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The thermomagnetic Curie-motor for the conversion of heat into mechanical energy

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Abstract — The Curie-motor converts heat into mechanical energy when one side of its mobile soft magnetic rotor in the magnetic field is heated up to Curie temperature. The saturation flux density of the heated rotor material decreases, the energy of the magnetic field stored at this location increases. The magnetic rotor is pulled into the magnetic field. This paper presents the calculations simulating the dynamic behaviour of the motor when heated by focused solar radiation. Various design principles are shown, potential applications are described and discussed. The simulations show that the motor can generate magnetic forces as strong as a conventional magnetic device of similar size and identical saturation flux density of the rotor. However, the achievable speed is low. © 2001 Éditions scientifiques et médicales Elsevier SAS

heat / mechanical energy / magnetic energy / Curie temperature / solar radiation

Nomenclature

b	width of the magnetic rotor/ the armature	m
$\boldsymbol{B}$	magnetic flux density, induction	V·s·m^{-2}
B_A	flux density in the gap	V·s·m^{-2}
B_S	saturation flux density	V·s·m^{-2}
$B_{S_{max}}$	maximum saturation flux density	V·s·m^{-2}
d	thickness of the rotor	m
e_n	unit vector	
F	force	N
F_m	magnetic force	N
$\dot{g}$	heat generation rate	W·m^{-3}
$\boldsymbol{H}$	magnetic field strength	A·m^{-1}
k	thermal coductivity	W·m^{-1}·K^{-1}
M	module in the explicit difference method	
N	magnetic North Pole	
$\dot{q}$	heat flux	W·m^{-2}
S	magnetic South Pole	
s	distance	m
s_A	length of the rotor in the gap	m
t	time	s
T	thermodynamic temperature	K
V	volume	m^3
W_m	energy of the magnetic field	J
w_m	energy density of the magnetic field	J·m^{-3}
v	velocity	mm·s^{-1}
x	coordinate	
P	power	W

Greek symbols

α	absorptivity;	
	thermal diffusivity	m^2·s^{-1}
Δx	section size in x-direction	m
ϑ	temperature	°C
ϑ_A	temperature of the armature/rotor	°C
ϑ_C	Curie temperature	°C
ϑ_U	ambient temperature	°C
η_{therm}	thermal efficiency	
η_{ex}	exergetic efficiency	

1. INTRODUCTION

A Curie-motor consists of a magnetic circuit with a movable soft magnetic rotor in its gap. In the gap one side of the rotor is heated up to Curie temperature. Thus the energy of the magnetic field there increases. A magnetic force arises between the heated and the still cold rotor sections. When the magnetic force increases above the external forces at the rotor, this is further

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pulled into the gap. By continuous heating a continuous movement of the rotor can be achieved.

This way to convert heat energy directly into mechanical energy has inspired many scientists since its discovery. This is reflected by many world wide patent applications [1–3]. In some cases an industrial applicability was tested [4–6], but not yet realized.

This may be caused by the fact, that heating up a material is a slow process, so that the anticipated dynamic does not allow such speeds as usual with electrical motors. And the Curie temperature is usually relatively high—at soft iron at about 1000 K. Thus the motor has a high demand for heat. Today materials with low Curie temperature are available, so that applications close to room temperature now become possible.

The motor can be designed in a simple way when a permanent magnet for the generation of the magnetic field is used, so that no coil with electric connections is necessary. The result is a simple and robust motor. Due to today's achievable energy densities of permanent magnets the motor will be attractive for small dimensions.

This paper presents designing instructions and calculations of the motor. Based on simulations an estimation of the performance of the optimized Curie-motor is made. Applications of the motor and its market potential are discussed.

1.1. Function and design

The basic function of the Curie-motor is explained by means of a model.

The design outlined in *figure 1* represents a linear motor, with a soft magnetic, movable armature—the 'flat rotor'. The magnetic field is generated by a fixed permanent magnet. A homogeneous magnetic field without leakage is assumed.

To operate the motor the warm side of the armature is heated by thermal radiation or by convection. The armature must usually be heated outside the gap, because this is not accessible.

By heat conduction along the armature, the temperature in the gap increases and the magnetic properties change, especially the saturation flux density of the armature material decreases. The cold side of the rotor is kept at initial temperature by cooling.

If the warm side of the armature is heated above Curie temperature, it behaves there magnetically like air or vacuum. Thus the energy density of the magnetic field increases. At the cold side the armature keeps its magnetic characteristics, the energy density remains low. A magnetic force results in direction of the higher energy density of the warm side. Since the armature is movable, it is drawn into this direction, if the magnetic force is greater than the sum of the external forces applied to the armature.

Under the mentioned conditions the Curie-motor performs like a conventional magnetic device.

In reality however, the Curie-motor will not produce a sharp boundary surface between warm and cold side. The boundary will rather be blurred due to the evolving temperature gradient. Also the temperature of the warm side will not be always above the Curie temperature. In this case the ferromagnetic properties of the material do not disappear completely, but a reduction of the saturation flux density depending on the temperature will occur. This results also in an increase of the energy density of the magnetic field, producing also a magnetic force. This is smaller than in a conventional magnetic device.

Beside the linear form of the Curie motor, there are designs allowing rotational movements as shown in *figure 2*.

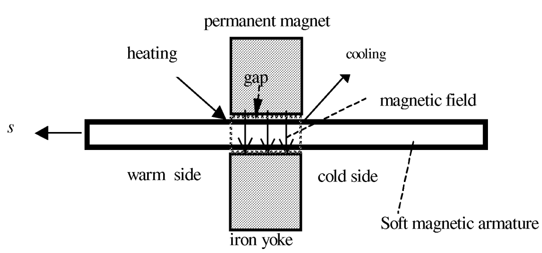

Figure 1. Model, function of the Curie-motor.

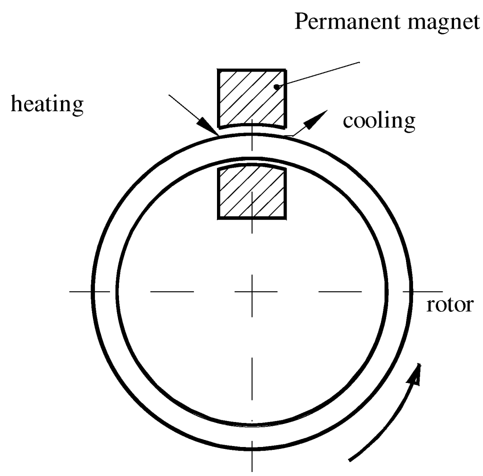

Figure 2. Curie-motor, rotational version.

2. ANALYSIS

In the following paragraph the basic procedure of calculating the dynamic behaviour of the Curie-motor is described:

The magnetic force F_m must be determined under operating conditions.

F_m can be calculated from the change of energy of the magnetic field, $\mathrm{d}W_m$ as follows:

$$\boldsymbol{F}_m = \frac{-\,\mathrm{d}W_m}{\mathrm{d}s}\boldsymbol{e}_n \tag{1}$$

with

$$W_m = \int_V w_m \,\mathrm{d}V \tag{2}$$

and

$$w_m = \int_{B=0}^{B_A} H(B)\,\mathrm{d}B \tag{3}$$

with w_m as the energy density of the magnetic field. V is the volume of the rotor or the armature in the gap.

The energy density depends on the magnetic flux density in the gap and on the saturation flux density of the rotor material in the gap. The saturation flux density has to be determined from the hysteresis curve of the rotor material (*figure 3*).

For the Curie-motor the initial curve is important, because the material is always magnetized from the unmagnetic state. From the initial curve the saturation flux density and the energy density of the magnetic field can be read, as outlined in a schematic initial curve, *figure 4*.

We assume, that the magnetic flux density B_A in the gap is greater than the saturation flux density B_S of the rotor material in order to make maximum use of the capability of the material.

As can be seen the energy density depends significantly from the saturation flux density of the material. Since this depends on the temperature, the temperature distribution in the rotor-material must be known. The heat conduction equation

$$\rho c(\vartheta)\frac{\partial \vartheta}{\partial t} = \mathrm{div}\big[\lambda(\vartheta)\,\mathrm{grad}\,\vartheta\big] + \dot{W}(\vartheta, \mathbf{x}, t) \tag{4}$$

is to evaluate, considering the heating and cooling of the rotor as well as the initial values. From the transient temperature field the corresponding magnetic properties are determined for every point of the rotor. With the operating point of the permanent magnet and with (3), the energy of the magnetic field can be determined. With (1) the magnetic force can be calculated. When the magnetic force exceeds the external forces acting on the rotor, the rotor is accelerated. The mechanical power of the motor can be determined from that.

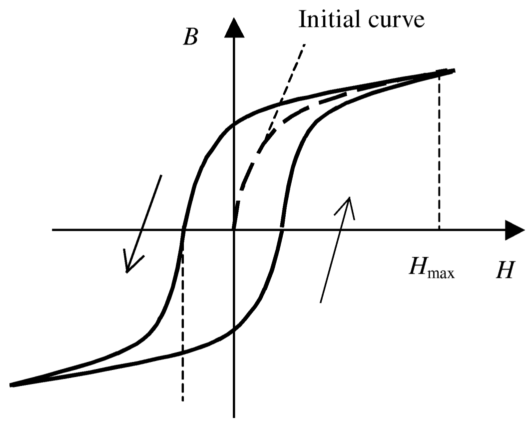

Figure 3. Hysteresis curve. Magnetic flux density B as a function of the field strength H, initial curve and hysteresis loop of ferromagnetic materials.

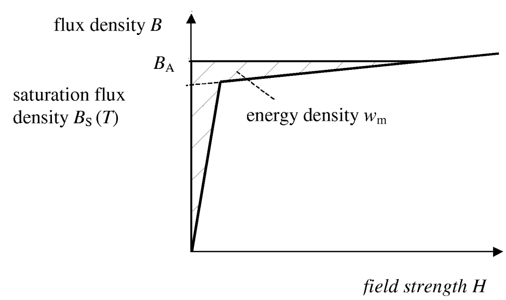

Figure 4. Schematic initial curve.

The calculation is represented in [7] in detail.

3. MATERIAL PROPERTIES

Important for the Curie-motor are the temperature dependent properties of the soft magnetic rotor material, in particular the dependence of the saturation flux density. According to [8] this is similar for all ferromagnetic materials and it is shown in *figure 5*.

It can be recognized that the saturation flux density decreases with increasing temperature and becomes zero at a temperature characteristic for the material, the Curie temperature. With decreasing temperature the saturation flux density moves to a maximum value, that is designated as $B_{S_{max}}$. In the following we name the tempera-

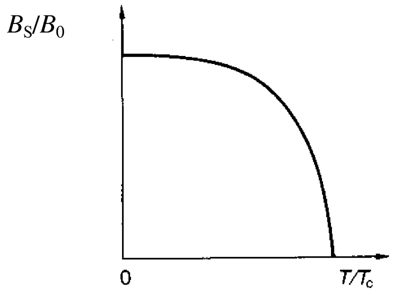

Figure 5. Dependence of the saturation flux density of the temperature, standardized representation.

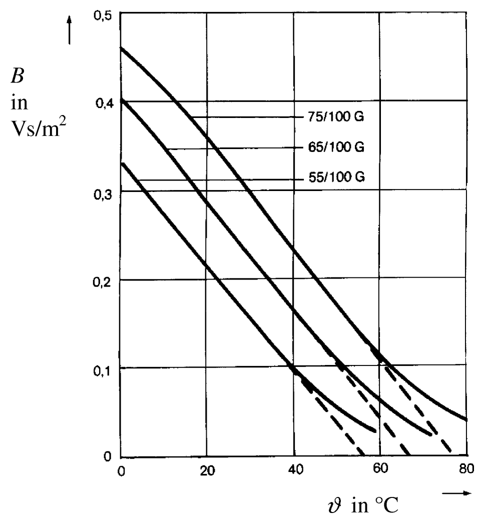

Figure 6. Saturation flux density B as a function of temperature B of Thermoflux®[9]. Three variants, Curie temperature 55 °C, 65 °C and 75 °C.

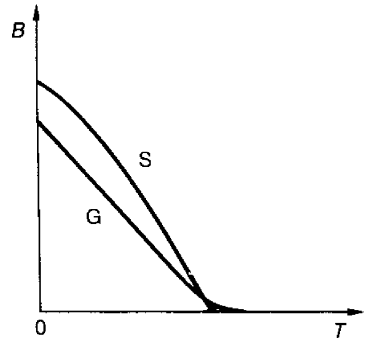

Figure 7. Saturation flux density of Thermoflux, Variants S and G [9].

ture at which the maximum saturation flux density $B_{S_{\max}}$ is reached, reference temperature ϑ_0.

As shown in [8], this maximum saturation flux density is reached theoretically at $T = 0$ K.

For practical applications however the flat rise of the saturation flux density at low temperatures is of less importance. The reference temperature relevant for application is therefore higher than 0 K. For the operation of the Curie-motor the temperature range near to the Curie temperature is favourable. $B_{S_{\max}}$ is then the saturation flux density at the lower temperature boundary of the application. This lower temperature boundary becomes the reference temperature ϑ_0. A set of materials with different Curie temperatures and different values $B_{S_{\max}}$ are commercially available. So the Curie-motor can be optimized with a suitable material choice for the application at various working temperatures.

Soft magnetic materials with low Curie temperature are especially interesting in order to be able to use the motor close to room temperature. The material Thermoflux, an iron-nickel alloy, is very suitable. Its Curie temperature can be tuned by the nickel content between +30 °C and +120 °C. In *figure 6* the saturation flux density as a function of temperature is shown.

By appropriate processing methods the gradient of the saturation flux density depending on the temperature can be varied, *figure 7*. This has an important influence on the necessary temperature difference between warm and cold side of the Curie-motor and is therefore an important design-parameter.

4. NUMERICAL MODEL

The model of the motor in *figure 8* is the base for the numerical analysis of the operational behaviour.

Without essential restriction [7], the calculation of the transient temperature distribution can be handled as a geometrically linear problem with constant material values. The heat conduction equation is valid in the following form:

$$\frac{\partial \vartheta}{\partial t} = \alpha \frac{\partial^2 \vartheta}{\partial x^2} \tag{5}$$

It efficiently can be solved numerically through the explicit difference method [10]. Therefore the armature is divided in x-direction into sections of the size Δx. The temperature ϑ in a segment x_i at the time t_k is

$$\vartheta_i^k = \vartheta(x_i, t_k)$$

The calculation of the temperatures is made by the finite difference equation derived from equation (5)

$$\vartheta_i^{k+1} = M\vartheta_{i-1}^k + (1 - 2M)\vartheta_i^k + M\vartheta_{i+1}^k \tag{6}$$

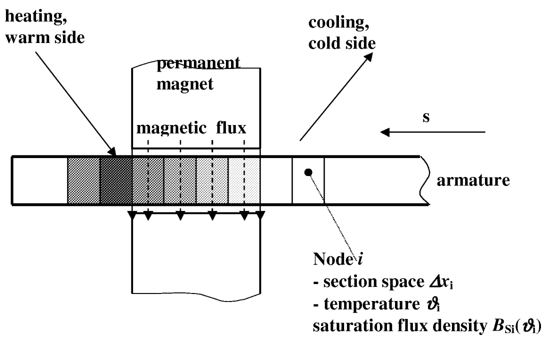

Figure 8. Model for the numeric analysis.

with

$$M = a\Delta t/\Delta x^2$$

the module of the computation that must be less than 1/2 for stability reasons.

The results of these calculations can be applied to the rotating Curie-motor if the rotor shows a small curvature. In addition the first computing section must be linked with the last segment due to the closed structure of the rotor.

For the calculation of the operational behaviour of the Curie-motor it is necessary to consider heating and cooling not only at the right and the left boundary of the armature, but at all other sections as well. Therefore the explicit difference equation is considered for the case, when heat generation occurs.

Here is valid:

$$\vartheta_i^{k+1} = M\vartheta_{i-1}^k + (1-2M)\vartheta_i^k + M\vartheta_{i+1}^k + \left(M\Delta x^2/\lambda\right)\dot{g}_i^k \qquad (7)$$

where $\dot{g}_i^k$ is the heat generation rate related to the volume of a section. By replacing $\dot{g}_i^k$ by a heat flux $\dot{q}_i^k$ related to the surface of the section, as occurs in case of heating through convection or radiation, the following is valid:

$$\vartheta_i^{k+1} = M\vartheta_{i-1}^k + (1-2M)\vartheta_i^k + M\vartheta_{i+1}^k + \left(\frac{M\Delta\, x^2}{d\lambda}\right)\dot{q}_i^k \qquad (8)$$

In accordance with the derivation $\dot{q}_i^k$ is positive in case of heating the armature.

4.1. Geometry and material data

The following dates are supposed to be valid for the calculations:

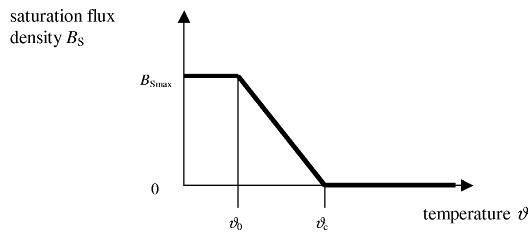

Figure 9. Saturation flux density depending on the temperature.

- Armature measures:

– Width, perpendicular to magnetic field and to direction of the motion, $b = 20$ mm.

– Length of the gap in direction of the motion, $s_A = 12$ mm.

– Thickness in field direction, $d = 1$ mm.

– Section size $\Delta x = 2$ mm.

- Materials:

– The permanent magnet is an AlNiCo-magnet, because of its high Curie temperature and its small sensitivity to temperature.

– Thermoflux is employed for the soft magnetic armature. Following dates are put as a basis: Curie temperature $\vartheta_C = 90\,°C$, maximum saturation flux density $B_{S_{max}} = 0.3$ V·s·m^{-2}, thermal conductivity $k = 15$ W·m^{-1}·K^{-1}. The temperature dependency of the saturation flux density is linearized by following approach: Reference temperature $\vartheta_0 = 40\,°C$, saturation flux density at ϑ_0 is $B_S = B_{S_{max}} = 0.3$ V·s·m^{-2}. The saturation flux density at the Curie temperature is $B_S = 0$; *figure 9*.

- The ambient temperature is $\vartheta_U = 20\,°C$.

4.2. Results

In the following simulations the operational behaviour of a Curie-motor is shown, which is heated by means of focused solar radiation. The cold side is cooled by free convection. If in case of small motors the cooled surface of the armature is not sufficient large to keep it at reference temperature, it must be cooled actively. This decreases the efficiency.

As pre-calculations showed, the radiation energy of natural solar radiation is not great enough to heat the warm side of the armature up to Curie temperature, since a strong cooling effect occurs simultaneously by heat conduction. Therefore for the simulations focused radiation is put as a basis. In real applications the radiation can be focused by lenses or concave mirrors.

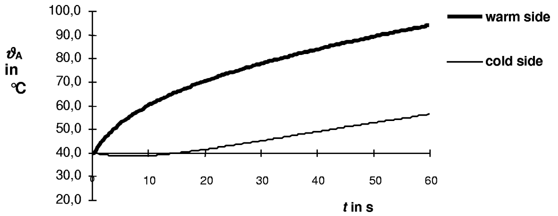

Figure 10. Armature temperature of warm and cold side, fixed armature.

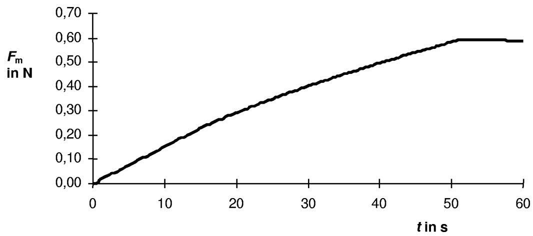

Figure 11. Magnetic force, fixed armature.

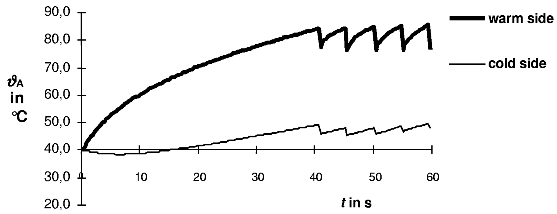

Figure 12. Armature temperatures, armature in motion.

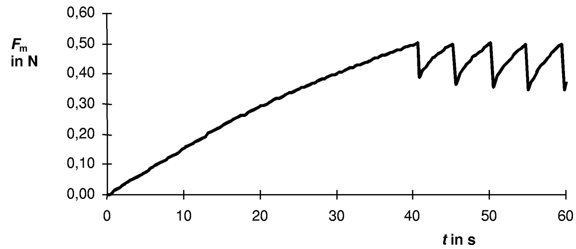

Figure 13. Magnetic force, armature in motion, external load $F = 0.5$ N.

Actually a radiation of 60 000 $\mathrm{W{\cdot}m^{-2}}$ and an absorptivity $\alpha = 1$ is assumed.

For geometrical reasons the heating of the armature must occur outside of the gap since it is covered by the magnetic poles. The heating of the rotor material in the gap is effected by conduction. To avoid additional losses, the solar radiation must be focused close to the gap.

The heating of a fixed armature having an initial temperature of 40 °C is shown in *figure 10*. The temporal process of the armature on warm and cold side is represented.

It shows that it takes about 50 s until the warm side reaches Curie temperature. Only after this initial period the motor achieves its maximum force, *figure 11*.

This magnetic force reaches a value like the average force calculated for a conventional magnetic device if an armature with the same saturation flux density is used.

For the evaluation of the dynamic behaviour an external load of $F = 0.5$ N acting on the armature is assumed. If the calculated magnetic force exceeds this value, the armature moves one section. The corresponding temporal process of temperature and the magnetic force are shown in *figures 12* and *13*.

Figure 13 shows, that after about 40 s the required force of $F = 0.5$ N is reached.

Further on, four steps, represented by the sawtooth pattern are shown. This corresponds to a distance of 8 mm in 20 s and an average velocity of only $v = 0.4\ \mathrm{mm{\cdot}s^{-1}}$.

With the force of $F = 0.5$ N the motor delivers a mechanical power of

$$P_{\mathrm{mech}} = 0.20{\cdot}10^{-3}\ \mathrm{W}$$

The power spent for the heating is

$$P_{\mathrm{zu}} = 2.4\ \mathrm{W}$$

The thermal efficiency is

$$\eta_{\mathrm{therm}} = \frac{P_{\mathrm{mech}}}{P_{\mathrm{zu}}} = \frac{0.20{\cdot}10^{-3}\ \mathrm{W}}{2.4\ \mathrm{W}} = 8.3{\cdot}10^{-5}$$

and thus very low.

For the determination of the exergetic efficiency first the efficiency of a Carnot-process between reference temperature and Curie temperature is calculated.

The thermal efficiency of the Carnot-process is:

$$\eta_{\mathrm{Carnot}} = 1 - T_{\mathrm{C}}/T_0 = 1 - 313/363 = 0.14$$

With the calculated thermal efficiency of $\eta_{\mathrm{therm}} = 8.3{\cdot}10^{-5}$ one receives an exergetic efficiency of

$$\eta_{\mathrm{ex}} = \eta_{\mathrm{therm}}/\eta_{\mathrm{Carnot}} = 5.9{\cdot}10^{-4}$$

is achieved, which is also very low.

The Curie-motor therefore is not suitable for the generation of significant mechanical energy from heat. If one wants anyhow to produce mechanic energy in a considerable order, the motor must be enlarged correspondingly, increasing the costs. The system is not economical for energy production.

4.3. Comparison to conventional magnetic devices

In a conventional magnetic system a soft magnetic armature is drawn into an air gap. A further motion is not possible, whilst the Curie-motor can produce a continuos motion.

With respect to forces it was shown, that both systems can achieve the same magnetic forces, if the following conditions are given: The warm side of the Curie-motor has Curie temperature, the cold side has reference-temperature. Further the gap and the saturation flux density of the armature must be the same in both cases.

Differences show however in the forces, when both devices are optimized with regard to magnetic force for application close to room temperature:

In a conventional magnetic system an armature material with great saturation flux density can be used. For the Curie-motor a material with low Curie temperature must be employed. Such materials have however a relatively small maximum saturation flux density. Thus also the maximum magnetic forces are smaller here. Since the magnetic force depends on the square of saturation flux density, the difference of the forces becomes considerable.

In applications at higher temperatures, materials with high saturation flux densities can be used for the Curie-motor. In this case the achievable forces under the mentioned conditions are as great as those of the conventional systems.

5. APPLICATION AND MARKET

The Curie-motor competes to systems that convert also heat or radiation into mechanical energy. The most important variants are Stirlingmotor or comparable heat engines, electrical motor plus solar cell and devices that use the memory-effect of specific alloys.

Compared with these devices the Curie-motor indicates the following advantages and disadvantages:

• Advantages:

+ force and torque at high temperature comparably to conventional magnetic devices,

+ simple structure,

+ robust,

+ small dimension design possible,

+ reverse direction of rotation just by exchanging of warm and cold side without further modification of the construction possible,

+ driving power by radiation possible,

+ adaptable for applications at different, also very high, temperatures through selection of suitable material.

• Disadvantages:

– force and torque at applications at room temperature smaller than with optimized conventional magnetic systems,

– in the comparison to the electrical motor only low speed achievable,

– small efficiency,

– high cost for a design for high power.

As shown, the motor is not suitable for the generation of greater power rates. However, for applications not requiring high power or speed, chances on the market are seen. To mention are:

• Motors of very small dimensions: If a permanent magnet is employed for the generation of the magnetic field, coils, necessary with an electro–mechanical device, are unnecessary. A heating-resistor can be used as a heat source which is smaller than a coil. Employing a radiation source, like a laser, allows flexible constructions by the decoupling of motor and heat source.

• Application in measurement and control: The Curie-motor develops its maximum force if one heats up the warm side to Curie temperature. So the force of the motor is also a measure of the temperature of the warm side. The Curie-motor can be used as a measuring drive in the control engineering. The advantage of the motor is, that it provides a continuous movement with corresponding application of heat. It shows thereby an integrating behaviour with integrated measuring. By selection of the appropriate material, the Curie temperature can be adapted to the particular requirements.

• Cooling of thermally loaded components. The heat transportation is supported here by the movement of the rotor.

• Tracking Systems:
The motor is conceivable for tracking with small demand for speed.

• Physical Demonstrator:
The motor can be used in the field “Demonstration of Physical Effects” for which a broad market with target audience of schools and universities exists [11]. With

the Curie-motor the temperature dependency of magnetic properties and heat conduction can be demonstrated impressively.

6. EXPERIMENTS

With a test set-up according to *figure 14* first experiments were carried out, basically confirming the simulation results.

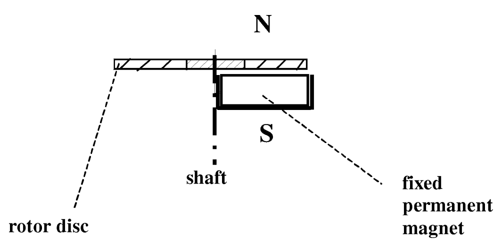

Figure 14. Draft of the experimental model.

The rotor of the experimental model is designed as a rotational disc which is attached in a low-friction way by means of a ball bearing.

This design is an especially robust and low-cost construction. The rotor was heated by hot water and focused solar radiation. To improve the heating through radiation, the surface was coated black.

In future this model will be optimized with regard to function and costs so that a marketing is possible, at first, as a physical demonstration model.

7. SUMMARY AND CONCLUSIONS

As the results of the simulations show, the Curie-motor can compete with conventional magnetic devices of comparable size and saturation flux density with regard to the magnetic force. Provided, the heat flux applied to the warm side of the motor is sufficiently great. So in case of heating by solar radiation the maximum force is achieved only by focusing with mirror or lens systems.

However, the computations show that the speed to be expected is small in comparison with electrical motors, the thermal efficiency is in the range of only some thousandth percent.

Thus only in exceptional cases the motor is suitable for the generation of higher speeds, but it can be used as an actuator due to the achievable forces.

Following constructive demands can be derived in order to achieve a high performance of the motor:

- The energy for the heating of the motor must be brought in close to the gap in a concentrated way. It is even more favourable to heat up the rotor directly in the gap. This is however hardly accessible because of the necessary magnetic poles.
- In order to keep the losses by conduction at a minimum, the rotor should consist of segments, isolated thermally from each other. Higher costs of such a design are compensated by a better thermal efficiency.
- The maximum saturation flux density of the rotor material should be as high as possible and the saturation flux density should rapidly decrease with the temperature. This is given for materials with high Curie temperature. With materials with a Curie temperature near room temperature the saturation flux density for the materials commercially available is comparably small, so that the achievable magnetic forces remain here likewise small.

Apart from the disadvantages of the motor, as low speed and low efficiency, a set of advantages can be stated, as for example its robustness and compact design, which make it favourable for specific applications, where particularly small dimensions are required. Further fields of application are tracking systems where small speeds are required.

The motor has advantages also for the use as a cooling device for sensitive thermally loaded components. The heat is transferred not only through conduction, but also through the movement of the rotor.

The motor is suitable also for applications, where the temperature is used as an input parameter for control-systems. It can be employed in this case as a measuring controller that allows continuous movements and shows so integrating behaviour.

Further applications as a physical demonstration model with which the effects of the temperature on magnetic properties are shown impressively are to be called.

Preliminary tests showed that one can realise the last-mentioned applications without considerable development effort and without special demands on the manufacturing. A rapid market entrance could be enabled by such an application.

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