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Practical Study of Magnetic Refrigeration Performance and Optimization

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Abstract: *Active Magnetic Refrigeration Apparatus is a novel device that has zero vapor pressure and causes, zero ozone depleting gases. The magnetic refrigerator has the prospective to become a realistic choice instead of present vapor compression refrigeration systems. In the present study a Magnetic refrigerator designed and constructed in Iraq (the first one as our knowledge), used as laboratory device to investigate the effects of many operational parameters on its performance. The results indicated that an experimental parallel plate AMR device demonstrates the high performance, and due to their relatively low pressure drop to the heat transfer performance and to be quite versatile, in terms of operational parameters and various aspects of the cooling capacity .The hot end had a prescribed temperature of 299K a zero cooling loads applied at the cold end. So, temperature span observes be about 11K, which evaluated as the difference temperature between the hot and cold ends of the magnetocaloric regenerator. All thermal losses through the regenerator housing and the cold end go to the ambient through the hot end, within an insulated cold end, due to, no heat exchangers were used at the cold and hot ends. Therefore, this test machine used to measure the no-load temperature span.*

Keywords: *Magnetic Refrigerator, Temperature Span, Gadolinium, Halbach magnet.*

I. Introduction

The magnetocaloric effect (MCE) first discovered by Warburg, who in 1881observed an increase of temperature, when brought an iron sample into an magnetic field and decrease, when the sample was removed out of it. Soon after this discovery, approximately in 1890, Tesla and Edison independently and unsuccessfully tried to benefit from this effect by running heat engines for “power production”. Many researchers worked on the theoretical explanation of this phenomenon since 1890. While the laboratory experimentation on this concept performed at the mid '70s by Brown who built and tested a Reciprocating magnetic refrigerator assembly. He used Gadolinium as the working medium [1]. For this, Brown design was the first magnetic refrigerator working at room temperature [2].

Two major developments occurred in 1997. The first development was in February 20, 1997.When the Ames Laboratory/Astronautics, showed a proof of principle of magnetic refrigerator demonstrating was unveiled and a viable and competitive cooling technology nears the room temperature region. That magnetic refrigeration is with potential energy savings of up to 30%. Furthermore, the magnetic refrigeration is an environmentally friendly technology. Since, it eliminates ozone depleting gases, and reduces the need for global warming greenhouse effect gases, and other hazardous gaseous refrigerants [3]. The second development was through the announcement of the discovery of the “Giant Magnetocaloric Effect” (GMCE) in Gd_5 (Si_2Ge_2)on June 9, 1997[3]. With the discovery of the Giant MCE, the development of magnetic refrigeration gained increased momentum.

Since then, the number of papers published in this field has grown exponentially [2]. The first room-temperature magnetic refrigerator containing Permanent Magnets designed and built in 2001 by the same group at Astronautics Corporation [4]. Thus, the start of the development of new generation family of magnetic refrigerators began.

The development of magnetic refrigeration at room temperature led to an increase the interest in the development of magnetic refrigerator devices, which associated to the search for new magnetocaloric materials with a Curie temperature close to room temperature [5]. Furthermore, these developments coupled with large improvements for the magnet design that suggested.

Kawanami [6] studied the optimum operating condition of magnetic refrigerator at room temperature for direct air-cooling. The basic components of the target system were a magnetic circuit including two permanent magnets. The test section was consisted of ten test cells, which enclose gadolinium chips as a magnetic working substance in prescribed packing rate. The system performances widely investigated both experimentally and analytically. The results reveal that the studied magnetic refrigerator has a maximum value of the cooling rate in an appropriate operating condition, when the setting the Curie point of the magnetic working substance to the starting temperature.

Engelbrecht [7] studied and developed a rotary regenerator bed utilizing practical and affordable permanent magnets of an active magnetic regenerator refrigeration system and predicted the practical limits of systems which use in space conditioning and refrigeration applications. The study shows that a packed sphere regenerator consisting of layered and non-layered alloys of Gadolinium and Erbium can achieve performance that was competitive with vapor compression technology for cool applications.

Astronautics Corporation group [8] built a Rotating Bed Magnetic Refrigerator (RBMR), as a near room temperature magnetic refrigeration device. They utilized a nominal 1.5 Tesla stationary permanent magnet and a rotating wheel that contained six active magnetic regenerator (AMR) beds. Thus, a rotary disk valves located coaxially with the bed wheel control heat transfer fluid flow to the beds. An electric heater provides a measurable heat load to fluid flowing on the cold side, while a brazed plate heat exchanger connected to a temperature controlled circulating bath controls the heat rejection temperature. The wheel drive motor and the pump both had a variable speed drives to control the cycle frequency and fluid flow rate, respectively.

Koga [9] patented a compact and highly efficient hybrid magnetic refrigerator includes a hybrid refrigerating apparatus. In this refrigerator an evaporator of a vapor compression refrigeration cycle and a heat exchanger of a magnetic refrigeration cycle were thermally connected. This magnetic refrigeration cycle was arranged with a superconducting magnet which applies a magnetic field in the refrigerant channel path between the heat exchangers, and a magnetic working material having magnetocaloric effect was taken in and out in this magnetic field. Egolf [10] invented a continuously rotary magnetic refrigerator or heat pump comprising one partially hollow rotating magnetocaloric ring member. This MR was able to operate in a continuously working process, and to be applied in industrial thermal processes that having a high efficiency and a low cost manufacturing. Kuhn [11] designed and constructed a, MagCool prototype, a continuous magnetic refrigeration device, which spans all the way from basic materials studies to the construction of a prototype. In this prototype the researcher used ceramic magnetocaloric materials, and then modeled the performance of a permanent magnet with optimum used of the flux and relatively low weight.

Engelbrecht [12] designed and built a reciprocating type device provided by a permanent Halbach magnet assembly as source of magnetic field gives an average flux density of 1.03 Tesla, to be a modular. All parts of the device can easily be replaced depending on the experiment. This makes the device highly versatile, with the possibility of performing a wide variety of different experiments. He investigated the effect of thermal conduction through the regenerator housing walls using flat plate regenerators. Each regenerator was tested over a range of hot reservoir temperatures under no load conditions. His results demonstrated that the layered regenerator provides a lower temperature span than the single material regenerator, because the two materials had T_{Curie} that too far apart for the regenerator design that tested.

Lozano [13] develop a prototype magnetic refrigeration device at the (DTU). However, a continuously rotating active magnetic regenerator using 2.8kg packed sphere regenerators of commercial grade Gd was employed. The magnetocaloric properties of the Gadolinium obtained experimentally and implemented in a 1-D numerical AMR model that includes also the parasitic losses from the prototype. The prototype displayed a high performance. On the other hand, the numerical modeling results agreed well with the experimental data for temperature span as a function of frequency and cooling capacity. Bahl [14] designed and constructed a novel rotary magnetic refrigeration device with a high performance, closed up to the requirements of commercial devices. The magnet and the flow system designed to allow almost continuous usage of both the magnetic field and the magnetocaloric material in cassettes. Each cassette contained an active magnetic regenerator bed.

The principal goal of this paper is to gains a fundamental physical understanding of the magnetic effect that combined the effects of dynamic response of an Active Magnetic Regenerative Refrigeration system.

II. Experimental Setup

Till now, no research for Magnetic Refrigerator at room temperature was sighted in Iraq from the local survey, as our knowledge. The main purpose for this study is to introduce the performance of an active magnetic regenerative refrigerator with high-purity magnetocaloric material. For this purpose 13 Gadolinium plates have a total weight of 92g used. Each plate has 0.9 mm thick, 25 mm wide and 40 mm long in the flow direction, separated by 0.8 mm for fluid flows through these channels. Polyvinylchloride plastic cylinder housing have 80mm long and an outer diameter of 40 mm, provided with rectangular regenerator at the middle, 25mm wide and 22mm high to confine the MCM and plastic plate guides, placed at both end of Gd plates. Also, two Perspex tubes with an external and internal diameter of 40mm and 34mm, respectively, fitted to the both end of the AMR cylinder. Two pistons moving within these Perspex tubes to force the heat transfer fluid through the AMR. The pistons are rigidly fixed to a mandrel such that they always move in phase. The pistons and the whole AMR assembly with its terminals are moved in and out of a magnetic field through the bore of the permanent Halbach cylinder magnet, controlled by pneumatic systems. While the permanent magnet, made of an alloy of Neodymium, Iron and Boron, has a chemical composition ($Nd_2Fe_{14}B$), consists of 16 segments giving maximum magnetic flux density of 1.5Tesla.

So, a reciprocating magnetic refrigeration device created with a suitable chosen prototypical bang market material for room temperature components and a suitable magnet device was build. This device specification, application and validation were totally reported in Ref [15]. It can be used to understand the behavior of actual experimental devices. Fig. 1 represents the Magnetic Refrigerator used in recent study.

Experimental Set-up Procedures

The Magnetic Refrigerator device placed in contact with the ambient temperature in order to test the machine's performance over a range of operating temperatures and to better control the experimental conditions. The hot end in a thermal contact with the ambient controlled room is thermally linked to ambient via the forced convection heat exchange. So, all thermal losses through the regenerator housing and cold end will go to the ambient temperature. Due to the bad thermal conductivity of Perspex tube, the hot end of the regenerator provided with a coil worked as a heat exchanger cooled by a small electric fan. The aid is to exchange heat with the ambient through the forced convection. While the cold end insulated and the outer wall of the regenerator housing in contact with the ambient.

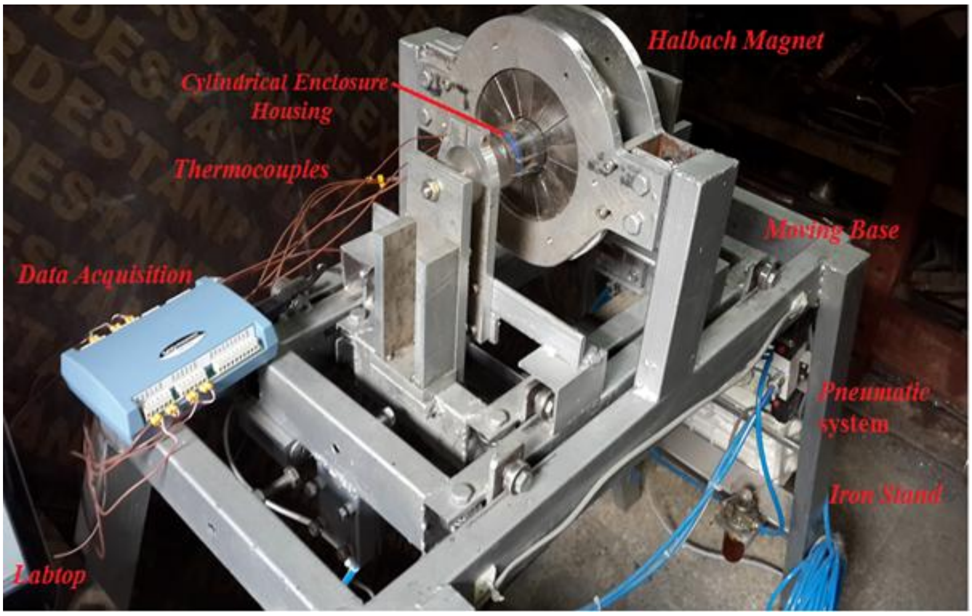

Fig. 1: A photograph of the magnetic refrigerator apparatus used in recent study.

The performance of the AMR is dependent on the heat transfer between the fluid and the regenerator. Therefore, the best performance is achieved when there is no temperature difference between the fluid and the regenerator. It is important to modify the operating temperature of the machine according to the material's transition temperature. Therefore, in each experiment, the ambient temperature set slightly above the material's transition temperature to ensure that the system operated near its optimal temperature range.

After the compressor was switched on, which connects to regulator (3-5 bars), a ball valve, lubrication system and to the Control system which divided and connected with two Pneumatic systems. The device started to operate, while, the mass flow rate was adjusted. The initial ambient temperature is controlled to be 293±5K, for all experiments.

At the beginning of any test, AMR controls approximately to a uniform ambient temperature, the power input, i.e. the velocity of the pneumatic system, the mass flow rate, all is adjusted. The Apparatus starts operating, and the AMR enters the permanent Halbach magnet and passes through its core, the Gd plate temperature gradient starts to develop gradually. The temperature profile established and eventually reached steady state temperature distribution.

The temperature on the hot end of the regenerator is rising. While the temperature between the layers and on the cold end, decreased gradually to their steady-state values, at the end of the hot blow period. Then, the AMR cycle time and the temperature at the various locations recording.

Due to, in some cases, the temperature may have oscillated in values due to the resolution of the digital thermometer system. However a period of at least 15 to 20 minutes was given prior to any data being recorded. The procedure, repeated for each experiment at each values setting until the maximum desirable value reach.

Due to the little mass of fluid flow, the experiments didn't reach the desired range with the suitable temperature span. Therefore, in order to control the starting of the fluid flow rate and to approximate step changes of the fluid flow at the beginning of the experiment, a control switch was used. In addition, due to the flow profile cannot be a true step changed; a stopwatch was used to measure the actual time variation of the fluid flow rate.

The Studied Parameters

The performance of an AMR depends on many parameters with a complex interrelationship. These parameters include the ratio between the heat capacity of the regenerator and the fluid, the piston stroke as well as the length of the AMR refrigeration cycle [16]. In addition, the maximum refrigeration capacity as a function of both of the temperature profile and the amount of fluid which enters the cold end are from the primary parameters that affect the MR performance. So, for the optimization technique, these parameters and others below were studied experimentally to evaluate the influence of each on the performance of the AMR:

- Heat transfer fluids.
- The piston stroke variation.
- The ambient temperature various.
- Cycle timing variation.

III. Results And Discussions

The comparison between the two heat transfers fluids correspond to its steady state temperature span, for a variation range of piston stroke lengths i.e. fluid displacement, is manifested in Fig. 2. The figure shows a good agreement for the fluids, in both experimental behaviors, T_{span} have the same curve shape, that a rapid initial increase of temperature span, until the maximum fluid displacement has reached, then followed by a slower decrease of T_{span} .These results illustrate that pure water produces the highest T_{span} than the mixture. As consequence, the performance of the AMR expected to be the best, thus, pure water can be chosen for the sequence experiments.

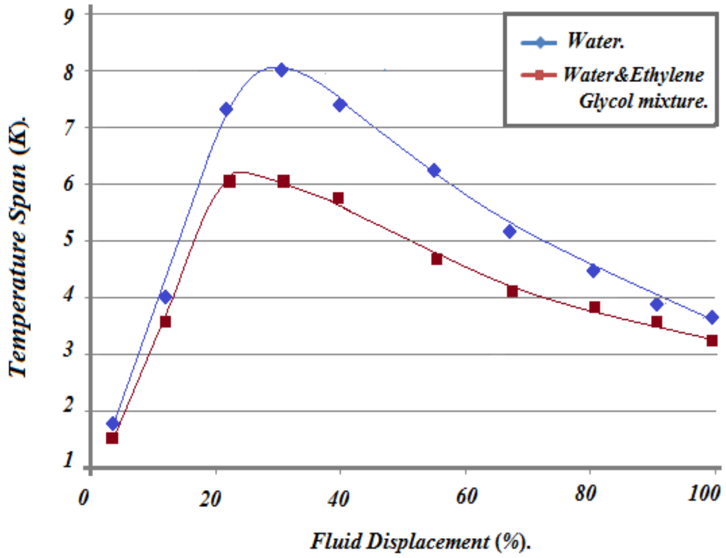

Fig. 2: The steady state Temperature Span, experimental data at a range of piston stroke 1.5cm lengths and τ_{tot} =8s, for both used heat transfer fluid

Fig. 3 shows the plotting of utilization as function of the no heat load temperature span. Since the temperature span exhibited a stronger dependence on fluid velocity in the flow channel. Thereby, for the low fluid velocity, a higher cycle time associates with a largest temperature span. A large temperature span, causing in a highest conduction loss to the surroundings, which achieve with a relatively slow fluid velocity (not the slowest - fluid velocity). So, thermal losses effects on the performance of the device more in the slow cycle than the faster cycle.

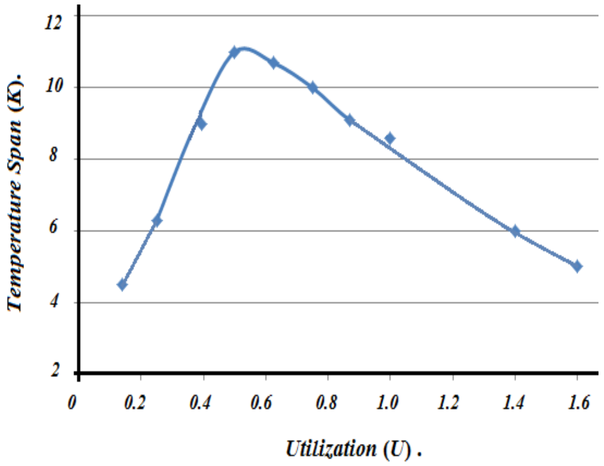

Fig. 3: The no heat load Temperature Span as function of utilization.

Fig. 4 illustrates the total cycle time versus different fluid velocities, for chosen Utilizations. As the utilization increases, the optimum cycle time increased too, for a constant velocity. Conversely, as the optimum fluid velocity increases the utilization increased for a constant cycle time.

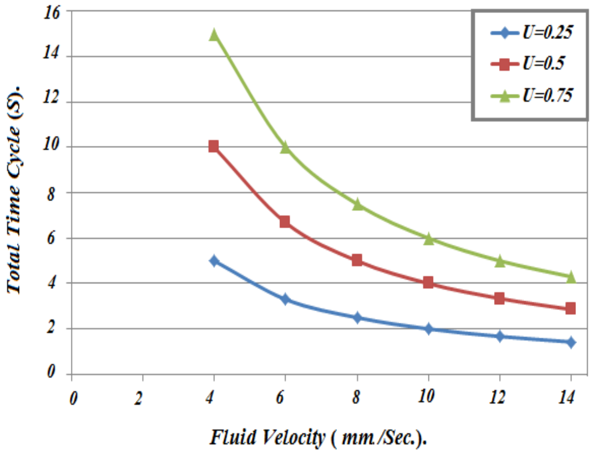

Fig. 4: The total cycle time when $\tau_1/\tau_2 = 1$, vs. different fluid velocities, for chosen utilizations, 0.25, 0.5 and 0.75, respectively.

New experiments results in terms of the zero-load temperature span as a function of the fluid velocity were plotted in Fig. 5, shown as fluid velocity increases the no-load temperature span will increase, too, reaches to its maximum value then be decreases rabidly, even if the fluid velocity still increases. The utilization values that characterized these experiments kept constant at 0.25, 0.5 and 0.75, respectively, by varying the fluid velocity and the timing of the AMR cycle. The results indicated that when the mass flow rate increased the fluid velocity will increase, too. It also caused in decreasing the time for the local heat transfer between the solid and the fluid, which leads to an overall less efficient of the regenerator. At a large mass flow rates, the regenerator has less efficient than at the smaller mass flow rate. Due to, the regenerator matrix flooded with heat transfer fluid. This condition was undesirable since the value of the COP is reduced dramatically by an increased pump work requirement.

The dependence of the volumetric flow rate with temperature span values plotted in Fig.6. In the second set of experiments, the hot end temperature kept approximately about 296K, and the volumetric flow rate varied. As the temperature span increases rabidly, the volumetric flow rate increases, too. The temperature span decreased at the higher volumetric flow rate, this may, due to the working pressure limitations, or for a possibility of an internal leakage at the hot or the cold side in the flow of the distribution system. The results indicated that it impossible to operate the device at flow rates above $80mm^3/sec$. However, the temperature span expected to continue to decrease at higher flow rates as viscous flow losses increased. So, the highest experimental temperature spans attained at volumetric flow rate about, $60mm^3/sec$, with a value of 11K.

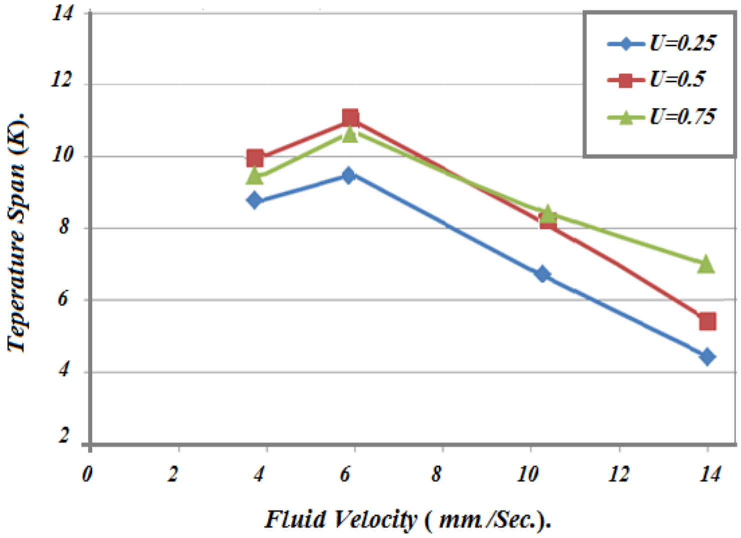

Fig. 5: The no heat load temperature span as function of fluid velocity for different chosen utilization.

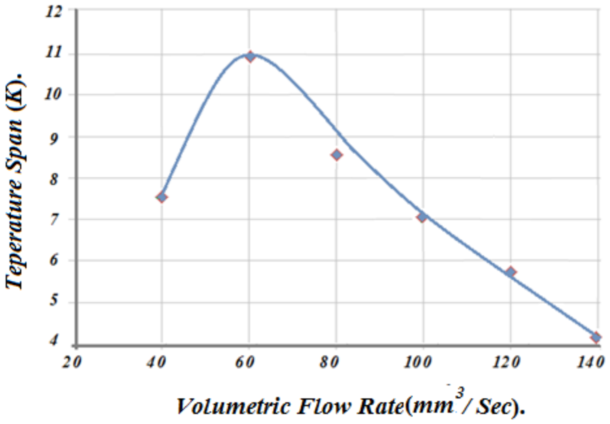

Fig. 6: Experimental data of the temperature span as a function of the volumetric flow rate.

On the other hand, Fig. 7 manifests the temperatures span curves at three different hot end temperatures, T_H, values approximately, 289, 293 and 296K, against three different charge pressures, 3, 4 and 5 Bar, respectively. Due to the increasing in utilization raised the pressure drop in the system. So, leads to increase the temperature span of the regenerator, up to the certain value. Thus, the charge pressure system observed of 3Bar, the T_{span} shows morelowering approximately, at about 296K, than the others charge pressures system, due to the lower utilization.

In spite of, the device performance characterized under the no load condition, another experiment run, includes the, T_{span} , through the regenerator, for a given hot ends temperature varies between, 292 and 298K for a cooling capacity, specified heat load, Q_C.

The regenerator cold end provides with a heat input source, through a resistance heating wire inserted in it, and connected to a power supply, thus, makes it possible to apply a heat load to the water. Fig. 8, illustrated the sensitivity of the temperature span at no-load, the cold end be insulated, typically Q_C = 0W, and, T_H = 298K, thus, T_{span} =10K. Conversely, at the applied load, with a heat input source be, Q_C = 3W, to be created and provide the measurement of performance for the Gadolinium, to associate as magnetocaloric material, operating parameters and regenerator configuration. Thus, due to the nature of this Reciprocating Active Magnetic Refrigeration test device, high cycle frequencies not feasible, in spite of this, the cooling power is relatively low and insufficient, for a fixed T_H, but seems the importance curve.

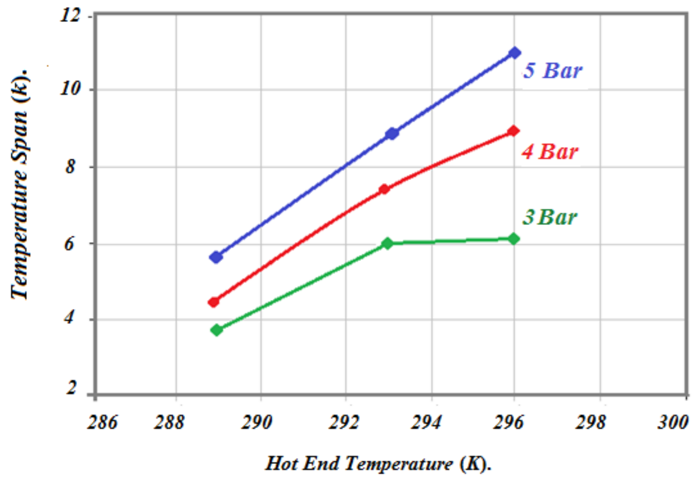

Fig.7: Temperature Span vs. T_H for the regenerator, Gd for, Qc = 0 W and utilizations corresponding to charge pressures of 3, 4 and 5 bar

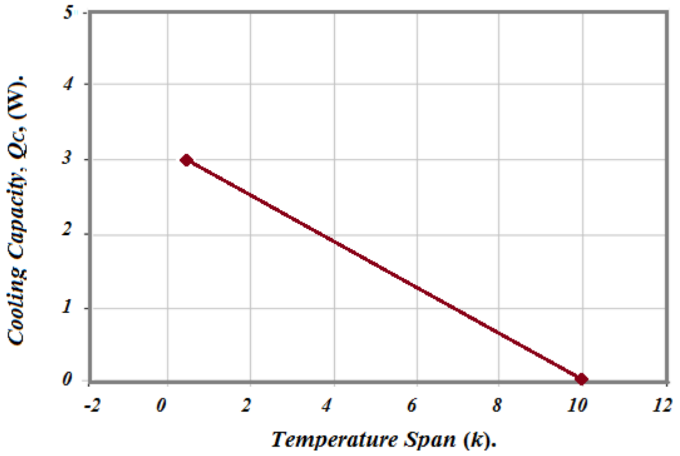

Fig.8: Cooling capacity, Q_C, verses temperature span for Gd regenerator corresponding to a charge pressure of 4 bar and T_H= 292& 298K

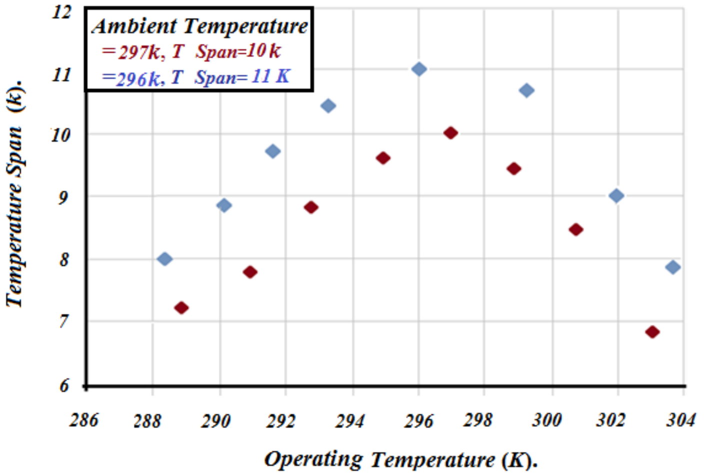

Fig.9: No-load temperature span as a function of the ambient temperature and the operating temperatures

Fig. 9 shows the results of the maximum achieved temperature spans, which are 10K and 11 K, for two different ambient temperatures 297 and 296K, respectively. The temperature span achieved when the hot end was allowed to rise more than 3K above ambient temperature. Even if the losses through the regenerator wall were relatively small, it possible, a thermal leak to the ambient caused a noticeable reduction in performance. In addition, due to the effects of the oxide that coated the gadolinium refrigerant surface during the experiments. This oxide may affect the heat transfer rate with the exchanged fluid, as a result, affect the device performance.

However, the second group of experiments for the piston stroke variation, the piston stroke length kept constant, while the cycle parameters were varied. Thus, due to the times spend for the different four individual steps of the AMR cycle, which associated with the total cycle time, have been varied. If the time for any single process is changed, the cycle time is also changed. The heat transfer fluid in these experiments, is displaced with a proportion 50% inside the regenerator, i.e. that the piston stroke length was kept constant at 10mm, thus, the heat transfer fluid was moved 50% of the length of the Gadolinium plates.

Table 1illustrates samples of set data for an total cycle time groupτ_{tot} = 6and 12sec, respectively, corresponding to different periods ratio,τ_1/τ_2, that areequal to,1, 1/2and 1/3, respectively. It is obvious that the minimum time for magnetization,τ_1, for this device was approximately 0.75s, with fluid flow period,$\tau_2$was determined equal to 2.25s, for the period ratio $\tau_1/\ \tau_2$= 1/3,for a total cycle time, τ_{tot} =6s.

Table 1: The different total time cycles corresponding three different periods ratio τ_1/τ_2, with a constant piston stroke length.

Cycles Periods.	τ_{tot} = *6sec* $\tau_1+\tau_2=3s$		*8sec* $4s$		*10sec* $5s$		*12sec* $6s$	
Period Ratio.	τ_1	τ_2	τ_1	τ_2	τ_1	τ_2	τ_1	τ_2
$\tau_1/\ \tau_2$ = *1*	**1.5**	**1.5**	**2**	**2**	**2.5**	**2.5**	**3**	**3**
$\tau_1/\ \tau_2$ = *1/2*	**1**	**2**	**1.33**	**2.67**	**1.67**	**3.33**	**2**	**4**
$\tau_1/\ \tau_2$ = *1/3*	**0.75**	**2.25**	**1**	**3**	**1.25**	**3.75**	**1.5**	**4.5**

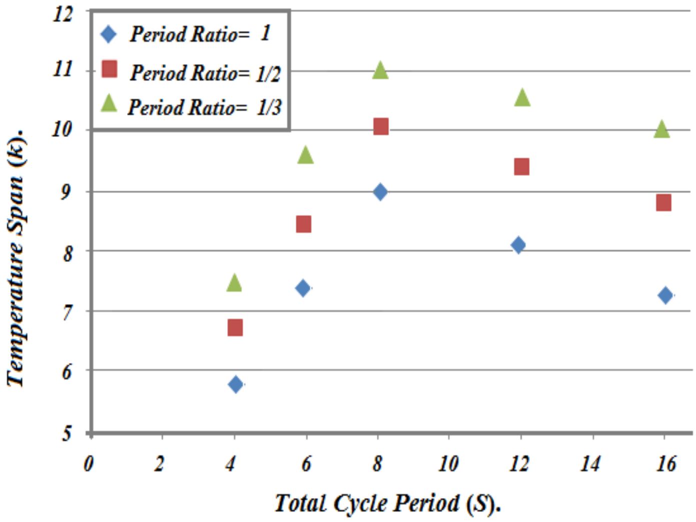

Fig. 10: The results of the parameter study of the temperature span, as a function of difference total cycle period at constant τ_1/τ_2=1, 1/2 and1/3, respectively.

Fig. 10, reveals the temperature span, T_{span} , as a function of the different total cycles period, and for three different period ratios values of τ_1/τ_2.The experimental results show that the maximum temperature spanwas obtained for the cycle has a total cycle time of 8sec., against the minimum period ratio valueτ_1/τ_2 equal to 1/3which results in an T_{span} approximatelyof 11K. According to these results, for a constant cycle time, the magnetization period can be reduced to increase the AMR performance, thus, obtains the best performance whenτ_1/τ_2 was as low as possible. Additionally, it means that the blow period must start almost immediately after the regenerator material has been magnetized or demagnetized. Any temperature difference between the regenerator and the fluid before the blow periods have no affect the AMR performance significantly.

Fig.11 presents the results of theT_{span} , but as a function of a difference values of the period ratio, τ_1/τ_2. The temperature span was observed increased as τ_1/τ_2has small values,less than one,$\tau_1/\tau_2 < 1$, associated with the experimental data predictions cycle's periods,4, 6, 8, 12and 16sec, respectively. The best performance was obtained for lower values of $\tau_1/\tau_2 < 1$, as observed for the cycle period about8s, which produce the highest temperature span, while a cycle period of 4s produces the lowest temperature span.

Fig. 12 manifests the temperatures of each of thermocouples indicated in the both plots. The figure shows that the temperature profile within the heat transfer fluid in the regenerator before the hot and the cold blow, respectively, observed that, when the fluid entering the regenerator from the cold-to-hot side, vista versus has almost a constant temperature near the regenerator edges, thus a good agreement.

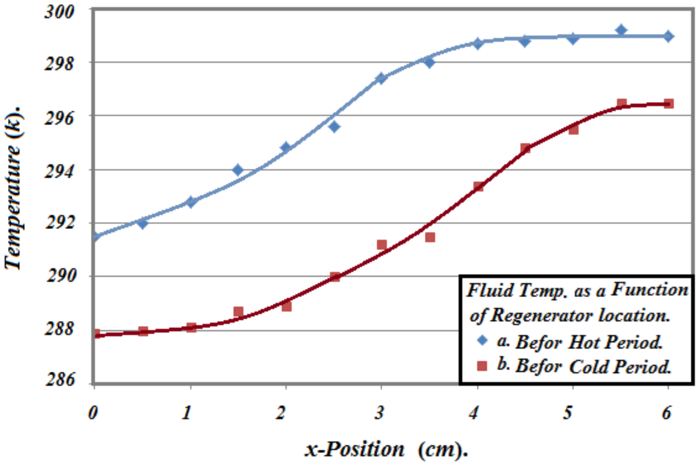

Fig.12: The indicate experimentally measured data points of the temperature profiles within the heat transfer fluid at steady state for a cycle period of 8s, a. before the cold blow. b. before the hot blow

IV. Conclusions

For Active Magnetic Refrigeration systems, at room temperature has basically zero vapor pressure and consequently causes, zero ozone depleting gases. The magnetic refrigeration has the prospective to become a realistic choice instead of present vapor compression refrigeration systems. From the present study, the following results are concluded:

- An experimental parallel plate AMR device demonstrates the high performance due to their relatively low pressure drop to the heat transfer performance and to be quite versatile, in terms of operational parameters and various aspects of the cooling capacity.
- The temperature behavior results of the Gadolinium as a refrigerant MCM is measured during operation of the AMR device, concludes that it is possible to obtain more significant COP in an AMR with a parallel-plate regenerator, by using 1.5T, as the strength of the magnetic field, associated with a total cycle time 8s, for a blow period ratio about 0.33.
- The hot end had a prescribed temperature of 299K a zero cooling loads applied at the cold end. So, temperature span be about 11K, that evaluated as the difference temperature between the hot and cold ends of the magnetocaloric regenerator, was observed. So, the theory for the transient operation of the AMR associated with the gradual temperature divergence due to regeneration throughout the magnetocaloric refrigerant bed was discussed.
- All thermal losses through the regenerator housing and the cold end go to the ambient, within an insulated cold end, and no heat exchangers were used at the cold and hot ends, therefore this test machine was used to measure the no-load temperature span.
- The effects the time of the magnetization and demagnetization processes associated with fluid blow periods, operation time, geometry and volume of the housing and regenerator material, porosity, heat capacities, magnetic material, thermal conductivity, heat transfer coefficient for practical applications.

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