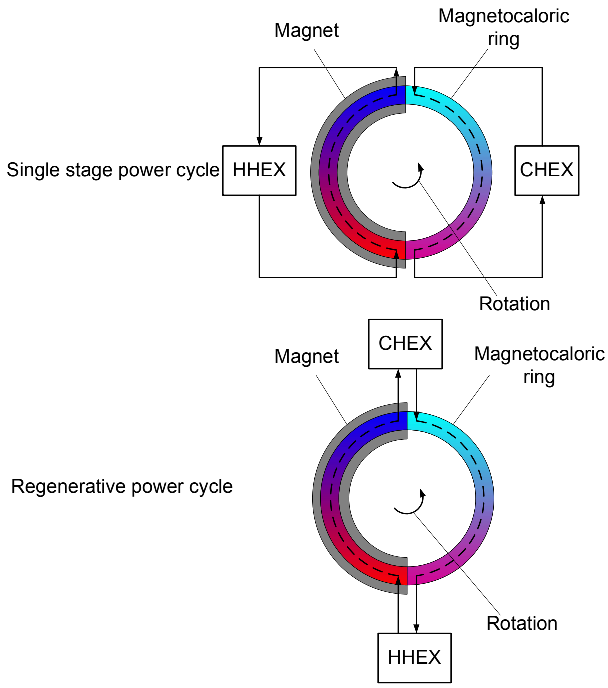


Figure 3: *Examples of the rotary, single stage and regenerative magnetic power production cycles with an application of permanent magnets.*

One should note that a static power generator may be designed by applying permanent magnets. However, a very specific design would be required in order to perform large magnetic flux density changes in the magneto caloric material. In a Brayton magnetic power conversion machine (as shown in FIG.'s 2 and 3) four processes in a cycle occur as follows: adiabatic magnetization, heating in a constant field, adiabatic demagnetization, cooling in a constant field.

In FIG. 3 two different cases of the rotary magnetic power conversion machine are presented. Here a magneto caloric ring rotates through a static magnetic field. The first one shown in the upper figure presents a simple single stage device, where the temperature difference between heat source and heat sink is not very large. In cases of a large temperature span between the heat source and the heat sink, a large number of such "stages" must be applied. The second example, shown in the bottom part of the figure, presents a regenerative rotary magnetic power device. In this - in a steady state condition - a larger temperature span is possible to be obtained. However, the temperature span cannot be very large, because an efficient operation is limited by the temperature interval around the Curie temperature in which the magneto caloric effect occurs. To overcome this obstacle, it is possible to apply the layered bed technique. In this method different materials are positioned at different locations in a manner that each operates close to its optimal temperature, which is the materials Curie temperature.

1.3. Advantages, drawbacks and future perspectives of magnetic power generation

The magnetic power generation shows advantages in comparison with the conventional technology:

- "Green" technology, no direct use of fossil fuels, but rather utilization of heat energy from natural resources (solar, geothermal) or waste heat energy utilization
- Noiseless technology (no compressor or internal combustion engine) and low vibrations
- High exergy efficiency. The magnetization and demagnetization are practically reversible, leading theoretically to a 20-30% higher exergy efficiency than in conventional systems
- Simple design of machines with small number of moving parts
- Low maintenance costs
- Small pressure differences are only required to overcome the frictional losses due to the transport of a working fluid.

On the other hand some disadvantages occur:

- Most magneto caloric materials and permanent magnet materials are expensive, especially as long as no mass production has been established
- Magneto caloric materials as well as machines need to be developed to allow higher frequencies of the rectilinear and rotary motion
- Electronic components must be protected from magnetic fields. But notify that these fields are static, of short range and may be shielded
- Permanent magnets have a limited field strength. Electro magnets and superconducting magnets require additional cooling and are (too) expensive
- Temperature changes are limited. Multi-stage (regenerative) machines loose efficiency by heat transfer between the stages
- Moving machines require a high precision to avoid a magnetic field reduction due to gaps between the magnets and the magneto caloric material
- Magneto caloric materials are at the moment not available for different temperatures of operation, and they require multi-layers, especially when operating between larger temperature spans.

Considering the present developments of magneto caloric materials, permanent magnet assemblies and magneto caloric devices, one may predict the following for a medium term period:

- High magnetic flux densities provided (e.g. > 1.5 Tesla)

- Special layered or even hybrid magneto caloric materials with a at least higher magneto caloric effect than that of gadolinium and with a small hysteresis effect
- Low pressure losses and improved heat transfer efficiencies of magneto caloric porous structures
- Higher frequencies of operation of magnetic power generators (e.g. ≥ 5 Hz)
- Volume fractions of magneto caloric material in the porous structure around 30% or above for liquid/liquid or gas/liquid applications and volume fractions of around 10%-15% for gas/gas applications.

2. PROJECT GOALS

The main objective of this project is to search for and to identify different applications and their domains of heat utilization where magnetic power generation could present a serious alternative to the conventional energy conversion technology. The evaluation is performed on a very broad basis. It shows an interesting potential for some specific applications. The work of this study is structured in the following manner:

1) Brief presentation of the technology „Magnetic Power Conversion“
2) Calculation methods
3) Presentation of existing technologies and the possibility of their replacement by the magnetic power generation
4) A list and short descriptions of possible applications of magnetic power conversion and results on technical characteristics
5) Selected most feasible applications
6) Brief description of alternative and comparable technologies (e.g. Thermoelectrics, Stirling, Organic Rankine Cycles, etc)
7) Proposal for future work.

The study was focused primarily on investigating the following heat sources:

- Solar (flat plate collector, evacuated tube collector, parabolic through systems, solar tower systems and solar dish systems)
- Geothermal (e.g. as in Organic Rankine Cycle, Kalina cycle, etc.)
- Industrial waste heat
- Transport waste heat (note that at the moment there is no power conversion technology available on the market)
- Cogeneration (including fuel cells and nuclear) “waste” heat
- Special power systems (e.g. space applications, subambient applications).

3. CALCULATION METHODS

For the purpose of this feasibility study, special methods were developed to evaluate efficiencies, volumes and masses of magnetic power generators. Some methods are modifications of models presented in previous studies, as for instance in Ref. [21]. The following works led to the development of these unique studies or methods:

- Study of magneto caloric material properties (e.g. gadolinium)
- Study and numerical simulation of the properties of permanent magnet assemblies
- Collecting and presenting data on conventional heat-to-power conversion technologies

- Development of a model to determine the heat transfer efficiency of a magnetic power generation device
- Development of a model to predict the fluid flow efficiency in a magnetic power conversion device
- Modification of an existing geometrical model describing the magneto caloric porous structure
- Mathematical-physical description of energy losses and their related efficiency reductions
- The implementation of exergy and thermodnyamic efficiency calculations into the physical model
- The development of models (by empirical and numerical analysis) for the volume and mass determination of different parts of a magnetic power generation device as also their overall quantities.

The calculations were based on Excel and its Macros, Matlab and some Finite Element Analysis Tools (FEA) frequently applied in the field of magnetism (on the market available standard software: Finite Element Method Magnetics Calculations FEMM 3.1). The large number of different power generation applications studied in this project required a rather simple calculation method, which on the other hand could be applied successfully in a study of a very broad range of different technologies.

Comparing magnetic power conversion technologies with the conventional counterparts, it is rather difficult to present their efficiencies at the same operation conditions. This is especially true for power conversion systems, which utilize pure exergy in form of e.g. fossil fuels, biomass, alcohols, nuclear fuels or hydrogen. Therefore, for a fair comparison, identical operation conditions have to be considered, especially those related to the form and temperature of the heat source and heat sink. A problem for good comparison also occurred, because there is no world's standard methodology, which would bring results of efficiencies of different technologies to a comparable basis.

The selection of magneto caloric material's properties was based on the rare earth material gadolinium (Gd), by applying data from a mean field analysis [18]. Because research on magneto caloric materials for power production has started only few years ago, in the analysis it is assumed that fictive materials with the properties of Gd are available over the entire temperature range under consideration.

For the conventional technology (e.g. binary geothermal systems) experimentally determined values were taken and compared with pure theoretically determined values of the magnetic power generation systems. Because of the present state of development of the magnetic power generation technology, it is impossible to already have measured data available. Therefore, to obtain a fair comparison, it is very important to take all the possible losses into consideration and to perform the study rather conservative than too optimistic. In a future stage the predicted results should be experimentally verified. The losses, which were incorporated into the physical model, are the following:

1) Energy losses in an electric generator
2) Hysteresis effect of magneto caloric material
3) Eddy currents in magnetic parts
4) Heat transfer losses between the stages of the process
5) Heat transfer losses in the heat exchangers at the source and sink
6) Heat losses to the environment
7) Energy losses given by the fluid flows through the porous structures with their pressure drops
8) Internal losses of pumps or ventilators.

The magnetic power generators were divided into two main groups, each defined by its specific working fluid. Such working fluids are applied as heat transfer media inside the magneto caloric porous structures. The two main groups are liquid-based and gas-based magnetic power conversion machines. The two main groups are further divided depending on the heat transfer at cold and hot heat exchangers (heat sink and heat source respectively):

- Magnetic Power Generators applying liquids
  - Power Generators applying gas / liquid
  - Power Generators applying liquid / liquid
- Magnetic Power Generators applying gas
  - Power Generators applying gas / gas.

In FIG. 4 the temperature intervals of the different fluids considered in this analysis are shown. The analysis of the liquid based magnetic power machines was performed with the physical properties of the presented liquids, each chosen to apply in its distinct temperature interval. For example at temperatures above 120°C it was assumed that the power conversion device is filled by a special heat transfer liquid; such a liquid is for example Paratherm NF [19]. Because this liquid has a rather high viscosity at temperatures below 100°C, it makes sense to only apply it at high temperatures, namely where water cannot be applied. In the analysis a rather conservative approach was made, namely it was assumed that the temperature levels of the heat sources are between 120 °C and 350 °C and furthermore that the Paratherm NF fluid is applied in all stages at all occurring temperatures of the heat sink. So the Paratherm fluid was even taken for temperatures below 120°C. In this range compared to water this fluid leads to a little higher fluid friction losses. In the temperature range above 350°C one should apply gases or special fluids. Such could be for example Bi–Pb alloys. While the first have rather bad heat transfer properties, due to their viscosity the second lead to high pressure losses. In the analysis it was assumed that the Bi-Pb alloys are applied for heat sinks with temperatures equal or above 350°C and for all related temperatures of the heat sources.

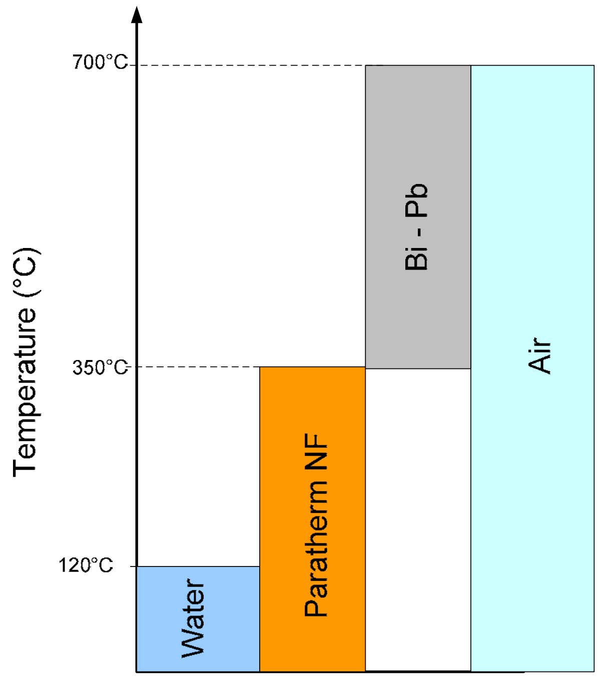


Figure 4: *Fluids and their temperature levels of operation, which are applied in the present analysis.*

4. ACCOMPLISHED WORK AND ACHIEVED RESULTS

4.1. Introduction

A comprehensive study of all power conversion technologies, which were briefly presented in Ref.'s [1] and [2], led to a selection of possible application domains of magnetic power conversion machines.

At the present stage of development of permanent magnets, all the magnetic power conversion systems, which are operating with high temperature heat sources (e.g. >350°C) are not really feasible. The reason for this is a lack of suitable magneto caloric materials working under such conditions.

An alternative is to use superconducting magnets. However, they should be applied only in very large units. For low temperatures of the heat sources, a magnetic flux density of 5 Tesla would already lead to a very good efficiency, while for higher temperature levels (where special metal liquids or gases are applied) a very good efficiency could be achieved by applying magnetic flux densities of approximately 10 Tesla.

In this study a new analysis has been applied to evaluate the different systems. The thermodynamic efficiencies and the exergy efficiencies of all the systems under consideration were calculated by applying the specially developed thermodynamic model.

The present study and analysis reveals a very interesting result, namely that for systems with low-temperature heat sources the exergy efficiencies may be very high. A first conclusion of this new insight is that probably no other energy conversion method can compete with magnetic power conversion in this area of application. But one has to be aware that low exergy heat sources cannot lead to very high thermodynamic efficiencies. This can immediately be seen by calculating the Carnot efficiency, which is the highest obtainable efficiency at all. Finally we must recognize that still new magneto caloric materials with higher Curie temperatures will be developed, so that also the high-exergy region becomes more and more accessible for the magnetic technology.

4.2. Magnetic Power Generators with liquids

Magnetic power generators applying liquids may be referred to utilization of heat at rather moderate temperature levels, because their behaviours depend on the properties of the applied liquids. For temperature levels above 350°C these liquids may be metals in the liquid state. Such systems require a safe operation (also in the case of a solidification). Magnetic power generators applying liquids can utilize heat almost from any heat source.

4.2.1. Magnetic power generators applying liquid/liquid

In the analysis depending on the temperature level of the heat source the selection of the accurate heat transfer fluid was made. In the range between 40°C to 120°C it is common to apply water as heat transfer fluid. Beyond this temperature applications with special heat transfer fluids, as e.g. an industrial fluid named Paratherm [19], are common. In this case the calculations were performed for a magnetic power generator, which applies this fluid in the entire range of its operation. It has to be noted that in real systems a more efficient method is an operation with different working fluids depending on the heat source temperature. For example, a water based magnetic power generator works at temperatures below 120°C. If the heat sink shows temperatures of more than 120°C and less than 350 °C the Paratherm fluid may be applied. In this manner high viscosities are avoided, which may occur if high-temperature fluids are applied below 120°C. Between 350°C up to very high temperature levels, a special liquidized metal is usually applied. FIG.'s 5 and 7 show the thermodynamic efficiency and FIG.'s 6 and 8 the exergy efficiency of a magnetic power generator in which liquid / liquid transfer fluids are applied. This means that the heat transfer fluid in the external heat exchangers is liquid and that also the heat transfer fluid in the magneto caloric power generator - with a 10 % volume fraction of magneto caloric material - is liquid.

The efficiency and exergy efficency are depending on the magnetic flux density, the temperature of the heat source, the temperature of the heat sink and the frequency of operation. Additionally, a characteristic efficiency of a corresponding Organic Rankine cycle (binary geothermal system, see in Ref. [20]) is shown for comparison. It is a large advantage compared to conventional systems that a magnetic power generator may operate at any temperature level. From FIG. 7 one notes that a good exergy efficiency may be obtained even with a heat source temperature below 100°C depending on the magnetic flux density. In order to be competitive with conventional systems, in magnetic machines the magnetic flux density should be approximately 1.5 to 2 Tesla if water is applied as heat transfer fluid. Such a magnetic flux density would also be sufficient, if the system operates with heat sources up to 350°C (using e.g. Paratherm fluid). However, if the Paratherm fluid is applied in the entire range of temperatures, e.g. from 25°C up to 350°C, as it follows from FIG.'s 5 and 7 the magnetic flux density should be higher (e.g. 3 Tesla and beyond). The reason is a high viscosity of this fluid at lower temperatures. Systems operating with higher temperature heat source levels than those in which water is applied are usually large systems. In such machines the application of superconducting magnets becomes more efficient than that of permanent magnets. Superconducting magnets should have magnetic field strength above 5 Tesla. In this higher temperature range magnetic power generation presents a very good alternative to conventional systems. Furthermore, there is no evidence in the literature that power generation systems with heat sources below 100°C (low exergy heat sources) exist. On the other hand magnetic power generation should make this possible due to the occurrence of a higher exergy efficiency than that of conventional ones.

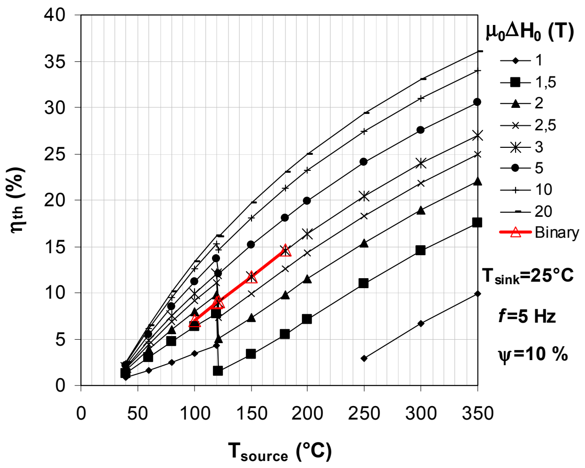


Figure 5: Thermodynamic efficiency of a magnetic power generator with liquid / liquid circuits.

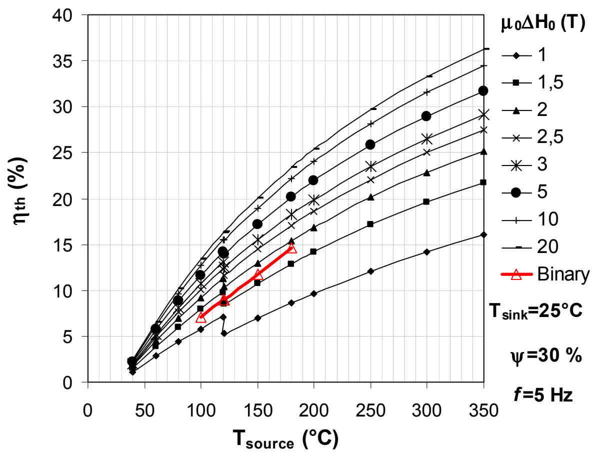


***Figure 6:** Exergy efficiency of a magnetic power generator with liquid / liquid circuits.*

If the volume fraction of the magneto caloric material in the porous structure is 30%, the occurring high energy density enables a much higher efficiency. This may be noted by studying FIG.'s 6 and 8. In this case magnetic flux densities close to or above 1.5 Tesla lead to better efficiencies for the entire temperature range compared to the efficency of e.g. a binary geothermal plant. The results show that with heat source temperatures even below 120°C, by applying permanent magnets with 2 Tesla magnetic flux density, the thermodynamic efficiency can reach 12% and the exergy efficiency 45%. These are extraordinary good results compared to those of existing conventional technologies. The equivalent thermodynamic efficiency, as obtained with a binary system operating at 120°C, may be achieved by a magnetic power generation machine, if it has a heat source temperature of 95°C and a magnetic field strength of only 2 Tesla.

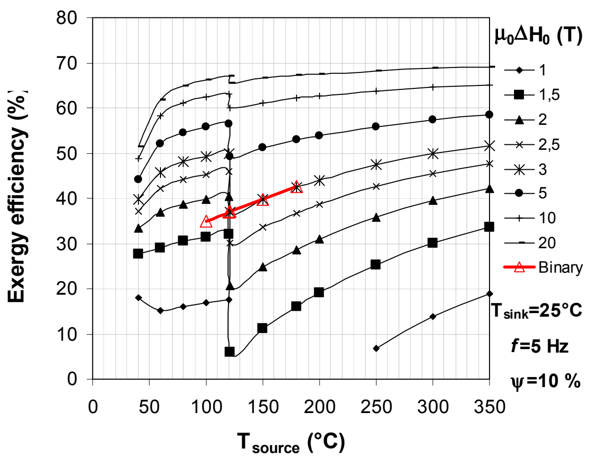


***Figure 7:** Exergy efficiency of a magnetic power generator applying liquid / liquid transport fluids and having heat exchangers with 10 % volume fraction.*

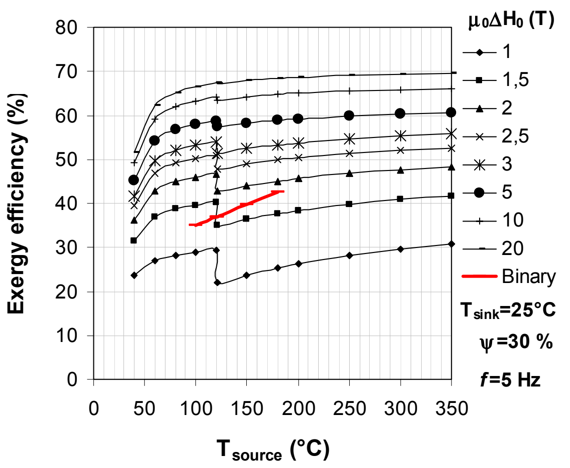


***Figure 8** Exergy efficiency of a magnetic power generator applying liquid / liquid transport fluids and having heat exchangers with 30 % volume fraction.*

FIG.'s 5-8 present efficiencies all at a frequency of operation of 5 Hz. If the frequency is lower, the efficiency is usually substantially better. But a lower frequency leads to a larger and more expensive device. In the case of an application of superconducting magnets, the thermodynamic efficiency at low temperatures (e.g. <120°C) may reach some 15%, which is almost the double value of that of a binary energy conversion system. The corresponding exergy efficiency is also high, namely 65%.

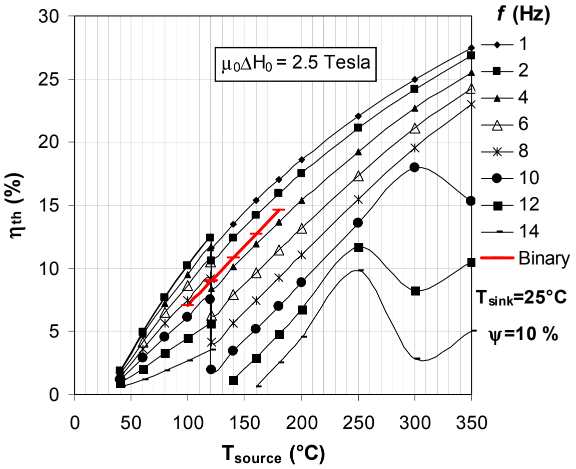


Figure 9: *Thermodynamic efficiency of a magnetic power generator (liquid / liquid) with 10 % volume fraction depending on the frequency of operation with a magnetic flux density of 2.5 Tesla.*

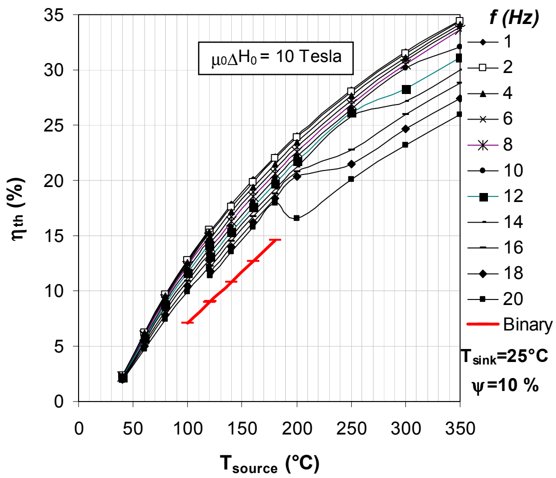


Figure 10: *Thermodynamic efficiency of a magnetic power generator (liquid / liquid) with 10 % volume fraction depending on the frequency of operation with a magnetic flux density of 10 Tesla.*

A conclusion is that for liquid based systems with a temperature of the heat source up to 350°C one should foresee higher volume fractions of the magneto caloric material in the porous structure. By this the energy density is increased and the relative contribution of losses is reduced. If permanent magnets are applied the magnetic flux density should be approximately 1.5 Tesla in order to obtain a magnetic power station, which is competitive to a conventional one. Large scale systems favour the application of superconducting magnet assemblies. Such applications are e.g. a geothermal power plant (see FIG. 13), a solar through system (see FIG. 12) or other large scale systems with power conversion rates of more than a few Megawatt. The temperature levels of such systems are usually in the range of 350 °C. When applying heat sources with temperatures between 120 and 350°C, preferably two magnetic power generation systems are interesting, one is operating with low exergy heat and applying water as working fluid and the other is operating with a special heat transfer fluid (e.g. Paratherm) above 120°C. As was already mentioned for temperature ranges beyond 350°C special liquidized metals, such are for example Bi-Pb alloys, should be applied. These systems would operate at heat sink temperatures of 350°C. That enables a further use of heat in a second magnetic power generation system with its corresponding heat transfer fluid and heat source temperature only limited by the evaporation of liquid metals. A higher heat sink temperature lowers the viscosity, which rapidly increases with decrease of temperature, yielding to solidification when the eutectic temperature level is obtained. FIG.'s 15-18 show the thermodynamic efficiency (note that the thermodynamic efficiency is low, because of a high temperature of the heat sink) and exergy efficiency of a magnetic power generator for two different volume fractions, namely 10 % and 30 %, respectively. From FIG.'s 15 and 17 one learns that for 10 % volume fraction this kind of system would not be able to operate with permanent magnets, but only with superconducting ones. The last may be the case only in large scale systems. However, increasing the volume fraction to 30 %, the efficiency substantially increases. This may be seen in FIG.'s 16 and 18. In this case the minimal magnetic flux in order to have exergy efficiencies higher than 35 % should be around 2 Tesla. Such high temperature systems would require a certain heat storage in order to prevent solidification of the liquid metal. Such is occurring, for example, if liquid salts are applied in a concentrated solar power system. An example of heat utilization at this temperature levels may be by a solar tower system or solar dish system converting renewable energy. However, many other different heat sources are available, for example in CHP plants (including different types of fuel cells), industrial processes, transport means, etc. For a large scale magnetic power generation system operating with superconducting magnets a very high exergy efficiency of almost 70 % may be achieved (see FIG. 18). This shows that the magnetic power generation technology, as an alternative, may be very efficient also at higher temperature levels.

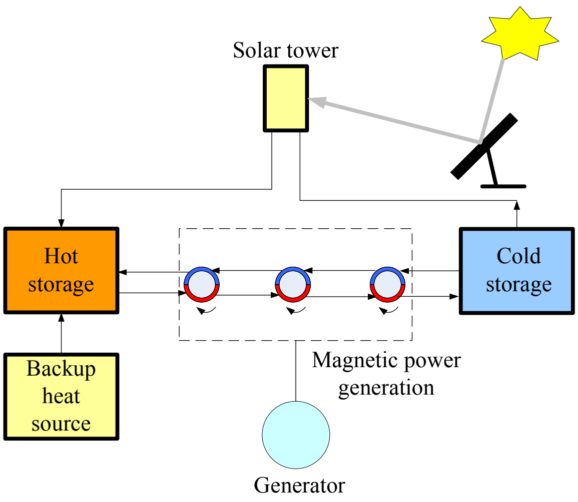


Figure 11: An example of a solar tower magnetic power generation system with heat source temperatures approximately up to 550°C.

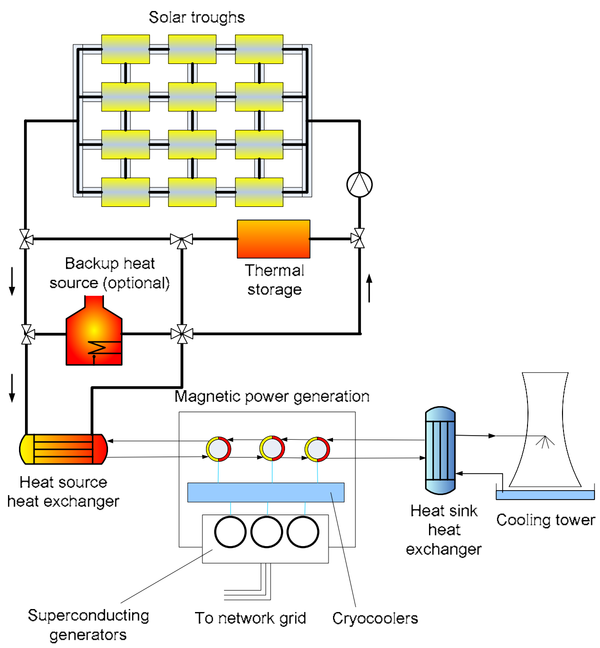


Figure 12: An example of a solar through magnetic power generation system with heat source temperatures approximately up to 300-400°C.

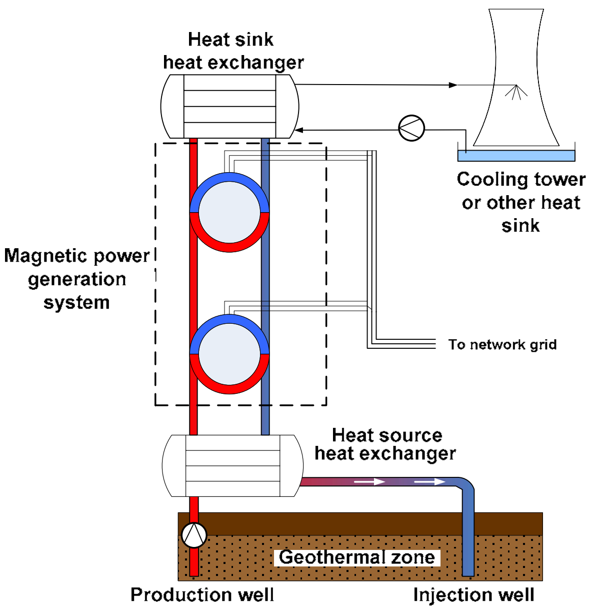


Figure 13: An example of a geothermal magnetic power generation system with a heat source temperature of approximately 180°C.

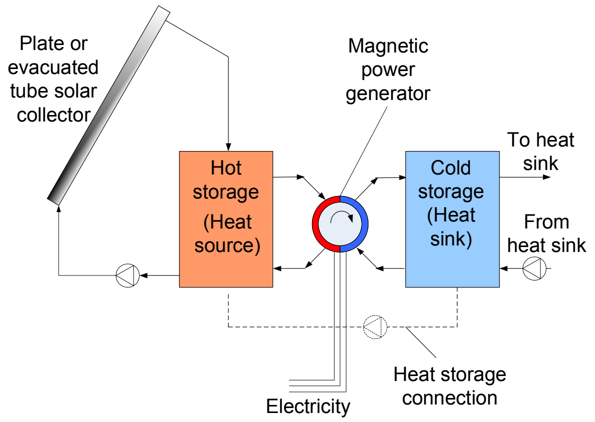
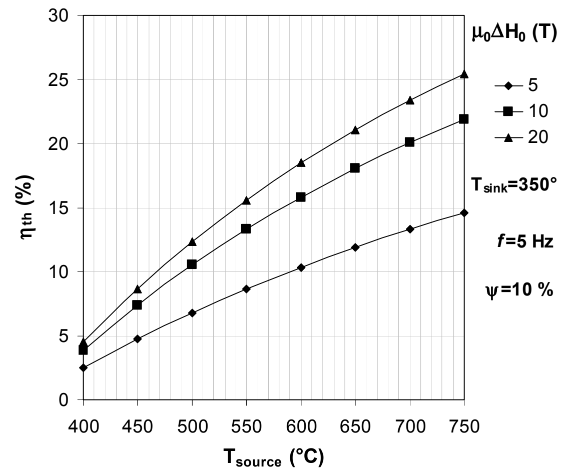


Figure 14: An example of the solar plate or evacuated tube collector magnetic power generation system (heat sources approximately 60-180°C)

FIG.'s 15-18 do not present the entire temperature span. When utilizing heat from a heat source of 750°C and a heat sink of 25°C one should calculate the overall exergy efficiency by applying weighted exergy efficiencies. A weighting factor method may be applied for all temperature differences of each partial system. Here this specal method cannot be outlined in more detail.



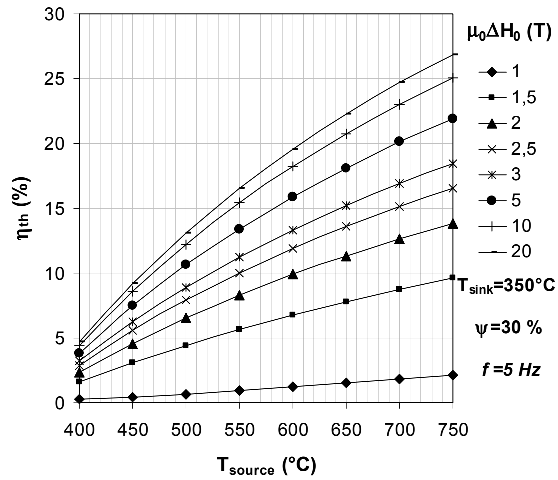
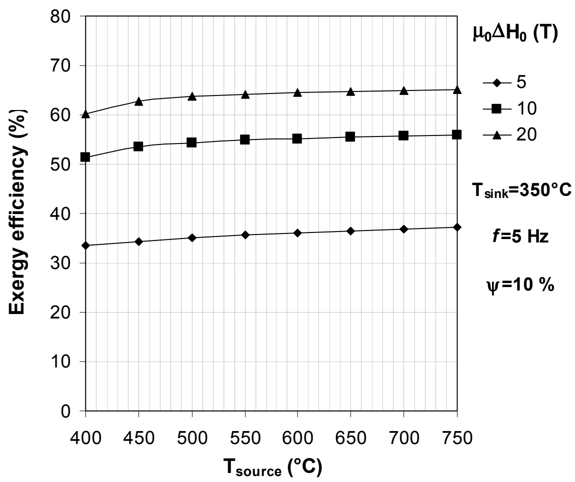


Figure 15: *The thermodynamic efficiency of a liquid / liquid magnetic power generator for temperature levels beyond 350°C (with special attention to the temperature difference between heat sink and heat source) for 10 % volume fraction is shown.*

Figure 16: *The thermodynamic efficiency of a liquid / liquid magnetic power generator for temperature levels beyond 350°C (with special attention to the temperature difference between heat sink and heat source) for 30 % volume fraction.*

A very important information is the total volume and the total mass of a system. These quantities are directly related to the investment cost of a machine. For an example of the liquid / liquid magnetic power generator an analysis was made for small scale applications with permanent magnets, based on a magnetic flux density of 2 Tesla. The total electric power output of the device was defined to be 5 kW of electric power. FIG.'s 19 and 20 show examples of the total mass and the total volume of such a device, depending on the frequency of operation and the heat source temperature.



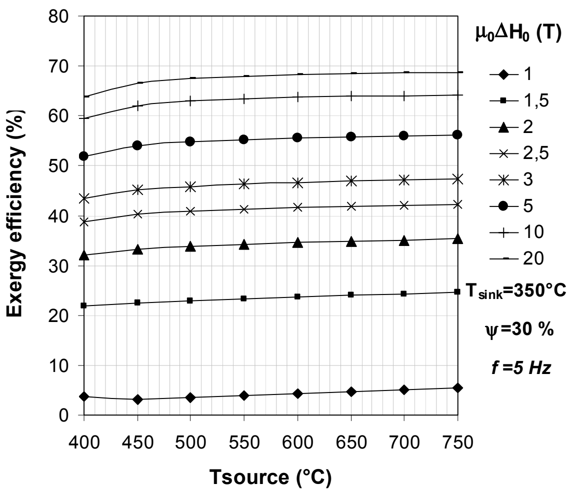
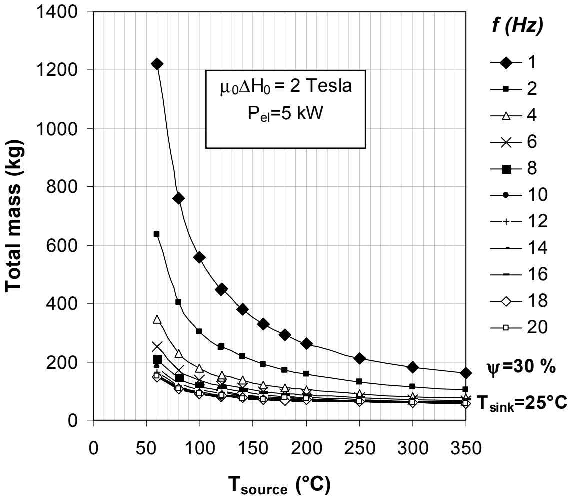


Figure 17: *Exergy efficiency of a magnetic power generator (liquid / liquid) for temperature levels beyond 350°C and 10% volume fraction.*

Figure 18: *Exergy efficiency of a magnetic power generator (liquid / liquid) for temperature levels beyond 350°C and 30% volume fraction.*

As one may note from Fig.'s 19 and 20, the frequency of operation strongly determines the total mass and the total volume of a device. However, the values start to converge around 5 Hz. That is at present the highest obtainable frequency of prototypes in the magnetic refrigeration domain. Higher temperatures of heat sources increase the efficiency, therefore they lead to a decrease of the total mass and the total volume. The total volume of a device does not present such a large disadvantage (challenge to decrease) as this may be expected for the total mass of the system, which is given by the heavy permanent magnets. Therefore special efforts should be taken when designing permanent magnet based magnetic power generators to obtain smallest possible values.



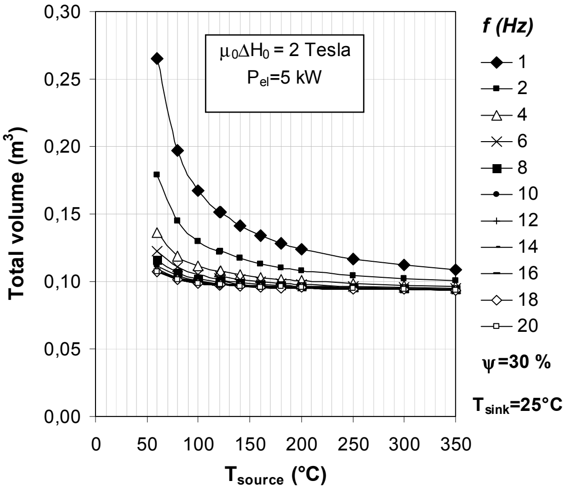


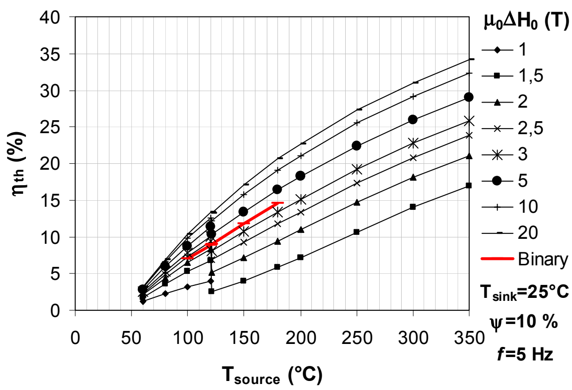
Figure 19: *The total mass of a magnetic power generator (liquid / liquid) based on permanent magnets for different frequencies of operation and different temperatures of the heat source.*

Figure 20: *The total volume of a magnetic power generator (liquid / liquid) based on permanent magnets for different frequencies of operation and different temperatures of the heat source.*

A group of individual houses where solar evacuated tube collectors to produce heat were mounted may be an example of an application with permanent magnets (see FIG. 14). Considering a 5 kW power conversion with a heat source with a temperature of 120°C and a heat sink at 25°C, a frequency of 5 Hz and a magnetic filed strength of 2 Tesla, after our model calculations would lead to a volume of 0.1 m^3 and a total machine mass of 130 kg. In this volume, however, housing and external heat exchangers are not yet included. Furthermore, the thermodynamic efficiency of such a system would be 11 % with a good exergy efficiency of 47%. In this example the losses in the evacuated tube collector were not taken into account. The system would require around 45 kW of heat power input at 120°C from the evacuated tube collectors.

4.2.2. Magnetic power generators applying gas/liquid

Utilization of heat is often related to gas/liquid applications, where gas is available as heat source and liquid is used as the heat transfer fluid in the magnetic power generator. Heat sources in form of a gas may usually be found as waste heat from exhaust gases from internal combustion engines, incineration, power plants (e.g. gas turbines, fuel cells) and some other industrial processes. A special case could be related to a solar dish system, where its temperature is reaching some 750°C or even beyond. FIG.'s 21 and 22 show the thermodynamic efficiency and the exergy efficiency of a gas / liquid-based magnetic power generator for temperatures of the heat sources up to 350°C having a 10 % volume packing degree.



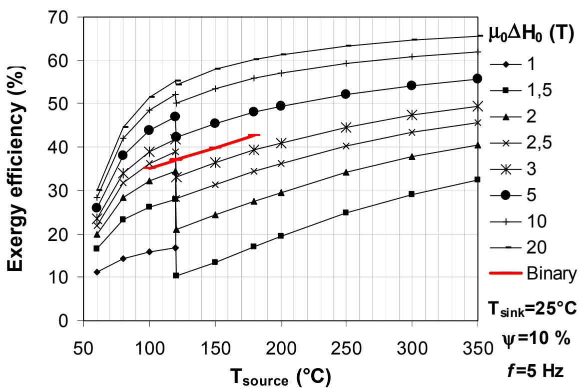


Figure 21: *Thermodynamic efficiency of a magnetic power generator (gas / liquid).*

Figure 22: *Exergy efficiency of a magnetic power generator (gas / liquid).*

Comparing results extracted from FIG.'s 21 and 22 and FIG.'s 5 and 7, a reduction of the efficiency due to the irreversible heat transfer losses may be noted. However, in liquid-based magnetic power generators a volume fraction of 10 % is rather small. Therefore, more efficient are applications with higher volume fractions. Large power densities provided by high volume fractions of magnetocaloric material in the turning wheels enables high efficiencies of operation also for magnetic power generators applying two working fluids, one in gaseous and the other in a liquid state. This may be observed in FIG.'s 25-26. The minimal magnetic flux density - sufficient to beat conventional power generation technologies - is around 2 Tesla. However, it has to be noted that many gaseous heat source applications are related to large scale units. That makes applications with superconducting magnets especially interesting. Furthermore, the electricity may be generated with superconducting generators, which show a very good compactness when compared to conventional ones.

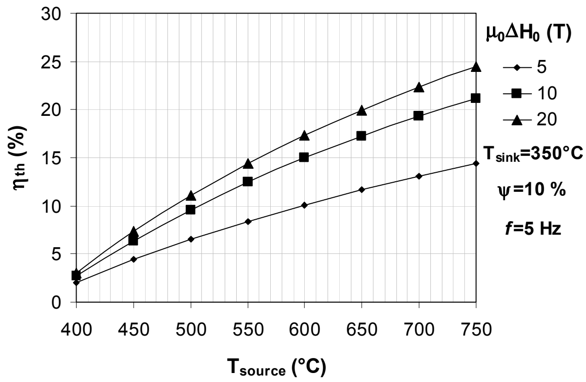


Figure 23: Thermodynamic efficiency of a magnetic power generator (gas / liquid) for temperature levels beyond 350°C (with special attention to the temperature difference between heat sink and heat source).

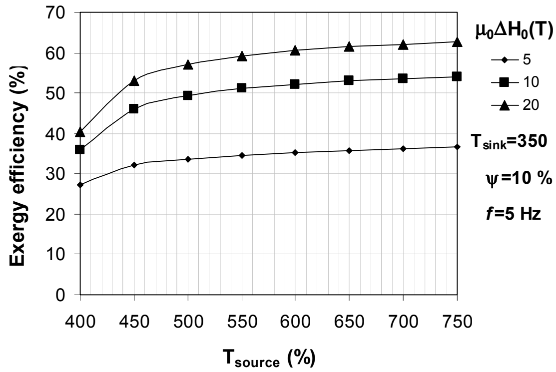


Figure 24: Exergy efficiency of a magnetic power generator (gas / liquid) for temperature levels beyond 350°C (with special attention to the temperature difference between heat sink and heat source).

High temperature magnetic power machines would also operate optimally if higher volume fractions of the magneto caloric material would be applied. For example one may compare results of FIG.'s 23-24 with those shown in FIG.'s 27 and 28. The latter present the thermodynamic efficiency and the exergy efficiency for a 30 % volume fraction filling degree magneto caloric material in high temperature applications.

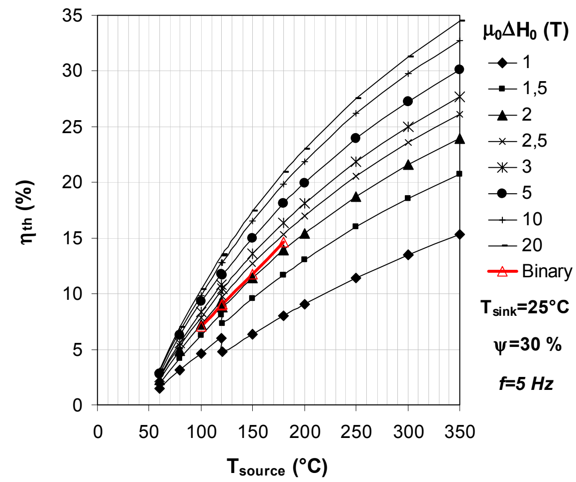


Figure 25: Thermodynamic efficiency of a magnetic power generator (gas / liquid) for a volume fraction of 30 %.

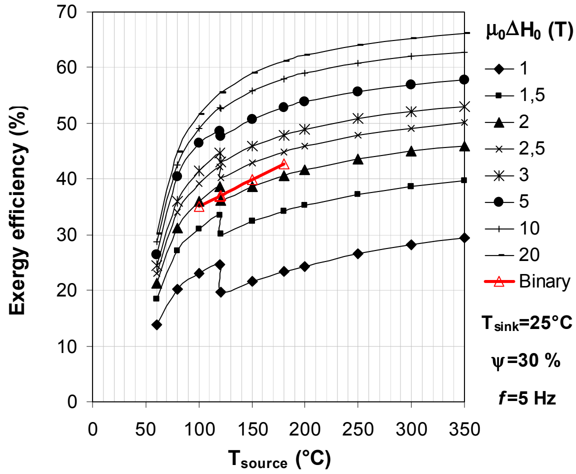


Figure 26: Exergy efficiency of a magnetic power generator (gas / liquid) for a volume fraction of 30 %.

With 10 % volume fraction of magneto caloric material high temperature systems working with gas / liquid require superconducting magnets. For such systems the exergy efficiency at 10 Tesla magnetic flux density may reach 55 %. Increasing the volume fraction under same conditions would lead to exergy efficiencies of 62 %. This difference (dependence) becomes even more obvious at lower temperatures of the heat source.

Note again that small thermodynamic efficiencies of these systems are related to the temperature span between heat source and heat sink.

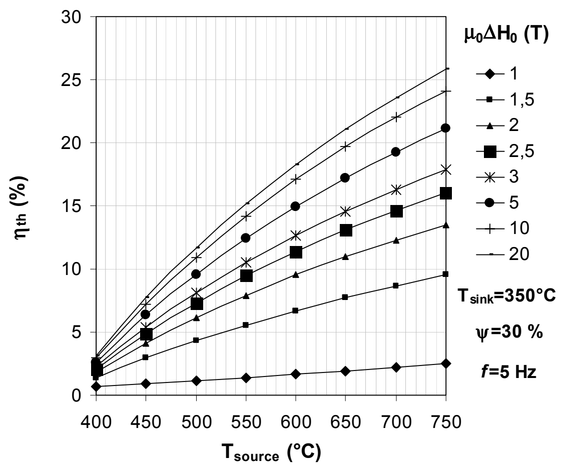


Figure 27: *Thermodynamic efficiency for a magnetic power generator (gas / liquid) for a volume fraction of 30%.*

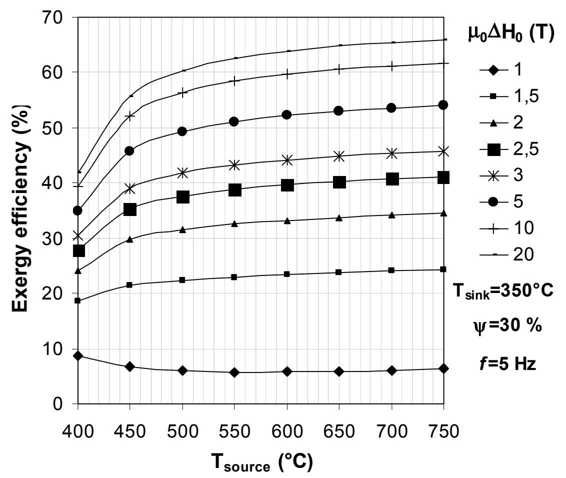


Figure 28: *Exergy efficiency for a magnetic power generator (gas / liquid) for a volume fraction of 30%.*

An example of a 1 MW "gas/liquid magnetic power generator" (2 Tesla magnetic flux density with permanent magnets and 30% volume fraction of magneto caloric material) was investigated in order to determine the total mass and the total volume for different operation conditions. It is assumed that two magnetic power generation units are applied for temperature levels above 350°C. The first system is operating as a "gas/liquid power generator" with the working fluid Bi-Pb in the temperature range 350-750°C. The second is operating below 350°C and is a "liquid / liquid generator" with the working fluid Paratherm. The exergy efficiency was calculated by weighting factors of the two systems for temperatures above 350°C. FIG. 29 shows an example of the exergy efficiency calculated for such a twofold system with a heat sink temperature of only 25°C.

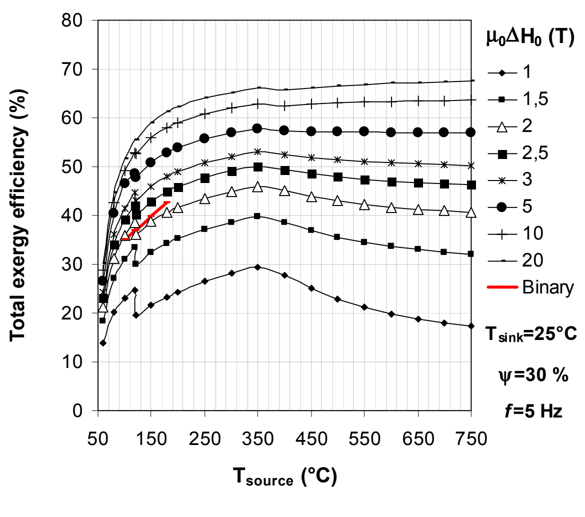


Figure 29: *The total exergy efficiency of the system applying gas / liquid working fluids.*

According to FIG. 29 the exergy efficiency is decreasing at temperature levels above 350°C. The reason is the lower exergy efficiency of the first stage (with viscous liquid metals) when compared to systems with more common heat transfer fluids. Despite that, a good exergy efficiency may already be obtained by applying a 2 Tesla magnetic flux density. This was also taken as basis for calculations of the total volume and the total mass of such a system. The results are shown in FIG.'s 30 and 31.

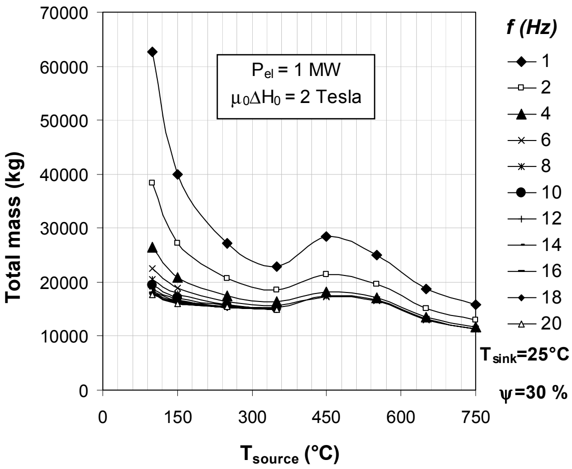


Figure 30: The total mass of a magnetic power generator (gas / liquid) based on permanent magnets depending on the frequency of operation and the temperature of the heat source.

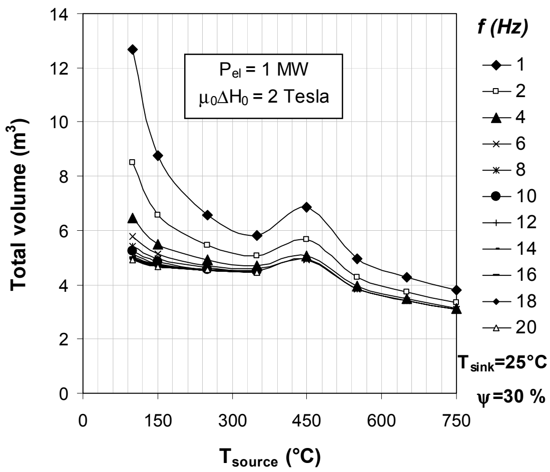


Figure 31: The total volume of a magnetic power generator (gas / liquid) based on permanent magnets depending on the frequency of operation and the temperature of the heat source.

In FIG.'s 30 and 31 the irregular shapes of the curves, which present the total volume and the total mass, are due to the reason that above 350°C a special liquid (Bi-Pb) is applied. A high viscosity and a lower exergy efficiency cause an increase of the required total mass. The "gas/liquid system" based on Bi-Pb cannot operate at high frequencies of operation. This follows because of a high fluid friction that would occur. The present development of the somehow inverse technology - namely magnetic refrigeration at room temperature - shows the possibility of running such systems with frequencies in the range of 5 Hz. FIG.'s 30 and 31 demonstrate that a frequency of 5 Hz also leads to an efficiency close to the asymptotic value of the curve.

4.3. Magnetic Power Generators applying gaseous fluids

If in a system the heat source is available as a hot gas, it is usually related to the utilization of waste heat, especially in transport, industry and in power plants. The last presents a case where magnetic power generation may be applied as the main power source (replacing the gas turbines) or as an alternative to the steam turbines in a combined gas-steam cogeneration plant. In this case hot gases exiting a gas turbine may be directly applied in the magnetic power generator, without any need of a condenser or a cooling tower. Ambient air can be used as heat sink for the magnetic power generator. Such an example is shown in Fig. 32. The efficiency of a gas-driven magnetic power generator strongly depends on the magnetic flux density and on the temperature level which is available. Examples of the thermodynamic efficiency and the exergy efficiency are presented in FIG.'s 33 and 34. According to these results, a gas driven magnetic power generator requires a very high magnetic field source. Such are not feasible at the present stage of development of permanent magnets. Therefore, these systems may operate efficiently only when applying superconducting magnets at rather high magnetic flux densities, e.g. at 10 Tesla and above. The exergy efficiency is rapidly increasing in the range of temperature levels up to 150°C, which may also be defined as the lowest temperature of heat source in order to obtain a good exergy efficiency. The gas driven magnetic power generation machine seems to be feasible and to be a good alternative to all the conventional technologies of heat-to-electrical power conversion.

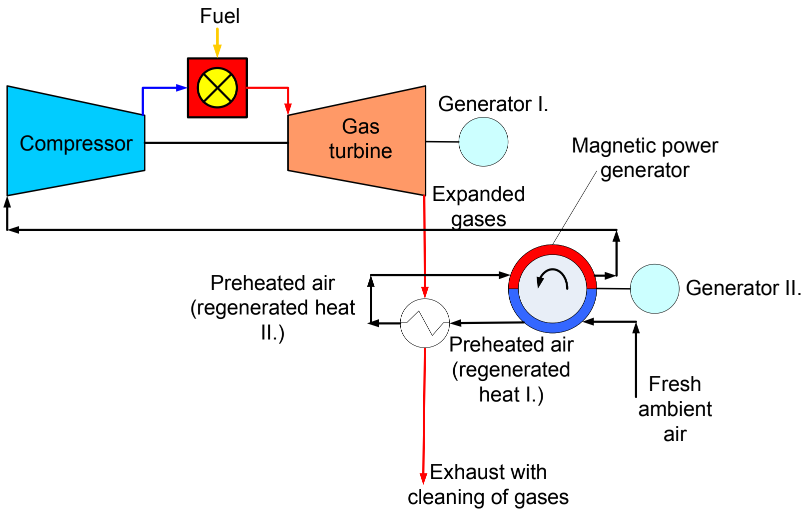


Figure 32: *An example of a combined gas turbine – magnetic power generator system.*

In transport vehicles this technology is feasible only in large scale applications, which for example occurs in the transport of goods on the sea. However, it is not feasible in cars or other land vehicles and in aircrafts. The reason is that superconducting magnet systems are meaningful only for large scale applications.

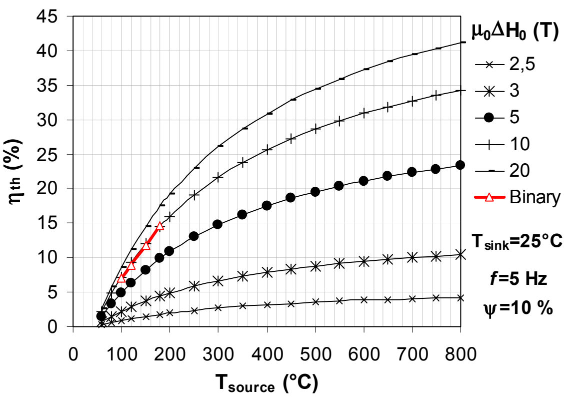


Figure 33: *Thermodynamic efficiency of a magnetic power generator (10 % volume fraction).*

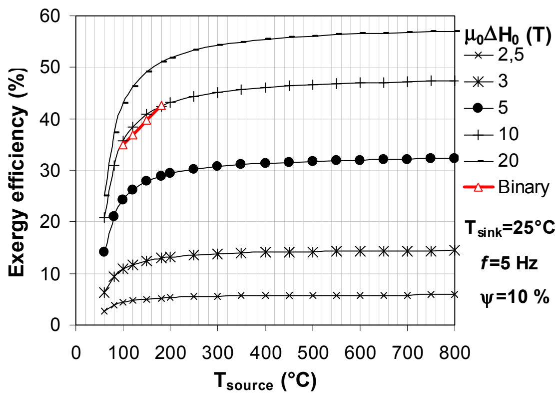


Figure 34: *Exergy efficiency of a magnetic power generator (10 % volume fraction).*

One should note that if a gas is applied as working fluid, the volume fraction of a magneto caloric material in the porous structure cannot be very high. For example a desired volume fraction of 30 % in a “gas/gas machine” is not suitable at all. If a heat source available is gaseous, a much better solution is the application of a “gas/liquid magnetic power generation system”. Such systems also lead to higher efficiencies.

5. LIST OF OCCURRING SYSTEMS

In the following section the reader finds an overview on the possible technical applications of magnetic power conversion. The investigated systems are the following ones:

a) Small solar power generation devices

- solar plate collector with a liquid fluid and with a generator based on permanent magnets
- evacuated tube solar collector with a liquid fluid and a generator based on permanent magnets

b) Large solar power generation devices

- Large evacuated tube systems
- Parabolic trough technology
- Power tower technology
- Solar dish technology

c) Large geothermal systems

d) Power of waste heat in transport vehicles

- Magnetic power generators using heat in large marine applications

e) Small scale power from cogeneration (poly-generation) plants including fuel cells

- Fuel cells
- Small CHP's (e.g. gas and diesel generators, gas turbines)

f) Large scale power from cogeneration (poly-generation) plants

- Fuel cells
- Large CHP's (e.g. gas turbines, combined power systems)
- Nuclear power

g) Power from waste heat from waste incineration plants

h) Power from heat in food industry processes

i) Power from waste heat from process technologies

j) Special systems

The goal of some special systems is the utilization of pure natural sources by energy or power conversion. These systems in general do not enable high thermodynamic efficiencies, but still may show a high exergy efficiency. Depending on the specific application permanent magnets or superconducting magnets may be applied. Examples of such systems are:

- Power conversion in a desert area using the temperature variation between the ambient (hot air or solar heated panel) and the soil. This system may also operate during night with inverse temperature levels of the heat source and heat sink
- Power conversion applying the temperature difference between outside air as a heat sink (e.g. far north regions) and soil or sea as heat source
- Space applications, where heat is supplied or rejected by radiation, space geothermal stations, variation of day / night temperatures in solar system (e.g. on the moon).

5.1. Selected examples of possible magnetic power generation systems

Here different possible technologies of magnetic power production are listed and evaluated depending on the heat source temperature level, the type of the heat transfer fluid, the thermodynamic and the exergy efficiency, the total volume and the total mass. Furthermore, predictions of a market penetration in near future are outlined, despite of the difficulties of performing such a task. In this study, for systems applying permanent magnets, it is assumed that the magnetic flux density is 2 Tesla and for superconducting magnets the magnetic flux density is fixed at 10 Tesla. In all the presented examples the heat sink temperature is assumed to be 25°C. A frequency of operation of 5 Hz was taken as a basis for the calculations. Systems based on “gas/gas applications” were not analysed here, despite that some of these systems - especially such based on superconductors - could be feasible. However, as shown in Chapt. 4, “gas/liquid systems” show much higher efficiencies than “gas/gas systems”, because of the higher volume fraction of magneto caloric material. Higher packing degrees lead to higher energy densities and thus a substantial reduction of the relative losses.

Table 1: *Examples of applications with temperatures of the related heat sources below 100°C.*

Heat source temperature (°C)	Type of heat transfer fluid L/L G/L G/G	Applications	Thermodynamic efficiency (%) (Exergy efficiency) (%) ***Same for superconducting extra large scale system (10 Tesla)***	Total mass for 5 kW_{el} (kg) (Total mass for 1 MW_{el}) (tons) Data only for permanent magnet based system	Possiblity of technology to market penetration mark √ - very low √√ - low √√√ - medium √√√√ - high √√√√√ - very high
60-90°C	L/L	Solar plate collector	4.5-8.2 % (43-46 %) ***6.2-11.2%*** ***(59-62 %)***	170-290 kg (23-32 tons)	*Small scale* √√√√ *Large scale* √ *Supercond..* √
60-100	L/L	Geothermal	4.5-9.2 % (43-46 %) ***6.2-12.7%*** ***(59-63 %)***	Only large scale (22-32 tons)	*Small scale* √ *Large scale* √√ *Supercond..* √√√√√
60-100	L/L	Industrial waste heat, waste heat from CHP’s including polymer electrolyte membrane and alkali fuel cell	4.5-9.2 % (43-46 %) ***6.2-12.7%*** ***(59-63 %)***	150-290 kg (22-32 tons)	*Small scale* √√√√ *Large scale* √√√√ *Supercond..* √√√√√
70-100	L/L	Transport vehicles (cooling water for engines)	5.8-9.2 % (44-46 %) ***6.2-12.7%*** ***(59-63 %)***	150-230 kg (22-28 tons)	*Small scale* √ *Large scale* √ *Supercond..* √√ (the last only in large scale marine applications)

Results in Table 1 show that some of the presented technologies would be interesting in future applications. The reason is a very high exergy efficiency, which enables heat utilization of numerous different sources above 80°C. The results in Table 2 depend on the heat transport fluid that is applied. For example liquid / liquid-based magnetic power generators show a very good thermodynamic efficiency. Despite low exergy of heat between 100-200°C (heat source level), “liquid / liquid applications” may efficiently convert the small amount of exergy of heat into useful exergy of electricity. Land and air transport vehicles are usually small scale units. A power of e.g. 5 kW is rather high for such an application. Therefore, the conclusion is that in the domain of energy conversion in transport vehicles the only interesting domain is the one of large scale applications. Such a domain is the marine transport (cruisers, carriers, Navy ships, etc).

Table 2: *Examples of applications with temperatures of the heat source between 100-200°C.*

Heat source temperature (°C)	**Heat transfer fluid L/L G/L G/G**	**Applications**	**Thermodynamic efficiency (%) (Exergy efficiency) (%) *Same for supercon-ducting extra large scale system (10 Tesla)***	**Total mass for 5 kW_{el} (kg) (Total mass for 1 MW_{el}) (tons) Data only for perma-nent magnet based system**	**Possiblity of tech-nology to market penetration mark √ - very low √√ - low √√√ - medium √√√√ - high √√√√√ - very high**
100-180°C	L/L	Solar evacuated tube collector	9 -15% (45-46 %) ***12.3-22% (63-65 %)***	100-150 kg (18-22 tons)	*Small scale* √√√√ *Large scale* √√ *Supercond..* √√
100-180°C	L/L	Geothermal	9 - 15% (45-46 %) ***12.3-22% (63-65 %)***	Only large scale (18-22 tons)	*Large scale* √√√√ *Supercond..* √√√√√
100-200°C	L/L G/L	Industrial waste heat, CHP's includ-ing phosphor acid fuel cells	9-17 % (L/L) (46%) (L/L) ***12.3-24%* (L/L)** ***(63-65 %)* (L/L)** 7-15 % (G/L) (36 - 42 %) (G/L) ***10 -24%* (G/L)** ***(49 -59%)* (G/L)**	93-150 kg (L/L) (17- 22) (L/L) 97-183 kg (G/L) (18-24 tons) (G/L)	*For L / L* *Small scale* √√√√ *Large scale* √√√√ *Supercond..* √√√√√ *For G / L* *Small scale* √√√ *Large scale* √√√ *Supercond..* √√√√
100-200°C	L/L G/L	Transport vehicles	Same values as line above	93-150 kg (L/L) (17-22 tons) (L/L) 97-183 kg (G/L) (18-24 tons) (G/L)	*For L / L* *Small scale* √√ *Large scale* √√√√ *Supercond..* √√√√√ (large scale only in marine applications) *For G / L* *Small scale* √√ *Large scale* √√√ *Supercond..* √√√√ (large scale only in marine applications)

According to Table 3 and some results shown in Chapt. 4 the most feasible applications exist for sys-tems with temperature levels below 350°C. This results because above this level special metal alloys must be applied. This increases the complexity of the system and also the price rises. For applications of systems with temperatures below 350°C almost all presented applications - except systems in the transport domain (a feasibility is proven only for marine applications) - present a very good alternative for a future application of magnetic power conversion. This may be proven for "liquid/liquid applica-tions", despite that for "gas/liquid applications" also good efficiencies are theoretically predicted. At present there is almost no efficient magneto caloric material which could be applied at temperatures above 400°C. The main reason is that research activities for this domain was not very actively per-formed by the material scientists community. Because high temperature "gas/liquid magnetic power generators" require a rather complex systems design, it is concluded that such systems may be ap-plied only in large scale applications. This is also a reason why in Table 4 the total masses of small scale systems are not presented. For large scale systems the calculations have shown excellent re-sults, which leads to the conclusion that also such applications should be investigated in the future.

Table 3: *Examples of applications with temperatures of their heat source between 200-400°C.*

Heat source temperature (°C)	**Heat transfer fluid L/L G/L G/G**	**Applications**	**Thermodynamic efficiency (%) (Exergy efficiency) (%)** ***Same for supercon-ducting extra large scale system (10 Tesla)***	**Total mass for 5 kW_{el} (kg) (Total mass for 1 MW_{el}) (tons)** **Data only for perma-nent magnet based system**	**Possiblity of technology to market penetra-tion mark √ - very low √√ - low √√√ - medium √√√√ - high √√√√√ - very high**
300-400°C	L/L G/L	Solar parabolic-through technology	21 – 27 % (L/L) (44 – 48 %) (L/L) ***31 – 38 % (L/L)*** ***(64– 66 %) (L/L)*** 22-25 % (G/L) (45 %) (G/L) ***30 – 34 % (G/L)*** ***(62 – 63%) (G/L)***	Large scale only (16 ton) (L/L) Large scale only (16 ton) (G/L)	*For L / L* *Large scale* √√√√ *Supercond..* √√√√√ *For G / L* *Large scale* √√√ *Supercond..* √√√√√
200-400°C	L/L G/L	Industrial waste heat, CHP's, Incin-eration	17 – 27 % (L/L) (46 – 48 %) (L/L) ***24 – 38 % (L/L)*** ***(64– 66 %) (L/L)*** 15 – 25 % (G/L) (42 –45 %) (G/L) ***22 – 35 % (G/L)*** ***(59 – 63%) (G/L)***	76-93 kg (L/L) (16-17.5 tons) (L/L) 77-97 kg (G/L) (16-18 tons) (G/L)	*For L / L* *Small scale* √√√√ *Large scale* √√√√ *Supercond..* √√√√√ *For G / L* *Small scale* √√√√ *Large scale* √√√√ *Supercond..* √√√√√
200-400°C	G/L	Transport vehicles (e.g. catalyst, rear muffer)	15 –25 % (G/L) (42 –45 %) (G/L) ***22 – 35 % (G/L)*** ***(59 – 63%) (G/L)***	77-97 kg (G/L) (16-18 tons) (G/L)	*Small scale* √√√ *Large scale* √√√ *Supercond..* √√√√√ (large scale only in marine application)

Table 4: *Examples of applications with temperatures of their heat source between 400-750°C (only for gas/liquid).*

Heat source temperature (°C)	**Heat transfer fluid L/L G/L G/G**	**Applications**	**Thermodynamic efficiency (%) (Exergy efficiency) (%)** ***Same for supercon-ducting extra large scale system (10 Tesla)***	**Total mass for small scale 5 kW$_{el}$ (kg) (Total mass for large scale 1 MW$_{el}$) (tons)** **Data only for perma-nent magnet based system**	**Possiblity of technology to market penetra-tion mark** **√ - very low** **√√ - low** **√√√ - medium** **√√√√ - high** **√√√√√ - very high**
400-550	G/L	Solar tower technol-ogy	25 –27 % (G/L) (41 –45 %) (G/L) *35 – 42 % (G/L)* *(63%) (G/L)*	Large applications only (17 tons) (G/L)	*Large scale* √√√√ *Supercond..* √√√√√
400-750	G/L	Industrial waste heat, CHP's, Incin-eration	25 –29 % (G/L) (41 –45 %) (G/L) *35 – 45 % (G/L)* *(63%) (G/L)*	Large applications only (11-17 tons) (G/L)	*Large scale* √√√√ *Supercond..* √√√√√
600-750	G/L	Molten carbonate fuel cells, solid oxide fuel cell	28 –29 % (G/L) (41 –45 %) (G/L) *41 – 42 % (G/L)* *(63 – 64 %) (G/L)*	Large applications only (11-17 tons) (G/L)	*Large scale* √√√√ *Supercond..* √√√√√
400 - 550	G/L	Transport vehicles (catalyst)	25 –27 % (G/L) (41 –45 %) (G/L) *35 – 42 % (G/L)* *(63%) (G/L)*	Large applications only (17 tons) (G/L)	*Large scale* √√√√ *Supercond..* √√√√√ (large scale only in marine applica-tions)

5.2. Proposed best applications of magnetic power generation

The most feasible magnetic power conversion technologies are detected and proposed according to their temperature level and type of heat source. The selection procedure took into account the present and near future availability of magneto caloric materials. This was also a reason, why applications with temperatures of heat sources higher than e.g. 350°C were not selected and classified as suitable. Furthermore, this study shows that all the applications with temperature sources below 80°C most probably would not lead to a good economic exploitation, because of the very low thermodynamic efficiency, despite that they show an excellent exergy efficiency. Therefore, a selection was only taken from the applications listed in Tables 1, 2 and 3. Despite that systems with heat source temperature levels of 80-100°C cannot provide a high thermodynamic efficiency, it has to be emphasized that such heat sources present an enormous (nearby unlimited) potential. This is the case especially when natural sources are regarded and also numerous waste heat sources show this feature. Because magnetic power generators for different applications not differ in their design so much, the proposed best applications are based only on the temperature levels of the heat source and the connected working fluid and not on the specific application. It may be generally stated that the most feasible applications of the magnetic power generation technology are found to be systems with heat source temperature levels below 350°C. The largest number of feasible systems occur even in the domain of even lower temperature level systems, namely such with temperatures below 200°C (see Table 5).

Table 5: *Proposed best applications of magnetic power generation.*

Type of source	Temperature 80-100°C	Temperature 100°C – 200°C	Temperature 200°C – 350°C
Solar	80-90°C Small scale permanent magnet liquid / liquid type magnetic power generator utilizing plate collectors	120°C-180°C Small scale permanent magnet liquid / liquid type magnetic power generator utilizing evacuated tube collectors	300-350°C Large scale permanent magnet or superconducting liquid / liquid type magnetic power generator utilizing parabolic through technology
Geothermal	80-100°C Large scale superconducting liquid / liquid type magnetic power generator utilizing low temperature geothermal heat	100°C-180°C Large scale superconducting liquid / liquid type magnetic power generator utilizing high temperature geothermal heat	/
Waste heat in Fuel Cells	80-100°C Small or large scale scale permanent magnet liquid / liquid type magnetic power generator utilizing heat from alkaline or polymer electrolyte membrane fuel cell	150-200°C Large scale permanent magnet liquid / liquid type magnetic power generator utilizing heat from phosphoric acid fuel cell	/
Waste heat in small CHP's	80-100°C Small scale permanent magnet liquid / liquid type magnetic power generator utilizing heat of cooling of gas / diesel piston generators	100°C-200°C Small scale permanent magnet gas / liquid type magnetic power generator utilizing heat of exhaust gases of higher temperatures	200°C-350°C Small scale permanent magnet gas/liquid type magnetic power generator utilizing heat of exhaust gases
Waste heat in industry	80-100°C Small large scale permanent magnet or extra large scale superconducting magnet liquid / liquid type magnetic power generator utilizing heat	100-200°C Small large scale permanent magnet or extra large scale superconducting magnet liquid/liquid and for higher temperatures gas / liquid type magnetic power generator utilizing heat	200-350°C Small large scale permanent magnet or extra large scale superconducting magnet liquid / liquid and for higher temperatures gas / liquid type magnetic power generator utilizing heat
Waste heat in large CHP's	80-100°C Small large scale permanent magnet or extra large scale superconducting magnet liquid / liquid type magnetic power generator utilizing heat	100-200°C Small large scale permanent magnet or extra large scale superconducting magnet liquid / liquid and for higher temperatures gas / liquid type magnetic power generator utilizing heat as steam, gases or water at lower temperatures	200-350°C Small large scale permanent magnet or extra large scale superconducting magnet liquid / liquid and for higher temperatures gas / liquid type magnetic power generator utilizing heat as steam, gases or water at lower temperatures
Waste heat in transport	80-100°C Large scale superconducting liquid / liquid type magnetic power generator utilizing heat from engines in large marine applications	100°C-200°C Large scale superconducting liquid / liquid or gas / liquid-magnetic power generator utilizing heat from exhaust gases in large marine applications	200°C-350°C Large scale superconducting liquid / liquid or gas / liquid magnetic power generator utilizing heat from exhaust gases in large marine applications

6. CONCLUSIONS AND OUTLOOK

This report demonstrates a large potential for the magnetic power conversion technology. It is a serious alternative to the conventional technologies, especially in domains where the systems heat is of low exergy, e.g. below 350°C. This kind of heat sources may be found in a variety of different applications. Also for conventional systems a successful conversion of heat into electricity is still not completely solved. Many efforts in research and development are still ongoing in thermoelectrics, Stirling machines, Organic Rankine Cycles (ORC), etc. This report shows that another technology, namely- magnetic power conversion, may be a serious candidate for a more economic energy conversion in the future.

The report demonstrates that the selection of an appropriate working fluid strongly influences the efficiency of magnetic power machines. Magnetic flux densities required to overcome the known efficiencies of existing conventional systems should be above 1.5 Tesla. Proposed magnetic machines should be equipped with wheels showing a filling degree of magneto caloric materials of approximately 30%. Furthermore, this is only obtainable in systems which are operating with liquids. Any additional increase of the magnetic flux density leads to a better efficiency. However, applications of magnetic flux densities above 2.5 Tesla would require superconducting magnets. This is only feasible in very large scale systems. For large systems the magnetic power conversion technology surely has a high potential. The results of this report reveal that the efficiency increase, influenced by the magnetic field strength, converges asymptotically towards a high magnetic field. Therefore, the conclusion is that superconducting magnet systems should be designed to obtain magnetic field strengths of approximately 10 Tesla. Furthermore, a high frequency of operation positively influences the reduction of the total volume and the total mass of a device. On the other hand a higher frequency decreases the efficiency of a machine. This relation is much stronger for permanent magnet based than for superconducting based systems. At high temperatures of the heat source the frequency of operation does not have a so strong effect on the efficiency. Results of this report show that volume fractions of the magneto caloric material in a porous wheel for the “liquid/liquid-” and “gas/liquid applications” should be some 30 %, while for gases this fraction must be reduced to approximately 10% to 15 %.

The last chapter of this report presents the most feasible magnetic power generation technologies, divided into groups by the temperature level and the type of their heat sources. Because numerous very good applications have been detected, the authors of this report propose the following application to be further investigated in the future (furthermore, a building of a corresponding prototype is proposed):

- Permanent magnet based small scale magnetic power generator (2 Tesla)
- Heat source temperature 120 °C / heat sink temperature 25°C
- Liquid / liquid based system with 30% of volume fraction
- Maximum frequency of operation 5 Hz
- Output electric power 1 kW
-

The main reasons for this proposal are the following:

- Present availability of magneto caloric materials is given only for low temperature levels
- The temperature difference between heat source and heat sink is not too large
- The heat source temperature allows an application of water or water based fluids
- Possibility of up-scaling by a complete or incomplete physical modeling technique is given
- The proposal covers a very large domain of different applications
- Such a device would present a first magnetic power generation prototype, performed not only for a demonstration of the effect leading to a Milliwatt power conversion rate as the Curie wheel and the Palmy wheel designed and built up-to-present
- It would also mean a start into a development of a future market-suited low exergy power conversiondevice, which is based on an extremely environmentally benign technology.

A further important task could be to perform a similar study as the present one, but for static magnetic power conversion machines. If a static block of magneto caloric material is periodically heated and cooled down again a surrounding coil of this block induces an electrical current. Such a device is simple to construct and could also be very promising.

NATIONAL AND INTERNATIONAL COLLABORATIONS

Because the work performed in this project and the efforts taken in other studies of magnetic heating and refrigeration are related, all the national and international collaborations, which are described in Ref. [22], are also contributing to this project. Instead of repeating them here, we refer to this reference.

Additionally it must be mentioned that by P.W. Egolf a DUO diploma work was initiated. DUO was recently introduced at the University of Applied Sciences of Western Switzerland and means a joint diploma work of a student of engineering and of economy. The related diploma works will be finalized end of this year. It must also be mentioned that experts from Nestlé in Vevey participate in this DUO diploma work with all their expertise. They have defined an example of waste heat treatment, which is evaluated for an application of the magnetic energy conversion technology by the two HEIG-VD diploma students

At present a Hesso (Haute Ecole Specialisé de Suisse Occidental) project with the name "Valotherm" is running in order to investigate a waste heat utilization by magnetic power conversion in greater detail.

BASF, Divison Future Technologies, shows a large interest in the magnetic power conversion technologies. Experts from this company started a collaboration with scientists from HEIG-VD/SIT.

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