ACTA TECHNICA CORVINIENSIS
BULLETIN OF ENGINEERING

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COMPUTATIONAL THERMAL ANALYSIS OF MULTIPLE DISC TYPE ROTARY MAGNETIC REFRIGERATION SYSTEM

Abstract:
Energy crisis and climate change are rocking the entire world at this moment. Refrigeration forms a major power consumer, ranging from domestic applications to industrial applications. Apart from a leading energy absorbing system, it also takes part in global warming by letting out harmful ozone depleting substances and hence turns against the environment. It is the right time to switch over from the conventional compressor based refrigeration systems. Magnetic refrigeration proves itself to be highly efficient and environmental friendly refrigeration system, making it to be the most promising source of cooling systems in the near future. Simulation of the magneto caloric refrigeration system using computational fluid dynamics approach forms the major part of this paper.

Keywords:
Magnetic refrigeration, magneto-caloric effect, magneto-caloric material, magnetic entropy, Computational Fluid Dynamics, star CCM plus

INTRODUCTION - MAGNETIC REFRIGERATION

With alarming issues like ozone layer depletion, global warming and climate changes, the conventional systems have to make their way through environmental-friendly application areas. Refrigerators play a significant role in environmental pollution by releasing harmful ozone layer penetrating agents. Hence, a new process must be devised for refrigeration technology which must be free from the polluting agents and also it must be able to work under low energy consumption. Since power conserved is power produced, the system should be capable of working with high efficiency. Magnetic refrigeration technology provides a promising future in this regard by being a vibration free, noise free, eco-friendly, non-polluting, highly efficient refrigeration technology. This paper gives a basic idea on magnetic refrigeration explaining the magneto caloric effect, the associated thermodynamic relations and cycles, heat transfer system along with the validation of design using gadolinium discs for refrigeration using computational fluid dynamics simulation.

COMPARISON WITH CONVENTIONAL REFRIGERATION

The efficiency of magnetic refrigeration can be 30–60% of Carnot cycle, whereas the efficiency of vapour compression refrigeration is only 5–10% of Carnot cycle[15]. Therefore, the magnetic refrigeration is expected to have great applicable prospects.

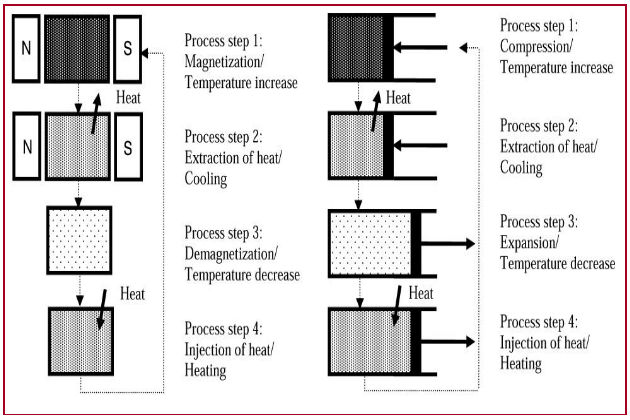

Fig 1.1 Comparisons between Magnetic Refrigeration and Vapour Compression Refrigeration [3]

MAGNETO-CALORIC EFFECT

Magnetic refrigeration utilizes the magneto-caloric effect. This effect causes a temperature change when a certain metal is exposed to a magnetic field. All transition metals and lanthanide series elements obey this effect. This tends the metal to heat up as a magnetic field is applied. As the magnetic field is applied, the magnetic moments of the atom align. When the field is removed, the material cool down since the magnetic moments become randomly oriented. The phenomenon is shown in Fig 1.2.

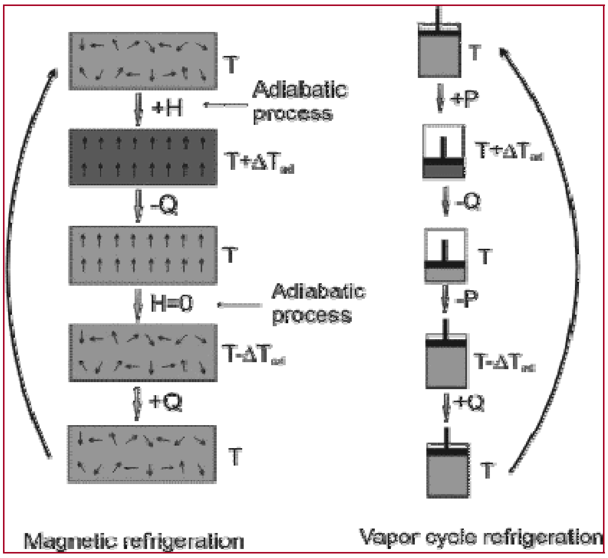

Fig 1.2 Magnetic Refrigeration with Dipole arrangement

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Magnetic refrigeration is an environment-safe refrigeration technology. The magnetic refrigeration does not have ozone-depleting and greenhouse effects for employing magnetic materials as refrigeration media. What is more, the magnetic refrigeration unit can be compact, for the magnetic entropy density of magnetic material is larger than that of refrigerant gas. The magnetic field of magnetic refrigeration can be supplied by electromagnet, superconductor or permanent magnets, which have no need for compressors with movable components, large rotational speed, mechanical vibration, noise, bad stability and short longevity.

LITERATURE SURVEY – INPUT POWER CALCULATION

Peng Li et al (2006) suggests that, according to the laws of thermodynamics, a real refrigerator operating between two heat reservoirs with cooler end (Cold heat exchanger) at T_c with refrigeration capacity Q_c and hotter end (Hot heat exchanger) at T_h with heat rejection rate Q_h, requires the input power W per cycle.

$W = ((T_h/T_c) - 1)Q_c + T_h \cdot \Delta S_{gen}$ [6] (3.1)

ΔS_{gen} – Entropy generation rate due to irreversible losses in a refrigeration cycle

COOLING LOAD CALCULATION

C. Zimm et al (2006) formulated the following:

Cooling load $Q_c = a.M_{dot}.C_f.\Delta T_b$ [14] (3.2)

M_{dot} – fluid flow rate
C_f – Heat capacity of the fluid
ΔT_b – Temperature change in the material
a – Coefficient (the coefficient a is close to 1 for moderate fluid flow rates of the fluid)

L.A. Tagliafico et al (2006) suggested that, for a given fluid, the heat transfer process mainly depends on[7]
(i) Relative velocity between fluid and disk,
(ii) Disk geometry,
(iii) MCM porosity (or void fraction),
(iv) Ratio between heat transfer area and MCM volume,
(v) Average particle dimension (related to the previous).

ASSUMPTIONS

The main assumptions and simplifications, useful to shorten the description without any loose of generality, are as follows:

1. *Steady state regime: all the considered quantities do not depend on time*

2. *Negligible heat and mass transfer losses towards the outside of the refrigerator*
3. *MCM adiabatic processes will be also considered internally reversible, that is isentropic. This is not a severe assumption, since MCE is almost reversible, except in the case of pronounced hysteretic behaviour of the MCM, which usually does not occur at the very low cycle frequency used in these devices. Thus, the MCM Brayton cycle is composed of internally reversible processes while entropy production occurs at fluid-solid interface due to the heat transfer processes across a finite temperature difference, and, inside the fluid, to friction losses and mixing.*
4. *The thermo-physical properties of the intermediary fluid (constant pressure specific heat, viscosity, thermal conductivity, density, and so on) have been assumed constant, and computed at the mean working temperature experimented all over the cycle.*
5. *The MCE has been assumed instantaneous: that is the refrigerating material takes no time to change its temperature when the external magnetic field suddenly changes.*

MAGNETO-CALORIC EFFECT AND ENTROPY

B. F. Yu et al (2003) found that entropy of magnet at constant pressure, S(T,H), which is both magnetic field and temperature dependant, consists of the magnetic entropy (S_M), the lattice entropy (S_L), and the electronic entropy (S_E):

$$S(T,H) = S_M(T,H) + S_L(T) + S_E(T)[13] \quad (3.3)$$

In the above formation, SM is a function of both H and T, but SL and SE are functions of T only. As a result, only the magnetic entropy, SM, can be controlled by changing the strength of magnetic field[10].

MAGNETIC MATERIAL – SELECTION OF ROOM TEMPERATURE MAGNETIC MATERIAL

The gross cooling capacity is less than that of the condition of (S_L+S_E)~0. As the core of the magnetic refrigeration, several features of magnetic materials are required for application[2]:

- *Large total angular momentum number J and Lande factor g of ferromagnetic material, which are crucial to MCE;*
- *Modest Debye temperature (A high Debye temperature makes the fraction of lattice entropy small correspondingly in high temperature ranges);*
- *Modest Curie temperature in the vicinity of working temperature to guarantee that the large magnetic entropy change can be obtained in the whole temperature range of the cycle;*
- *Essentially zero magnetic hysteresis;*
- *Small specific heat and large thermal conductivity to ensure remarkable temperature change and rapid heat exchange;*
- *Large electric resistance to avoid the eddy current loss;*
- *Fine moulding and processing behaviour to fabricate the magnetic materials satisfactory to the magnetic refrigeration.*

The prototype magnetic material available for room temperature magnetic refrigeration is the lanthanide metal gadolinium (Gd). At the Curie temperature of 294 K, Gd undergoes a second-order paramagnetic - ferromagnetic phase transition. The Table 3.1 shows the values observed during research on Gd.

Table 3.1. Observations on Gd

ΔT_{ad}	ΔH
6	2
12	5
16	7.5
20	10

MAGNETIC REFRIGERATION CYCLE

Magnetic refrigerator completes cooling/ refrigeration by magnetic material through magnetic refrigeration cycle. In general a magnetic refrigeration cycle consists of magnetization and demagnetization in which heat is expelled and absorbed respectively, and two other benign middle processes. The basic cycles for magnetic refrigeration are magnetic Carnot cycle, magnetic Stirling cycle, magnetic Ericsson cycle and magnetic Brayton cycle, among which the magnetic Ericsson and Brayton cycles are applicable for room temperature magnetic refrigeration for the Ericsson and Brayton cycles employ a regenerator to achieve a large temperature span and are easy to operate[13]. Fig. 3.1 shows the Brayton cycle, which is employed in our research.

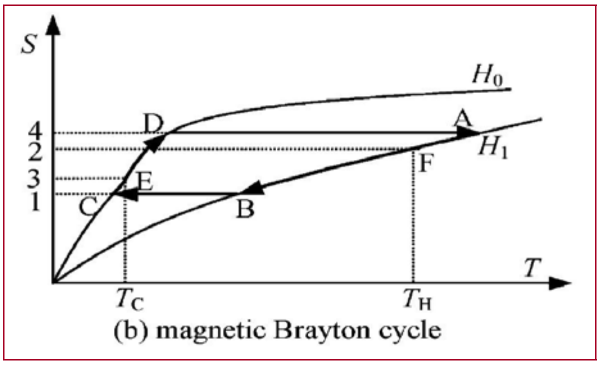

Figure 3.1. Magnetic Brayton Cycle

MAGNETIC BRAYTON CYCLE

Magnetic Brayton cycle consists of two adiabatic processes and two isofield processes as shown in Fig. 3.1. The magnetic refrigerant cycles between the magnetic field of H_0 and H_1, and the temperature of high and low temperature heat source T_H and T_C, respectively. During the isofield cooling process A-B (constant magnetic field of H_1), magnetic refrigerant expels heat of the area of AB14 as Fig. 3.1 indicates. During the isofield heating process C-D (constant magnetic field H_0), magnetic refrigerant absorbs heat of the area of DC14. No heat flows from and out of the magnetic refrigerant during the adiabatic magnetization process D-A and the adiabatic demagnetization B-C process. The Brayton cycle can exhibit optimal performance as well with magnetic refrigerants having parallel T–S curves.

FORM AND DESIGN OF MAGNETIC FIELD

There are two modes to apply magnetic field on magnetic refrigerant:
(a) both magnetic refrigerant and magnet are static. Pulsed magnetic field or alternate on-off magnetic field is applied. There is no driving device and the power consumption may be great;
(b) there is relative movement between magnet and magnetic refrigerant. The movement fashion may be reciprocating or rotary. In this way, the strength of magnetic field is stable whereas the extra mechanical power is needed due to the great magnetic attractive force. This method is made use in our research by making the magneto-caloric material to sweep into the magnetic field through the rotation of the material, which is later explained in the design sub-section.

Because the MCE is induced by magnetic field, the magnetic field strength plays a key role in the magnetic refrigeration. The specific MCE rate change at $T \sim T_C$ is ~ 3 K/T at lower fields and ~ 2.2 K/T at a higher 5 T field. It is still a difficulty to apply a high field.
The magnetic field has a serious influence on the magneto-caloric effect of the magnetic material. The adiabatic temperature change ΔTad is approximately proportional to the magnetic field $H^{2/3}$. Moreover, the field experienced by magnetic refrigerant is influenced by its temperature to some extent.

DESIGN OF MULTIPLE DISC TYPE ROTARY MAGNETIC REFRIGERATION SYSTEM - PROPOSED DESIGN

Principle: rotary magnetic refrigeration
Magnet: permanent magnet (sintered NdFeB)
Magnetic field intensity: 1.5 T
Magneto caloric Materials: Gadolinium (99 percent pure)
Number of stages: 1
Design cooling power: 50 W

CONSTRUCTION

The setup consists of a single stage containing a cylindrical chamber made of insulated material which houses the MCM discs. The chamber is split into two halves along the diameter by an insulated wall. Cooling takes place in one chamber and heating occurs simultaneously in the other chamber due to MCE. The working fluid flows over the surface of the MCM discs ensuring effective heat transfer. The constructional features of the discs are shown clearly in the figures 4.2.1, 4.2.2 and 4.2.3 for better understanding.

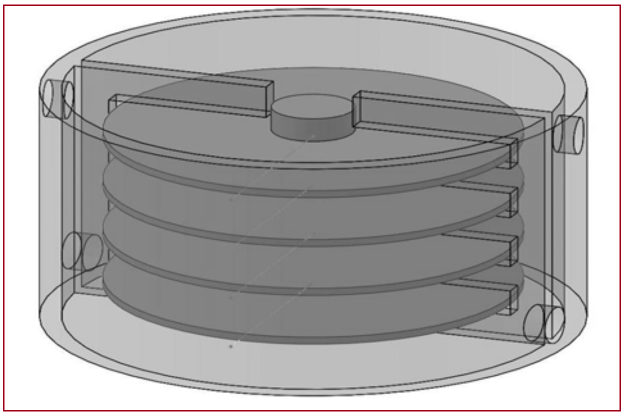

Figure 4.2.1. Complete assembly of the chamber

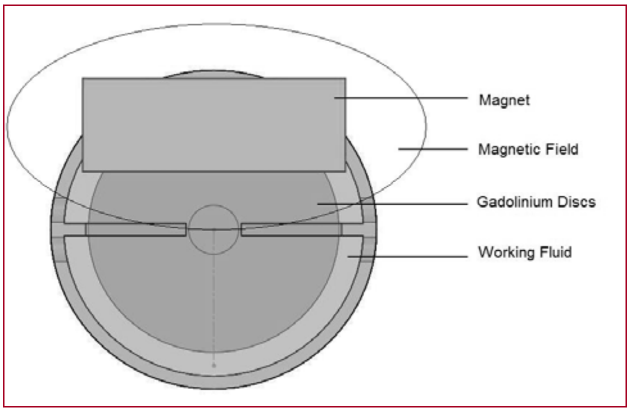

Figure 4.2.2. Chamber under magnetic field

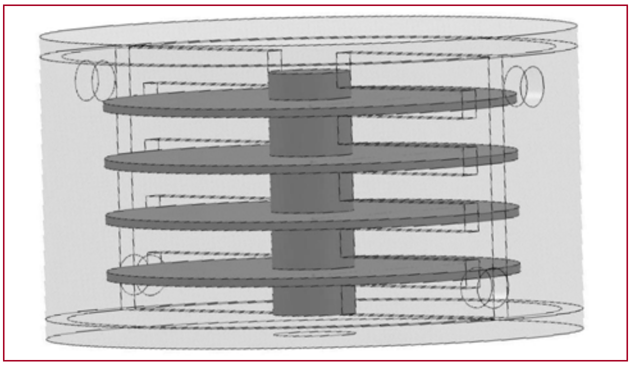

Figure 4.2.3. Entire assembly

SIMULATION USING COMPUTATIONAL FLUID DYNAMICS

The main aim of the research is to study the influence of rotating speed of the magneto-caloric material embedded discs on the magneto-caloric effect produced in the system. This objective is verified with the previously discussed design using the computational fluid dynamics software called STAR CCM plus. The system was modeled using STAR DESIGN software and the analysis was done using STAR CCM plus. At CD-adapco, the developer of STAR CCM plus, it is believed that CFD should be used where it is most effective: right at the start of the design process. In the past, CFD has struggled to keep pace with the rapidly evolving CAD data that is a feature of the earliest stages of design.

STAR-CCM+ and STAR-CD simulations can be setup, run and post-processed from within popular CAD and PLM environments such as SolidWorks, CATIA V5, Pro/ENGINEER and NX. No other approach will get you from CAD model to an accurate CFD solution more quickly or more reliably. CFD results are linked directly to the CAD geometry (a process called associativity). After any modification in the CAD model the simulation results can be updated almost instantly by clicking the "update solution" button, allowing the rapid and thorough investigation of the design space. Hence this software is used as a tool of Computational Fluid Dynamics, in order to get accurate and reliable results, when compared to the other available software in this platform. The following section will brief upon the design methodology and simulation techniques used in order to obtain the results. The figure 5.1 shows the model after getting imported into the Star CCM plus window.

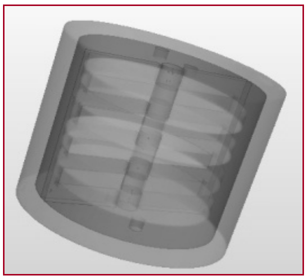

Figure 5.1. system after importing in STAR CCM plus

Design specifications:

- *Disc diameter: 70 mm*
- *Disc thickness: 7 mm*
- *Number of discs: 4*
- *Gap between discs: 7 mm*
- *Disc material: Gadolinium*
- *Working fluid: water*

Boundary conditions used for flow simulation:

- *Inlet velocity: 0.014 m/s*
- *Outlet flow split ratio: 1*
- *Internal energy generation rate of hot disc: 481125 W/cu. m*
- *Internal energy absorption rate of cold disc: 481125 W/cu. m*
- *Inlet temperature of working fluid: 298 K*
- *All other elements namely shaft, chamber and separator walls are assumed to obey adiabatic conditions.*
- *Each region was assigned to a separate physical model.*
- *The discs and shaft were assigned as moving reference frame model with a particular value of rotational speed and other elements were assigned as stationary.*
- *The simulation was iterated till the residuals reached their minimum values.*

Material properties:

- *Gadolinium:*
- *Density: 7900 kg/cu. m*
- *Specific heat capacity at constant pressure: 260 kJ/kg K*
- *Thermal conductivity: 10.6 W/m/K*

RESULTS AND DISCUSSIONS

The simulation results reveal that the maximum possible temperature span that can be obtained with this set up has an evident impact caused by the change in the rotational speed of the system, under the ideal conditions. Here, the system is considered to be homogeneous and steady state values are preferred for iterations. But, in real system there will be losses in enthalpy which will lead to a lower temperature span. The losses can be generally associated with the following aspects:

- Assumptions used in computational modelling and simulation
- Modelling
- Adiabatic processes
- Perfectly insulated systems
- Material homogeneity
- Ideal flow conditions
- Nature of Magneto-Caloric Material
- Fabrication Methodology
- Environmental stress
- Unaccountable losses.

The obtained results can be well represented with the help of the following table 6.1 clearly below:

Table 6.1. Observations recorded from Simulation results

Trial number	Rotational Speed (in rpm)	Maximum Temperature (in Kelvin)	Minimum Temperature (in Kelvin)	Temperature span (in Kelvin)
1	0	307.60	292.93	14.67
2	5	308.31	293.26	15.05
3	10	304.33	293.19	11.14
4	20	301.70	294.59	7.11

It is interesting to note from the above table that the temperature span decreases with increase in the rotational speed of the system, which can be more correctly told as the rotational frequency i.e. number of cycles made by the magneto-caloric material per unit time. This can be due to the fact that, the main factor concerned about the effective and efficient working of the magneto-caloric effect is attributed to the change in entropy of the magneto-caloric material, which forms the back bone of the induction of the temperature gradient within the system. Thus entropy transition is not a suddenly occurring phenomenon, as though illustrated by the theoretical thermodynamics. It is well known that each and every process, whether it comes under chemical, physical, electro-chemical or thermal field, it is associated with irreversibility. This irreversibility plays a major role in influencing the entropy change of any physical material. These irreversibility, in addition also lead to various losses which are unaccountable as well unavoidable in most of the cases, leading to overall efficiency drop of the system. Thus, it is necessary to make the system run effectively under the various working conditions.

The simulation result obtained by considering the system at static condition is given below in the figure 6.1. It shows that the maximum temperature attainable is 307.6 K and the minimum temperature at the cold side is 293.26K, with the temperature span of around 15.05 K.

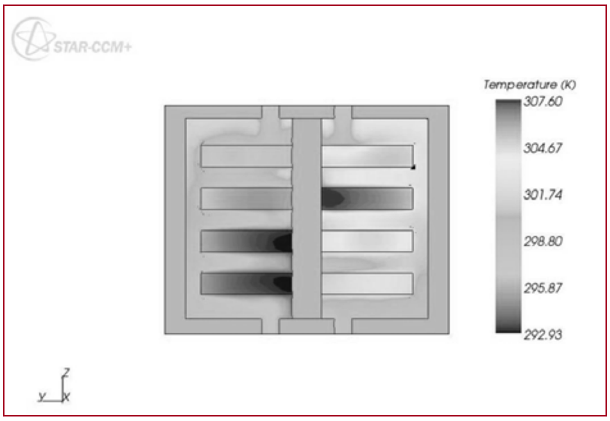

Figure 6.1. Temperature distribution inside the system at stationary condition – planar view

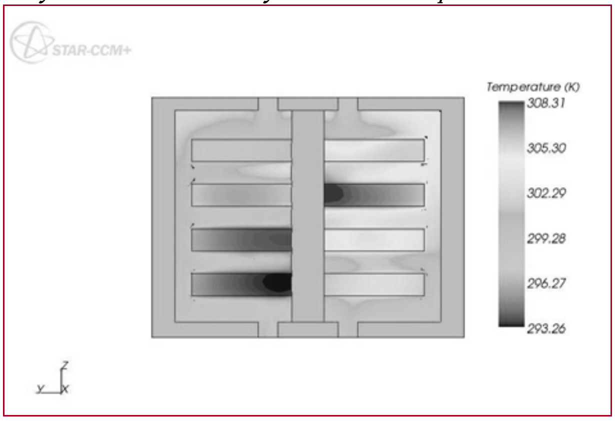

Figure 6.2. Temperature distribution inside the system at 5 rpm – planar view

The simulation result obtained by considering the system running at 5 rpm is given below in the figure 6.2. It shows that the maximum temperature attainable is 308.31 K and the *minimum temperature at the cold side is 293.26 K, with the temperature span of around 14.67 K.*

The simulation result obtained by considering the system running at 10 rpm is given below in the figure 6.3. It shows that the maximum temperature attainable is 304.33 K and the minimum temperature at the cold side is 293.19 K, with the temperature span of around 7.11 K.

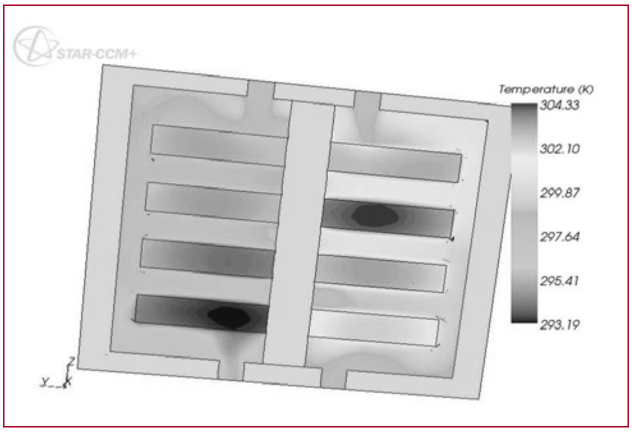

Figure 6.3. Temperature distribution inside the system at 10 rpm – planar view

The simulation result obtained by considering the system running at 20 rpm is given below in the figure 6.4. It shows that the maximum temperature attainable is 301.70 K and the minimum temperature at the cold side is 294.59 K, with the temperature span of around 11.14 K.

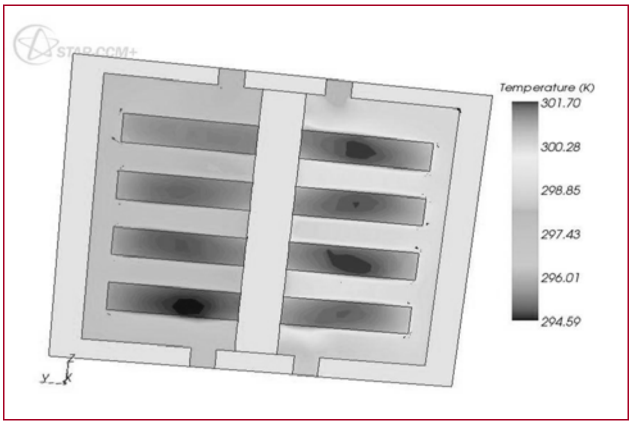

Figure 6.4. Temperature distribution inside the system at 20 rpm – planar view

CONCLUSIONS AND SCOPE FOR FUTURE WORK

The study reveals that for smaller magnetic fields high thermal spans are only possible, if the rotation frequency is low. That is a result of the connection of the rotation frequency and the fluid velocity, given by a criterion to keep the carry-over leakages small. And only small fluid velocities lead to small pressure losses in the porous structures of the rotary wheels. But, if these velocities must be small, also the angular velocity and the frequency must be low. The same conclusion is also suggested by the 2007 year Annual Report issued on 'application of magnetic refrigeration and its assessment' by the University Of Applied Sciences Of Western Switzerland [5]. This is very encouraging phenomenon, which also opens the door for similar researches to be carried out in the near future. Some of their suggestions similar to us are discussed in the following paragraphs.

Thus, we can say that applications with smaller temperature differences are much more favourable. This results from the limited adiabatic temperature difference of the magneto-caloric materials. The result then is that numerous cascading or regeneration stages have to be taken into consideration. These lead to additional heat transfer losses, so that the coefficient of performance is lower.

Furthermore, the restriction of an operation to a domain around the Curie temperature of the magneto-caloric material makes systems with steady operation conditions more favourable.

At higher magnetic fields the dependence on the rotational frequency is smaller. This is because a second loss, the irreversibility between stages, is also important. If the magnetic field strength is high, a lower number of stages must be foreseen, and these irreversibility are lower. And even more, because of fewer stages, fewer rotors in series occur, and also the pressure drop loss is smaller. That explains why high fields are very interesting for the magnetic/magneto-caloric machine design. Even though, the system is having a lot of advantages, the main drawback lies behind the fact that the cost of available magneto caloric materials are at peak and the permanent magnets suffer from yielding sufficient change in magnetic entropy of the material. Hence, in future lot of works should be carried out in finding out different magneto caloric materials and successful permanent magnets. We also propose to study machines with superconducting magnets with large cooling powers. The economy of such systems will be determined by the installation costs of superconducting magnets. A further study of all these aspects will lead to more information.

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ACTA TECHNICA CORVINIENSIS – BULLETIN of ENGINEERING
ISSN: 2067-3809 [CD-Rom, online]