REVIEW ON MAGNETIC REFRIGERATION AT ROOM TEMPERATURE USING MAGNETOCALORIC EFFECT

Shlok Choudhary[1], Suprabhat A.Mohod[2], Manoj B.Dhawade[3]

[1]*Department of Mechanical Engineering, Lokmanya Tilak College of Engineering, Koparkhairane, Navi Mumbai, (India)*

[2,3]*Asst. Professor, Department of Mechanical Engineering, Lokmanya Tilak College of Engineering, Koparkhairane, Navi Mumbai, (India)*

ABSTRACT

Refrigeration is a very basic need of people these days. From preservation of explosive chemical compounds, right down to keeping the food fresh, refrigeration has found so many applications that life just does not seem possible without it. Over the years most of the refrigeration techniques that have emerged, most prevalent of them are the cyclic, non cyclic, and thermoelectric refrigeration, each of them has some major disadvantages which need to be addressed beforehand. There are certain common problems such as decreased coefficient of performance of the refrigeration system, higher electricity consumption, and the refrigerants used are generally emitters of greenhouse gases which are not particularly environment friendly. One of the methods that does seem to eliminate most of these shortcomings is magnetic refrigeration, an adiabatic cooling process, which primarily deals with the principle of change in entropy and effect of external magnetic field on certain materials. This effect is also known as the magnetocaloric effect, and it is the cornerstone of magnetic refrigeration. The main material which exhibits Giant Magnetocaloric Effect is $Gd_5Si_2Ge_2$ *which was discovered by Gschneidner and Pecharsky in 1997. The primary prototype machine discussed here consists of a Halbach magnet assembly, with flat plate generators made of Gadolinium. The magnetic flux density applied is 1.75 Tesla.The technology is still an emerging one, and so far only prototypes have been presented to the world, and there are still a few challenges which are to be faced to make this technology commercially viable.*

Keywords: Active Magnetic Regenerative (AMR),Gadolinium, Giant Magnetocaloric Effect (GMCE), Halbach Cylinder, Magnetic Refrigeration, Magnetocaloric Effect (MCE)

I. INTRODUCTION

Mechanical refrigeration is the process using which heat is extracted from a point using an artificial heat-exchanger. Generally, refrigerants are used as materials for exchanging heat, that is, as working fluid. The earliest refrigerants that were discovered by people were water, air, and ice. The use of ice for preservation of food was first discovered by the Chinese and it is still used in the Arctic regions by eskimos to preserve food and other perishables. At the beginning of the 20th century, when people discovered about bacterial growth and other microorganism issues, they also found out that the growth of microbes was very slow at low temperatures, and a lot many of them could not survive at low temperature (less than 10°C), hence the requirements of refrigeration became even more imminent and it's applications for preserving eatables came further into use. The first mechanical refrigerators were made for making ice in 1860s. The use of refrigeration in cold storage, meat production, fisheries etc only became commercially viable after the 1900s when electricity generation for meeting power requirements was introduced more widely.

II. TYPES OF REFRIGERATION SYSTEM

Refrigeration can be achieved by using various methods. These can be broadly classified into these four categories, which are as follows:

Cyclic refrigeration system, Non-cyclic refrigeration system, Thermoelectric refrigeration system, and Magnetic refrigeration system.

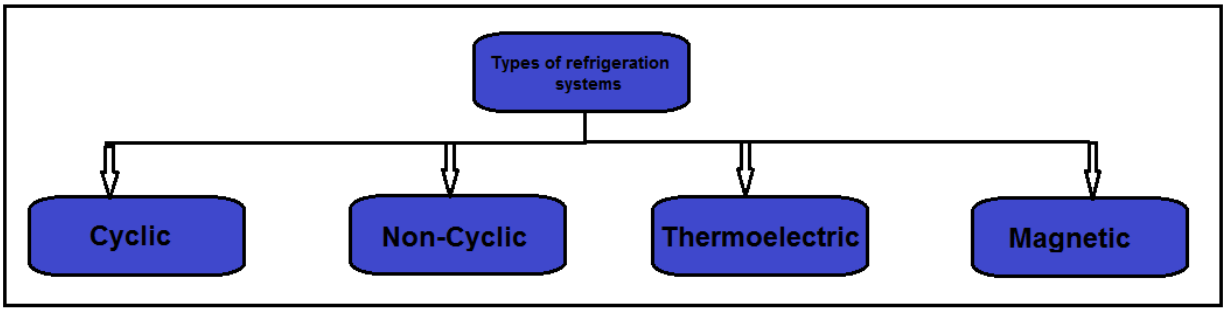

Figure 1. Classification of Refrigeration Methods

2.1 Cyclic Refrigeration

In cyclic method, heat extraction takes place from reservoir at lower temperature and is transferred to reservoir at higher temperature. According to 2nd law of thermodynamics, heat transfer should take place from higher temperature to lower temperature. So, for a cyclic process, work is done on system for reversal in direct of heat flow. The cycle is also referred to as Reverse Carnot Cycle.

2.2 Non Cyclic Refrigeration

In non cyclic method, the cooling is done by using materials such as regular ice and dry ice (solidified carbon dioxide). No electricity (external work) is provided, and no thermodynamic cycles take place in this method. This is useful only when the cooling requirements are needed in a smaller space, such as a laboratory, shops, smaller hotels, restaurants etc.

2.3 Thermoelectric Refrigeration

In thermoelectric cooling system, removal of heat from the substance is done by applying a voltage of constant polarity across junctions of two different metals. The principle on which this system works is called as the Peltier effect. These systems are primarily used in cooling of sensitive electronic equipment such as microprocessors and amplifiers. These are quite expensive and hence cannot be used for domestic purposes.

2.4 Magnetic refrigeration

The principle behind magnetic refrigeration is the magnetocaloric effect, or MCE. The magnetocaloric effect can be described as- when a suitable substance is kept in a magnetic field, its temperature increases, and decreases when the field is removed. The compounds which exhibit MCE at a large scale generally contain a lot of free electrons. These electrons have some magnetic moment of their own. When these electrons come under the influence of an external magnetic field, the spin of the electrons tends to line up in the same direction, which partially constrains their motion. This causes an entropy change (decrease in magnetic entropy) which results in a rise in temperature of the substance. When the heat is extracted by a fluid, the externally applied magnetic field is decreased. Thus, the magnetic moment of electrons becomes random and in disorder once again, which leads to cooling of the substance and thus promoting further heat extraction.

III. GADOLINIUM AND MCE

The most widely used metal for exhibiting the MCE is Gadolinium (Gd). It is a rare-earth metal with atomic number 64 and mass number 157.25. Gadolinium and some of its alloys such as $Gd_5Si_2Ge_2$ exhibit large magnetocaloric effect and are hence considered most suitable materials for magnetic refrigeration.

Some of the basic properties of Gadolinium are stated below

Table 1. Properties of Gadolinium

Properties of Gadolinium		
1.	Group	Lanthanides (rare earth)
2.	Period	6^{th}
3.	Block	F
4.	Atomic number	64
5.	Physical state at ambient temperature and pressure	Solid
6.	Electronic configuration	$[Xe]4f^7 5d^1 6s^2$
7.	Melting Point (M.Pt.) (°C)	1313
8.	Boiling Point (B. Pt.) (°C)	3273
9	Density (gm/cm^3)	7.90
10.	Mass number	157.25
11.	Primary isotope	^{158}Gd

Ferromagnetic properties of Gadolinium and its compounds are important since it is one of the few elements to exhibit magnetocaloric effect. These properties were first determined by Urbain, Trombe, and Weiss in 1935. The absolute saturation magnetization value was found to be 253.5 in cgs units, while Curie point was determined to be 16°C.

The Curie temperature is the critical temperature at and beyond which the ferromagnetic property of Gadolinium (or any other substance) vanishes and it starts exhibiting paramagnetic characteristics. The Gadolinium alloy $Gd_5Si_2Ge_2$ exhibits the Giant Magnetocaloric Effect, or GMCE. The alloy is made of 99% by weight low purity Gadolinium used for common commercial purpose. It was discovered that the maximum change in magnetic entropy was 17.55 $J.kg^{-1}.K^{-1}$, which was obtained for a magnetic field change of 0-5 T

(Tesla).

Gadolinium has some unique magnetic properties, due to which it finds itself used for numerous applications. This element does not really have large scale requirements the way iron and carbon does, but is rather used in niche applications which are highly specialized. Some of its applications are in the medical field. Due to its unique ferromagnetic properties, it is widely used as a contrast agent in magnetic resonance imaging, to provide better imaging results. Similar use of Gadolinium is seen in x-ray imaging, due to its property as a phosphor. Apart from that, it is used for neutron based therapy for targeting tumours. It is used for neutron radiography and for shielding purposes in nuclear reactors. But perhaps its greatest use could possibly be in the field of magnetic refrigeration at room temperature. The magnetic refrigeration method is more efficient and a greener alternative compared to the other more prevalent methods of refrigeration. The technology is still limited to experimental level and needs some more improvements to make it more viable from a commercial stand point.

IV. THE HALBACH CYLINDER

The magnetic system that is generally used for the prototype magnetic refrigerators is a cylindrical Halbach array type magnet. It is basically a magnetized cylindrical body made of ferromagnetic substances which produces a powerful magnetic field inside the cylinder while the outside field is ideally zero. Or, it can be magnetized in such a way such that there is a strong magnetic field outside the cylinder while inside the cylinder it is zero.

The main characteristic of Halbach cylinders are that they provide a static field since they are a type of permanent magnet. Although, sometimes the cylinders could be nested and by relative rotation of one cylinder with respect to the other, we can achieve the cancellation of field, as well as variation and adjustment of its direction.

V. ADVANTAGES OF USING MAGNETIC REFRIGERATION OVER OTHER METHODS

The main advantages of using magnetic refrigeration based on MCE are as follows:

- Improved COP (Coefficient of Performance)
- Better device efficiency
- Less CO_2 emission, thus enhanced energy savings and reduction in individual carbon footprint
- The refrigerant used is solid and non-volatile, hence there is no emission of greenhouse gases and thus they are a greener option and more eco-friendly

VI. APPLICATIONS OF REFRIGERATION

Refrigeration is very prevalent in households as well as industries. There are a number of applications for refrigeration, which are as follows:

- Separation of gas/vapour using fractional distillation in petroleum industry and for producing liquid nitrogen/hydrogen/oxygen etc.
- Dehumidification of air which is important for pharmaceutical manufacturing.
- Liquid gas storage (which is more volumetrically efficient)
- Refrigeration also has applications in cooling of exothermic reactions. This is widely used in manufacturing

of rayon, cellulose acetate, and synthetic rubber

- It is also useful in recovering solvents. Example: Carbon Tetrachloride in textile manufacturing
- One of the most common use is preserving materials such as rubber (non-synthetic), pharmaceutical drugs, and explosive compounds to ensure a long life
- Widely used for preserving dairy products, meat, and poultry both domestically and industrially
- Refrigeration is also used when cold treating of metals is to be done, since this can increase the tool life several times
- Used in the freeze drying method of manufacturing antibiotics
- One more application is in morgues, where dead bodies are to be preserved for post mortem cases or if their is a delay in burial/cremation

VII. REVIEW OF SOME RESEARCHERS

7.1 Jader Barbosa Jr et al. [1]:-Studied the most recent developments in the field of MCE refrigeration. He and his team first studied the experimental characteristics of MCE in some magnetic materials. Experiment was performed using a magnetic field on the given substance. The refrigerant material can be used in solid, bulky form or it can be used in powdered form. For field generation, a Halbach magnet arrangement is used to provide a magnetic flux density of the required magnitude, which is maintained uniformly at around 1.75T. The magnetocaloric effect was observed, where due to a change in magnetic entropy, an adiabatic change in the temperature of the material was observed. This effect has also been demonstrated by the use of a few other prototype devices, namely the first generation reciprocating active magnetic regenerative machines, as well as the second generation rotary AMR refrigeration machines.

7.1.1 Material Specification

- Use of Gadolinium as the MCE sample
- Use of $Nd_2Fe_{14}B$ Halbach magnet

7.1.2 Result

- Magnetic entropy decrease which causes adiabatic temperature changes
- The above phenomenon confirms MCE which can be demonstrated using a few prototype magnetic refrigerators as well

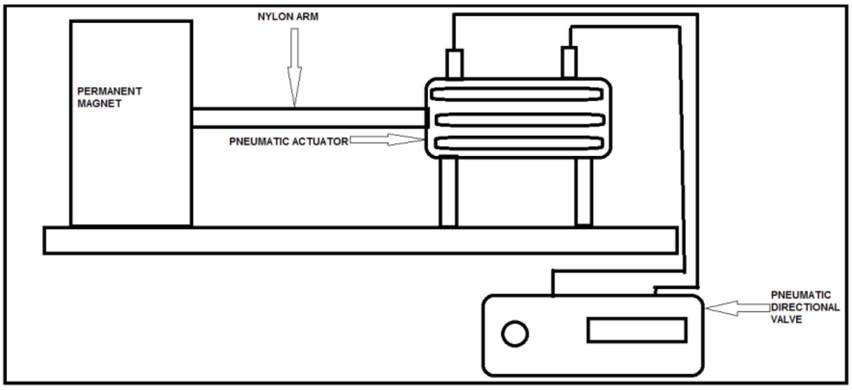

Figure 2. Experimental Setup

7.1.3 Experimental Setup

Experimental setup was designed and built to directly measure the magnetocaloric effect of certain materials which could exhibit relevant properties. It consisted of a Halbach magnet arrangement, a gadolinium sample in plate (or in powder) form, pneumatic actuator with an arm made of nylon, a T type thermocouple, insulated chamber, and a heat-exchanger unit.

7.1.4 Specifications

1. $Nd_2Fe_{14}B$ Halbach magnet assembly with a flux density uniformly maintained at 1.75 T
2. Pneumatic actuator with nylon arm
3. Thin T type thermocouple
4. Sample in bulk form in the form of two plates rectangular in shape which are insulated by a 5mm Polystyrene layer
5. Thermally insulated chamber with capacity of 29 Litres
6. Temperature control system consisting of Peltier modules and a copper coil heat-exchanger which is in turn connected to a thermal bath which is temperature controlled which allow the system to work within a range of 250-350K with tolerance of ±0.05K

7.1.5 Experimentation

After required temperature stabilization of the sample, the pneumatic actuator is activated by a solenoid valve. The actuator places the material (sample) in the magnet, which causes a change in the value of magnetic field from 0T to 1.75T, which results in magnetization of the material. The material is kept in the magnetic field for a few seconds. Then, the solenoid valve is closed, which causes the pneumatic actuator to move the sample outside the magnetic field which causes demagnetization of the material.

7.1.6 Results and Discussion

The adiabatic change in temperature is measured as the difference in the average temperatures of the sample when it is placed inside the magnetic field and then removed. The temperature changes due to presence of thermocouple, which has its own magnetic induction. The shape of sample influences the magnetic field, which is accounted for by N_D, also known as the demagnetization factor. Due to the consideration of this demagnetization factor, there is a decrease in internal magnetic field's intensity (H_{int}), relative to the magnetic field applied. N_D for an isothermal material is given as

$$H_{int} = H_{app} - N_D M \quad (1)$$

where H_{app} is the applied magnetic field. For this particular setup, $\mu_0 H_{app}$ = 1.75 T, where μ_0 is the free space permeability.

7.2 Kurt Engelbrecht et al. [2]:-In this research, a prototype magnetic refrigeration device meant for testing purpose was built at the Technical University of Denmark, or DTU. The prototype is modular in nature, and hence the replacement of parts is very easy. The device is reciprocating type and uses a Halbach magnet arrangement as a field source with average flux density of 1.03 T. The sample material used is a flat plate Gadolinium regenerator also containing $La(Fe,Co,Si)_{13}$, the plate is prepared by sintering the above two materials.

7.2.1 Material Specification

- Mono regenerator Active Magnetic Regenerative (AMR) device

- Regenerator of volume $15cm^3$ which does not include housing and external components
- Permanent Halbach cylinder magnet with average flux density of 1.03 Tesla, diameter of 42mm and height of 50mm

7.2.2 Results

- The effect of ambient temperature was tested in relation to the temperature of the cold and hot reservoirs. For a temperature of 22.5°C, the regenerator's no-load span was found to be 10.2°C in the range of 15.6° to 25.8°C. If the temperature of hot reservoir was allowed to rise 3°C above room (ambient) level, it lead to an increase in the temperature span of the device by 1°C. Since losses from regenerator are negligible, it can be concluded that there is a thermal leak between the cold reservoir and the ambient surroundings which could lead to a loss in performance.
- Test shows that a single material AMR refrigerator works its best when its Curie point lies within the working range of temperature of the device.

7.3Prakash Chawla et al. [3]:-In this research, the different types of magnetocaloric materials were studied. The paper also puts light on linear and rotary type of magnetic refrigeration devices, as well as Multistage machines using permanent magnets.

- Gadolinium and its alloys
- Perovskites and perovskite-like compounds

7.3.1 Results

- The temperature span needs to be minimized which can be done by reducing difference in the upper and lower temperature values, otherwise the system is just not efficient or viable
- MCE refrigerators are limited since the cooling effect can take place only close to the Curie point, and hence they cannot handle large variations in temperature

7.4 Houssem Rafik El-Hana Bouchekara et al. [4]:-This paper talks about the active magnetic regenerative (AMR) refrigeration devices. These devices overcome some of the problems that are faced when working with Gadolinium and its alloys for obtaining the MCE, and thus the problem of cooling capacity of load is slightly improved. Some of the different prototypes of magnetic refrigerators are also covered in this paper.

- Gadolinium and its alloys
- Magnetic refrigeration systems: Steyret, Brown, Kirol, Spanish, Japanese, Zimm, Canadian, Cooltech, G2Elab prototypes, and the Slovenian systems, based on monoblock magnets, Halbach cylinder, double Halbach cylinder, and Rotating Multiblock magnet system

7.4.1 Results

- The different types of devices, as well as shortcomings of magnetic refrigerators and ways of overcoming them using AMR devices was studied
- MCE gives best refrigeration when the difference between cold and hot reservoir temperatures is less and the Curie point is within the working range

7.5 Engin Gedik et al. [5]:-In this study, the principle of magnetocaloric effect, magnetic refrigeration, and basic types of magnetic refrigerators were studied. It also covered the different types of magnetocaloric materials, namely Gadolinium and its alloys, and some other materials.

- Gadolinium and its alloys
- Perovskites and perovskite-like materials

7.5.1 Results

- More energy saved when using magnetic refrigeration (increase of almost 30%), compared to regular gas-cycle refrigeration units
- MCE refrigeration works best when the difference in hot and cold reservoir temperatures is small and the Curie point lies within the working range of the device

7.6 J.S. Lewis et al. [6]:-In this paper, different types of magnetocaloric materials, such as Gadolinium and its alloys, mainly $Gd_5Si_2Ge_2$ (which exhibits giant magnetocaloric effect or GMCE), and the difference between MCE and GMCE exhibiting materials is that in case of GMCE material, there is a structural change which accompanies the MCE. It also studies the Active Magnetic Regenrative (AMR) refrigerators, such as the Japanese model (from the Chubu Electric Power Co. Inc.) which gives a maximum cooling power of 560 watt at a span of 0K, and the Zimm model with maximum cooling power of 44 watt at a temperature span of 0K.

- MCE and GMCE materials such as Gadolinium and its alloys
- Different types of AMR machines, namely the Japanese Chubu Electric model and the Zimm model

7.6.1 Results

- The highest possible coefficient of performance obtained so far is 2.4 by the Chubu Electric AMR machine at room temperature
- Commercial viability of magnetic refrigeration is possible by use of GMCE materials, permanent magnets, proper magnetocaloric refrigeration cycles, and better design for devices

7.7Aedah M. Jawad Mahdy et al. [7]:-In this research, a suitable magnetic refrigeration prototype device was constructed and studied using pure Gadolinium as the MCE exhibiting material. The magnetic assembly used was a Halbach cylinder generating flux density of 0.7 to 2.4 Tesla. Other materials used for housing etc were PVC and Perspex tubes. The fluids used for working were distilled water and mixture of water/ethylene glycol.

- Permanent NdFeB Halbach cylinder arrangement magnet generating magnetic flux density of values up to 2.4 Tesla
- 13 plates of 99.9% pure gadolinium with 0.9mm thickness, 25mm width, and a length of 40mm along direction of flow

7.7.1 Results

- Maximum no-load temperature span obtained was 11K
- The designed prototype is in agreement with similar prototypes built for other research facilities and gives similar results coming to magnetic refrigeration

VIII. CONCLUSION

Although magnetocaloric effect has a lot of merit when it comes to refrigeration at room temperature, its viability for commercialization is still at best questionable. The principle has an unmatched potential in the field of refrigeration, but there are many factors that are still to be overcome, chief among them are the availability and cost of materials, and proper design techniques which could lead to higher cooling capacity with an improvement in current coefficient of performance levels. However, the research is still going on, and certain prototypes have shown promising results, so the success of magnetic refrigeration technology may still be a possibility.

REFERENCES

[01] Jader Barbosa Jr., Jaime Lozano, Paulo Trevizoli: "MAGNETOCALORIC REFRIGERATION RESEARCH AT THE INCT IN COOLING AND THERMOPHYSICS". Proceedings of the ENCIT 2014

[02] Kurt Engelbrecht, Jesper Buch Jensen, Christian Robert Haffenden Bahl: "Experiments on a Modular Magnetic Refrigeration Device". Strojniški vestnik - Journal of Mechanical Engineering 58(2012)1, 3-8

[03] Prakash Chawla, Ankit Mathur: "A Review Paper on Development of Magnetic Refrigerator at Room Temperature". (IJIRSE) International Journal of Innovative Research in Science & Engineering

[04] Houssem Rafik El-Hana Bouchekara, Mouaaz Nahas: "Magnetic Refrigeration Technology at Room Temperature". Trends in Electromagnetism – From Fundamentals to Applications, 225-250

[05] Engin Gedik, Muhammet Kayfeci, Ali Keçebas, Hüseyin Kurt: "MAGNETIC REFRIGERATION TECHNOLOGY APPLICATIONS ON NEAR-ROOM TEMPERATURE". 5th International Advanced Technologies Symposium (IATS’09), May 13-15, 2009, Karabuk, Turkey

[06] J.S. Lewis, I. Chaer, S.A. Tassou: "FOSTERING THE DEVELOPMENT OF TECHNOLOGIES AND PRACTICES TO REDUCE THE ENERGY INPUTS INTO THE REFRIGERATION OF FOOD - Reviews of Alternative Refrigeration Technologies". Center for Energy and Built Environment Research School of Engineering and Design, Brunel University, July, 65-76

[07] Aedah M. Jawad Mahdy, Wahid S. Mohammad, Talib K. Mortada: "A Novel Design of a Domestic Magnetic Refrigerator". International Journal of Application or Innovation in Engineering and Management (IJAIEM), Volume 4, Issue 2, February 2015

[08] Zhang Tiebang, Chen Yungui, Fu Hao, Teng Baohua, Tang Yongbai, TU Mingjing: "The giant magnetocaloric effect in $Gd_5Si_2Ge_2$ with low purity gadolinium". Chinese Science Bulletin 2005 Vol. 50 No. 16. 1811-1814

[09] J.F. Elliot, S. Legvold, F.H. Spedding: "Some Magnetic Properties of Gadolinium Metal". PHYSICAL REVIEW, VOLUME 91.NUMBER 1, JULY 1, 1953

[10] Jyotish Chandra Debnath: "Novel magnetocaloric materials and room temperature magnetic refrigeration". University of Wollongong Online Thesis Collection, 2011

[11] M.D. Mukadam, S.M. Yusuf: "Magnetocaloric effect and magnetic cooling". BARC Newsletter, ISSUE NO 312, JAN-FEB. 2010

[12] Gschneidner, Karl, Vitalij Pecharsky, Carl Zimm, “Magnetic Cooling for Appliances”. International Appliance Technical Conference Proceedings, p. 144, May, 1999

[13] Dr. Robert O' Handley: "Magnetic Refrigeration: A Chilling Attraction- An Evaluation of Recent Materials and Technological Developments". 3.45 Magnetic Materials, Spring 2004, Department of

Materials Science and Engineering, Massachusetts Institute of Technology

[14] Jian Liu, Tino Gottschall. Konstantin P. Skokov, James D. Moore, Oliver Gutfleisch: "Giant magnetocaloric effect driven by structural transitions". Nature Materials 11, 620-626, (2012)

[15] Stinus Jeppensen: "Magnetocaloric Materials". University of Copenhagen and Fuel Cells and Solid State Chemistry Division, Risø DTU (Technological University of Denmark)

[16] K.A. Gchneidner Jr., V.K. Pecharsky, A.O. Tsokol: "Recent Development in Magnetocaloric Materials". INSTITUTE OF PHYSICS PUBLISHING, Rep. Prog. Phys. 68 (2005), 1479-1539