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Application of Multiferroic Alloy to Convert Waste Heat from Brine to Electricity

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ABSTRACT

This research entails an exploration of a special alloy (Ni45Co5Mn40Sn10) to convert waste heat from non- commercial geothermal wells to electricity. The alloy utilizes brine's heat from non-commercial geothermal wells. In this design, waste heat is directly converted to electricity using Multiferroic Alloys, thereby increasing the power output and efficiency as well as eliminating the need for heat exchangers before recycling the steam. The multiferroic alloy (Ni45Co5Mn40Sn10) is made up of Nickel, Cobalt, Manganese, and Tin. The alloy undergoes a reversible phase transformation from a nonmagnetic martensitic phase to a strong ferromagnetic austenite phase upon heating. When biased by a permanent magnet such as rare earth magnet and then heated, the change in phase from martensite which is nonmagnetic to Austenite which is magnetic causes a sudden increase of the magnetic moment which drives a current in the surrounding circuit as a consequence of Faraday's law.

The alloy undergoes low hysteresis reversible phase transformation and can be used even at small changes in temperatures such as 10Kelvins. In my preliminary studies, I designed a multiferroic (Ni45Co5Mn40Sn10) alloy that utilizes waste heat from brine to generate additional power. The alloy was surrounded by suitably placed coils and then placed adjacent to a permanent magnet. In the design, the steam coming from the well is used to heat the multiferroic alloy. The alloy then undergoes a reversible first order martensitic phase transformation from martensite at low temperature to austenite at high temperature. The martensitic phase is non-ferromagnetic while the austenite phase is highly ferromagnetic. The magnetic field momentum of the alloy increases rapidly when heated. Extreme fluctuation in the magnetic field momentum that cuts through the coil as the alloy transforms from non-ferromagnetic to ferromagnetic phase induces electromotive force into the coil (Faraday's law).

Cooling the alloy in the air through natural convection and conduction induces an electromotive force of opposite polarity in the coil. Heating and cooling of the alloy results in continuous power generation. The martensitic transformation is extremely fast due to low magnetic hysteresis, the absence of diffusion and the presence of low energy mode of transformation between the martensitic phase and austenite phase. The speed of interface transformation in the alloy tends to the speed of light in a material. The rapid martensitic phase transformation results in the production of electricity at high frequency. The frequency of power generation is further increased by having several turns of the coil around the magnet. The magnet is placed such that their fields produce multiple phases of current in the coils. The heating process is achieved through the transfer of heat by convection from the steam to the alloy. The cooling process is accomplished through heat transfer from the alloy to the atmosphere by natural convection and conduction.

Periodic heating and cooling of the alloy induce an alternating current in the coil. The temperature of the alloy will vary between the upper critical and lower critical temperatures to achieve continuous power generation. An optimized model results in steady and continuous power production through controlled steam flow into the alloy. Simulation studies indicate that the project can generate 15MW of electricity from brine. This will broaden the economic drivers in both developing and industrialized countries through increased and steady power production from geothermal wells which are currently unproductive.

1. INTRODUCTION

This research entails exploration of a special alloy (Ni45Co5Mn40Sn10) to convert waste heat from non- commercial geothermal wells to electricity. The alloy utilizes the heat from non-commercial geothermal wells. In this design, waste heat is directly converted to electricity using Multiferroic Alloys thereby increasing the power output and efficiency as well as eliminating the need for heat exchangers before recycling the steam.

The multiferroic alloy (Ni45Co5Mn40Sn10) is made up of Nickel, Cobalt, Manganese and Tin. The alloy undergoes reversible phase transformation from a nonmagnetic martensitic phase to a strong ferromagnetic austenite phase upon heating. When biased by a permanent magnet such as rare earth magnet and then heated, the change in phase from martensite which is nonmagnetic to Austenite which is magnetic causes a sudden increase of the magnetic moment which drives a current in the surrounding circuit as a consequence of Faraday's law. The alloy undergoes low hysteresis reversible phase transformation and can be used even at small changes in temperatures such as 10K.

1.1 Problem Statement

There are enormous losses of heat energy from the present non-commercial geothermal wells which leads to the conversion of the wells to re-injection wells or rejected wells. This is due to inadequate volume of steam in the well to efficiently rotate the turbines hence resulting to low power output. This research paper demonstrates how a multiferroic alloy can be used to directly convert the heat from the steam to electricity without necessarily having to rotate the turbines. This will improve the power output as well as the efficiency of power generation by utilizing the heat from the steam coming from the wells.

1.2 Research Objectives

1. To develop green energy from waste heat of non-commercial geothermal power plants through direct conversion of heat to electricity using multiferroic alloys.

2. To compare other techniques of conversion of heat to electricity with the multiferroic alloy device.
3. To improve the overall efficiency of power output in Geothermal power generation
4. To increase the energy output of Geothermal power plants
5. To develop potentially broad economic drivers and leadership in technology that aims to diversify electricity generation techniques

1.3 Research Hypothesis

1. The multiferroic alloy will be able to convert waste heat to electricity at a cost that is economically viable and justifiable for the project.
2. The temperature of the steam leaving the well is above 100^0C
3. The overall energy output and efficiency of power generation will be improved.

1.4 Research Scope

Use of waste heat from steam coming from non-commercial geothermal wells to generate electricity through the use of multiferroic alloys in Kenya. The research mainly focused on the steam leaving the wells at a temperature range of between 100°C to 170°C.

1.5 Research Limitation

1. Time constraint- I had limited time of only six Months to carry out the research.
2. Inadequate funds and facilities to conduct all the necessary lab experiments, making the prototypes and models for the research project.

1.6 Delimitations

I used computer simulation and modeling techniques for the various aspects of the project where prototypes and real experiments were too expensive to be conducted. This saved on time as well as the cost for the research.

2. LITERATURE REVIEW

2.1 Introduction

From the research conducted by the University of Minnesota engineering researchers, a unique alloy (Multiferroic alloy) was discovered that is both strongly ferromagnetic in one phase and non-Ferro magnetic in another phase. The material undergoes a phase transformation but with no diffusion and has an abrupt change in lattice parameters. The alloy Ni45Co5Mn40Sn10 has a strong ferromagnetic austenite phase with magnetization approaching that of iron, and a non-ferromagnetic martensitic phase. This material is suitable for energy conversion due to

- Absence of diffusion
- Presence of low energy mode of transformation between crystalline lattices (low hysteresis)
- Reversibility of the transformations
- Absence of other relaxation processes

These Multiferroic alloys have highly reversible phase transformations with a change in lattice parameters. This implies that stress will be present in the transition layer between the austenite/martensite interfaces. The stresses may cause dislocations and other defects that may lead to thermal hysteresis, migration of the transformation temperatures or failure. The alloy used for energy conversion is however made with a strategy that improvises reversibility of phase transformation and lowers hysteresis. In recent alloy development programs done by combinatorial synthesis methods, the thermal hysteresis of phase transformations has been dropped from 300 to less than 60c. The graphs depicting the various magnetization properties of Ni45Co5Mn40Sn10 under the influence of various variables such as temperature and field (Tesla) are shown below in figure 1.

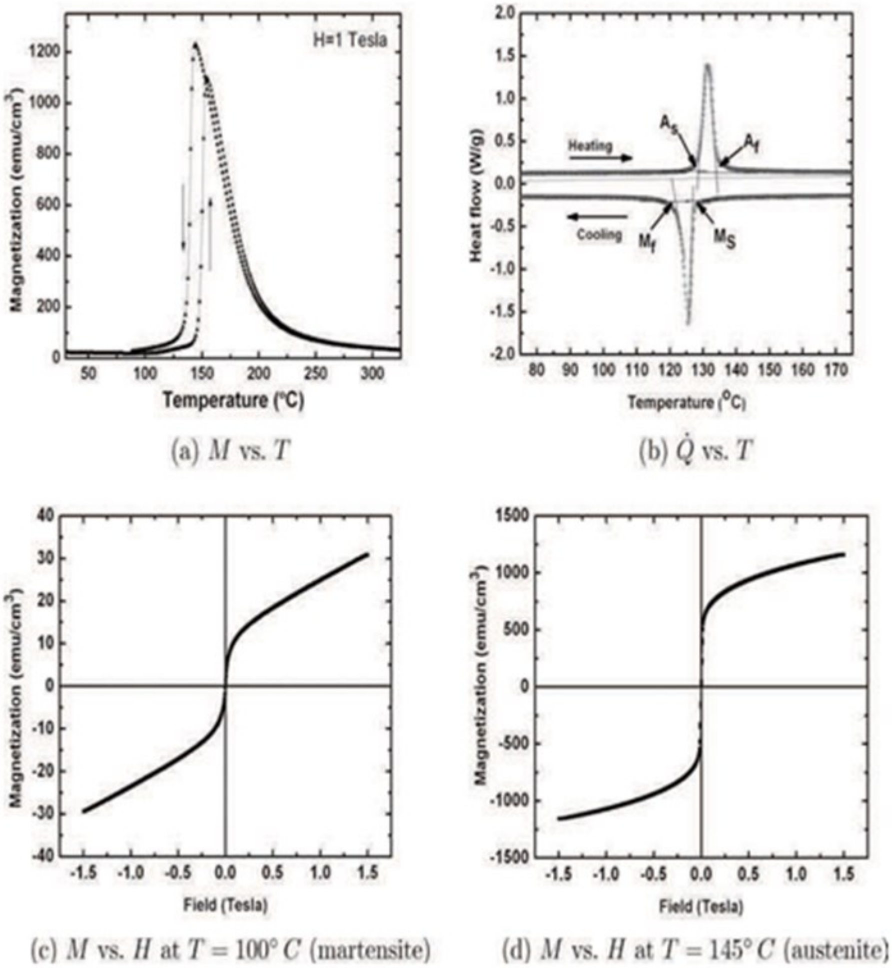


Figure 1: Srivastava, V., Song, Y., Bhatti, K., & James, R. D. (2011). The direct conversion of heat to electricity using multiferroic alloys. ***Advanced Energy Materials*****,** ***1*****(1), 97-104.**

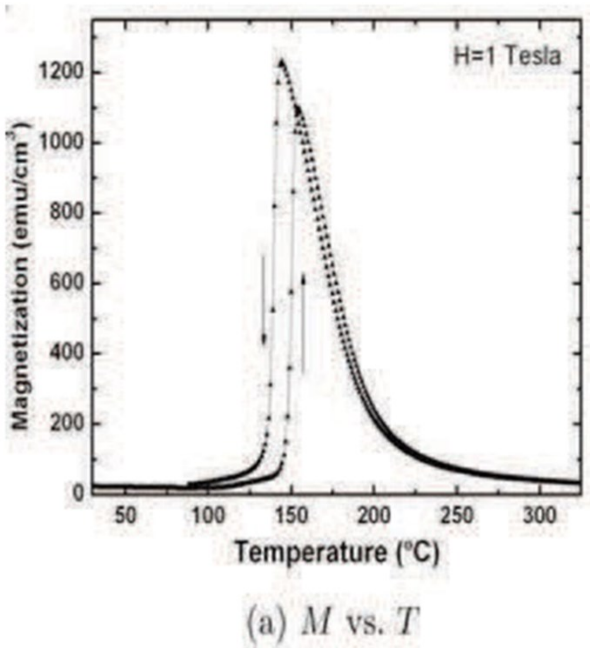
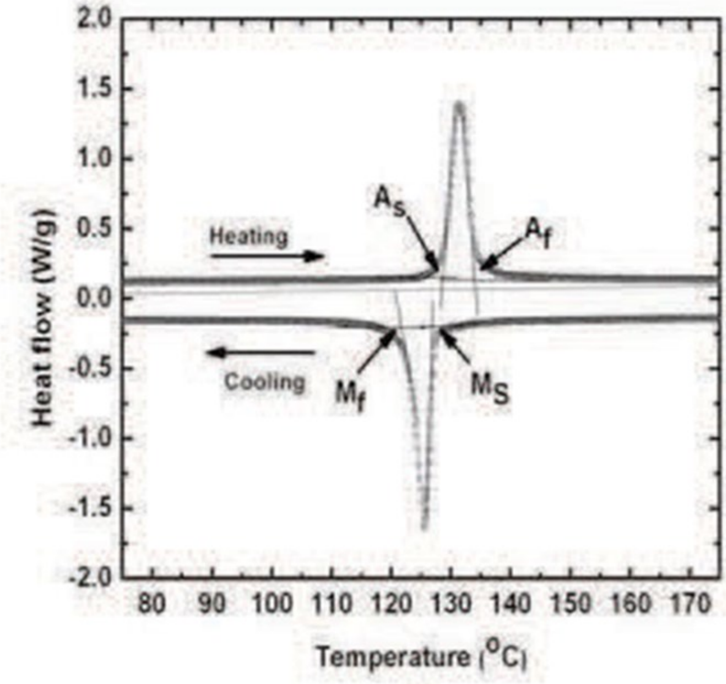
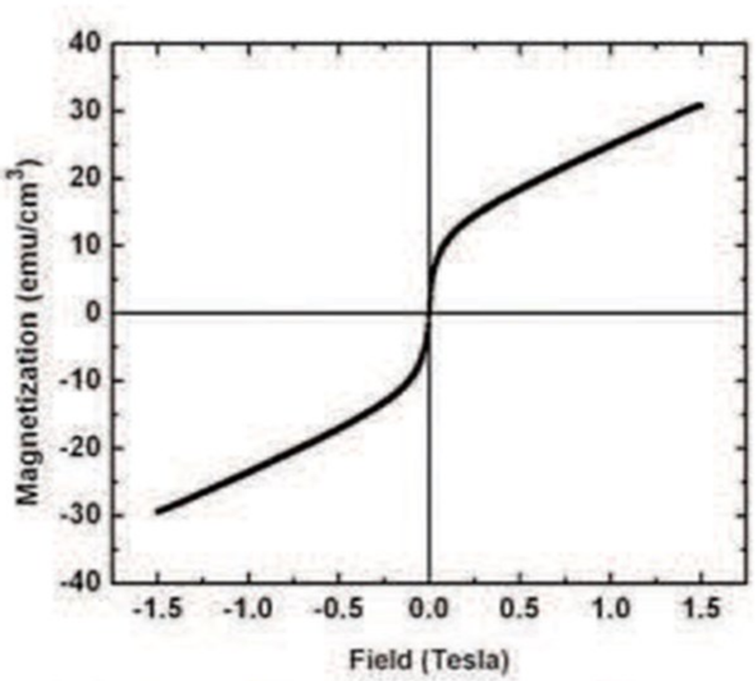


Figure 1a: A graph of magnetization against temperature under a field of one Tesla



(b) $\dot{Q}$ vs. T

Figure 2b: A graph of heat against temperature



(c) M vs. H at $T = 100° C$ (martensite)

Figure 3c: A graph of magnetization against field in martensite phase

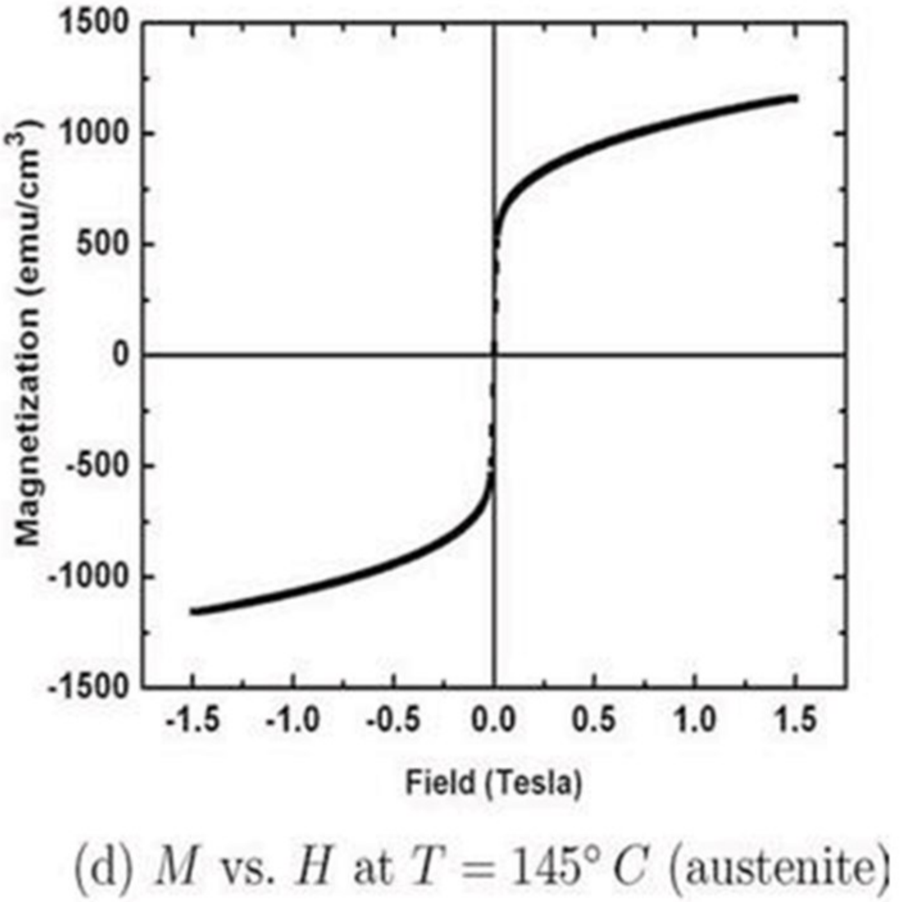


Figure 4d: A graph of magnetization against field in austenite phase

From **figure 1a,** the phase transformation upon heating under a field of 1 T increases magnetization from less than 10 emu/cm^3 in the martensite phase to more than 1100 emu/cm^3 in the austenite phase. **Figure 1c** shows an inhomogeneous structure containing a small fraction of ferromagnetic particles in a non-ferromagnetic matrix. The thermal hysteresis measured by calorimetry in **figure 1b** is As- Mf = 6°C, and the latent heat is16.5 J/g. From the curves obtained there is no remanence and coercivity, and this implies that the changes in magnetization contributed negligible loss to the devise. A permanent magnet such as rare earth is required to bias the material so that a uniformly magnetized sample is obtained upon heating to austenite.

2.2 Comparing the Multiferroic Alloy and Thermoelectric Materials

Thermoelectric materials are the other promising option that directly convert heat to electricity. It involves utilizing the seebeck effect to directly produce electricity from a temperature gradient. It also produces electricity without moving parts. However, the predicted voltage output for an optimized multiferroic alloy is comparable to that of a good thermoelectric material. The predicted power density of the alloy is higher than the highly efficient thermoelectric materials. Thermoelectric materials use a higher temperature difference than that of Multiferroic alloys, and therefore this necessitates the comparison between them. In comparing the two devises, a temperature difference of 10°C was used to support the first peak for multiferroic alloys which is its phase transformation value.

The voltage output of a Thermoelectric material is given by its seebeck coefficient. Bi^2Te^3 has a seebeck of −230µ V/k. The standard thermocouple with the best seebeck coefficient is Chromel-Constantan at 60µ V/k. At a temperature difference of 1°K the voltage output is 2.3mV for Bi^2Te^3 and 0.6VmV for Chromel- Constantan. TG 12-8 which is an optimized Thermoelectric generator developed by Marlow industries has a power density of 1.83 x 106erg/cm^3s. The highest energy density measured from the recent thermoelectric generator was 2.5 x 106erg/cm^3s. Scaling proportionally to 100C, this translates to 1.4 x 105erg/cm^3s.

2.3 Other Methods of Directly Converting heat to Electricity.

The table below shows how various phase transformations can take place in a material hence resulting in change of their properties such as magnetism, electric conductivity, permittivity or anisotropy. The material can then be suitably biased with either a permanent magnet or capacitor in order to generate electricity on an external coil with regards to Faraday's or Ohm's law as shown in table 1.

N	Phase 1	Phase 2	Biasing and electricity generation
1	Ferromagnetic	Nonmagnetic	Biasing by a permanent magnet; external
2	Ferroelectric	Nonferroelectric	Biasing by a capacitor; polarization-
3	Ferromagnetic; high anisotropy	Ferromagnetic; low anisotropy	Biasing by a permanent magnet, inter-mediate magnetic field; external coil.
4	Ferroelectric; high permittivity	Ferroelectric; low permittivity	Biasing by a capacitor, intermediate electric field; polarization-induced current
5	Ferroelectric	Nonpolar	Second-order transition;
6	Ferromagnetic	Nonmagnetic	Second-order transition;
7	Nonpolar; nonmagnetic	Nonpolar; nonmagnetic	Shape-memory engine driving generator biased

Table 1.

For all the cases above, one must pay attention to reversibility and low hysteresis. The multiferroic alloy discussed in this paper uses a big difference in magnetization of the two phases. Another alternative could be to have a transformation between phases having nearly the same magnetization but different magnetic anisotropy such as alloy Ni_2MnGa. In this case a carefully tuned applied field would easily rotate the magnetization in austenite phase but not in the other, leading to an effective large change of magnetic moment during transformation.

3. EXPERIMENTAL SETUP

3.1 Introduction

Through experimental research, I designed, modeled and simulated an optimal Geothermal power generation cycle that utilizes heat from steam leaving the non- commercial geothermal well to produce green energy.

Experimental parameters

Diameter of the alloy ($Ni_{45}Co_5Mn_{40}Sn_{10}$)

D = 10cm

Number of turns in the coil (copper) =1000

Average radius of the coil =14.25mm

Length of the coil = 8m

Steps involved in the design

I designed a multiferroic alloy $Ni_{45}Co_5Mn_{40}Sn_{10}$ with curved interior cavities to allow hot steam to get in and out as shown in the **figure 2** below. The steam cavities inside the alloy are designed with successive bends to allow maximum surface area for heat absorption.

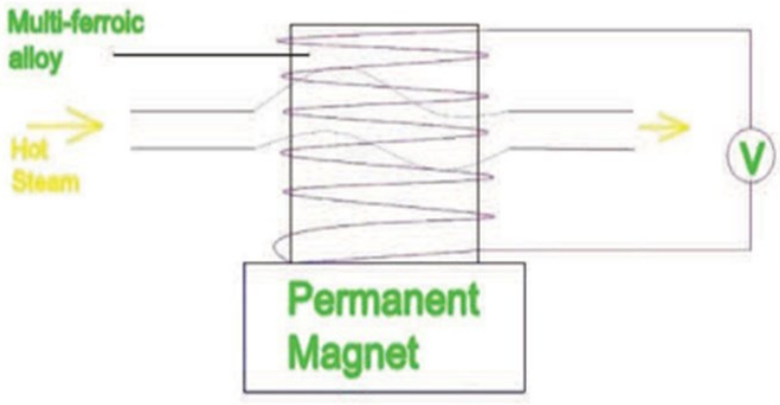


Figure 2: The experimental setup

- Suitably fix the alloy adjacent to the rare-earth permanent magnet for biasing.
- Surround the alloy with a coil and then connect the coil to a voltmeter.
- Allow hot steam at 50°C to pass through the alloy continuously and record the Voltage value after every five seconds.
- Air cool the alloy and record the voltage values after every five seconds
- Determine the temperature range during cooling and heating that results in the maximum power out. Note the periodic time when the output is maximum and then repeat the heating and cooling operations while maintaining the optimum period that results to maximum power output.
- Plot a graph of voltage against time for the optimized model and determine the maximum voltage recorded and the magnitude of current through the coil.

3.2 Methods of Data Collection

Experiments to determine the voltage output with corresponding temperatures and time

Computer and internet technology to model and simulate the voltage output of the alloy in a real geothermal power station.

Equipment Used

- A voltmeter for measuring voltage
- A thermometer for temperature measurement
- An Electric heater for heating water to steam
- A stop watch for measuring time

4. RESEARCH FINDINGS AND DISCUSSIONS

4.1 The Alloy Output During Heating

Experimental Results when Heating the Alloy

When the alloy is heated, it begins to transform from non-magnetic Martensitic phase to Austenite phase. Initially no current is recorded because the change in magnetic field intensity is not sufficient to induce current into the coil. After 15 seconds, the change in magnetic field intensity is sufficient to induce current into the coil. At 100°C, the alloy is completely ferromagnetic hence there is no change in magnetic field intensity and no current is induced into the coil.

Time(s)	0	5	10	15	20	25	30	35	40
Temp of the alloy	25	30	35	40	45	50	55	60	65
Voltage(V)	0.0	0.0	0.0	0.10	0.20	0.30	0.40	0.50	0.60

Time(s)	45	50	55	60	65	70	75
Temp of the alloy	70	75	80	85	90	95	100
Voltage(V)	0.70	0.80	0.81	0.70	0.40	0.10	0.0

Table 2a

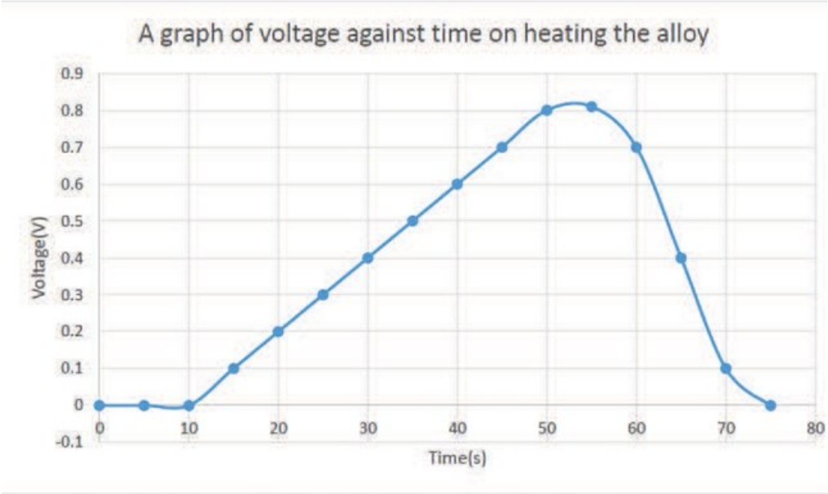


Figure 4: A graph of voltage against time on cooling the alloy

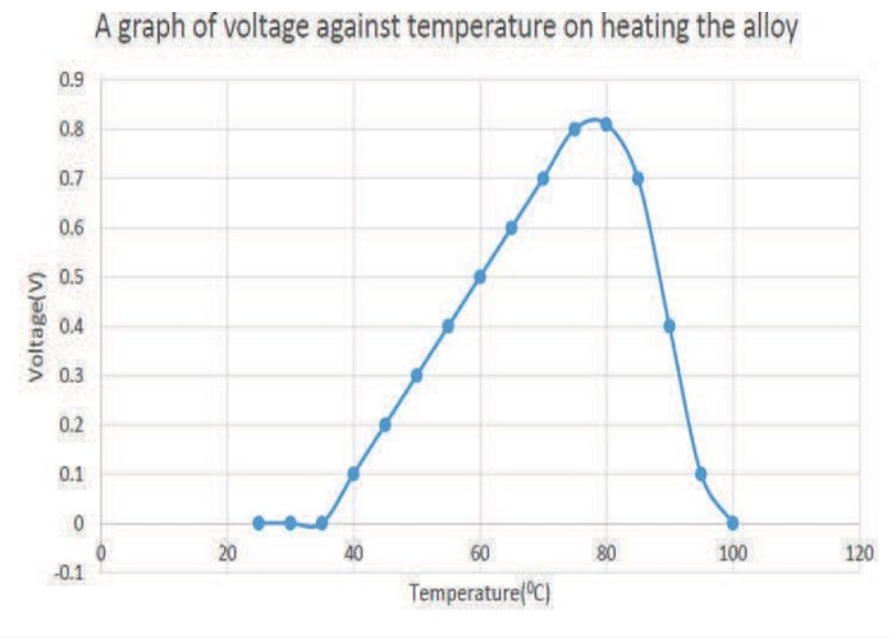


Figure 4.1: A graph of voltage against time on heating the alloy

Experimental Results when Cooling the Alloy

4.2 The Alloy's Output During Cooling

When the alloy is cooled, it begins to transform from magnetic Austenite phase to non- magnetic Martensitic phase. Initially no current is recorded because the change in magnetic field intensity is not sufficient to induce current into the coil. After 5 seconds, the change in magnetic field intensity is sufficient to induce current into the coil. At 36.4°C, the alloy is completely non-ferromagnetic hence there is no change in magnetic field intensity and no current is induced into the coil.

Time(s)	0	5	10	15	20	25	30	35	40
Temp of Alloy	100	95	89.8	85.7	81	75.3	70.5	65.8	61
Voltage(V)	0.0	0.1	0.41	0.70	0.80	0.77	0.68	0.59	0.47

Time(s)	45	50	55	60	65	70	75
Temp of the alloy	56.1	51.0	46.2	41.3	36.4	31.3	26.7
Voltage(V)	0.39	0.28	0.19	0.1	0.0	0.0	0.0

Table 2b

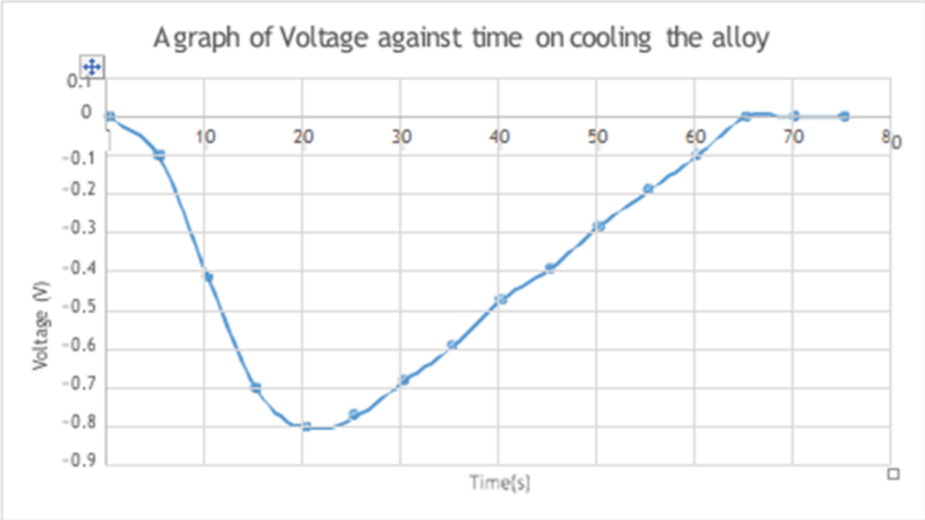


Figure 4.2: A graph of voltage against time on cooling the alloy

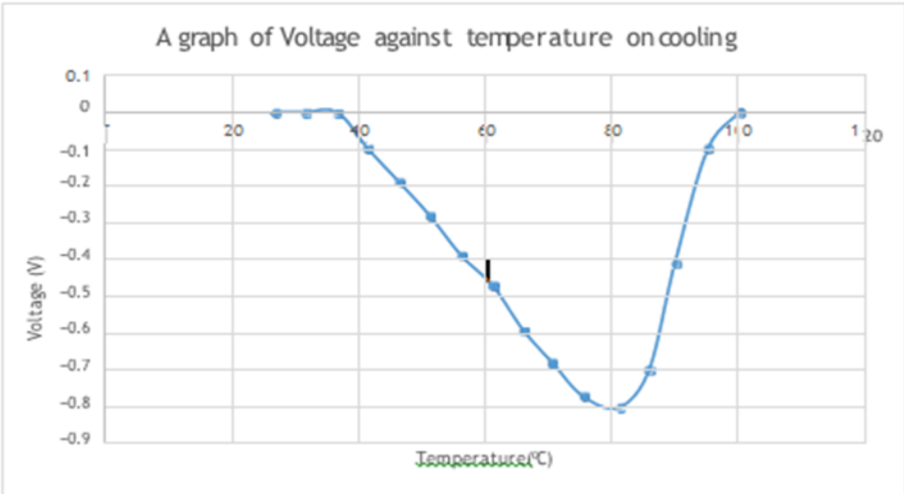


Figure 4.3: A graph of voltage against temperature on cooling the alloy

5. DISCUSSION OF THE FINDINGS

5.1 Introduction

When the steam is passed through the multiferroic alloy, heat energy is absorbed by the alloy and hence the temperature of the alloy increases. The alloy transforms from austenite phase which is non- ferromagnetic to martensite phase which is highly ferromagnetic. The average magnetization **M** is increased in the alloy resulting in the increase in the rate of change of magnetization d**M**/dt. The permanent magnet prevents demagnetization and provides the magnetic fields.

As the temperature of the alloy increases the magnetic momentum of the alloy keeps on increasing. This continuous change in the magnetic fields causes a relative motion between the fields and the coil and therefore induces current in the coil. The maximum induction occurs at a temperature of **80°C.** Beyond **95°C**, the alloy phase is completely ferromagnetic (saturated) with no fluctuation in magnetic field momentum. No current is therefore induced in the coil.

The electromotive force of opposite polarity is obtained is obtained by cooling the alloy. This is achieved through closure of the steam valve that lets steam into the alloy. Atmospheric air is then allowed to cool the alloy. During cooling, the austenite phase begins to transform into martensite. The magnetic momentum gradually reduces from the peak hence creating a relative motion between the coil and the magnetic field. This induces a current into the coil. Below **41.3°C**, the alloy phase is completely nonferromagnetic (martensite) and therefore no current is induced in the coil.

An optimized design varies the temperature between **95°C** to **45°C** in order to produce maximum power. The graphs of temperature of the alloy against time for heating and cooling in the literature review suggests that both heating and cooling processes are a function of time only. The processes are highly reversible due to low hysteresis. The graphs for both heating and cooling are of nearly the same shape for the alloy but curves in opposite directions.

From the results obtained experimentally it takes approximately 60 seconds to heat the alloy from 45°C to 95°C and also 60 seconds to cool the alloy from 95°C to 45°C. That is, from the 10th second to the 70th second of heating and cooling. For maximum output, the alloy is first heated up to 95°C for seventy seconds and then cooled and reheated periodically at an interval of sixty seconds. The steam is therefore supplied to the alloy for one minute and then the steam inlet valve closes and the steam exit valve opens to exit the steam and allow the atmospheric air to cool the alloy.

5.2 The Voltage Output for Heating and Cooling at an Interval of 60s is as Shown Below

Time(s)	10	15	20	25	30	35	40	45	50	55	60	65	70
Voltage(	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.81	0.7	0.4	0.1

Time	75	80	85	90	95	100	105	110	115	120	125
Volt	-00.1	-0.41	-0.70	-0.8	-0.77	-0.68	-0.59	-0.47	-0.39	-0.28	-0.19

Table 3

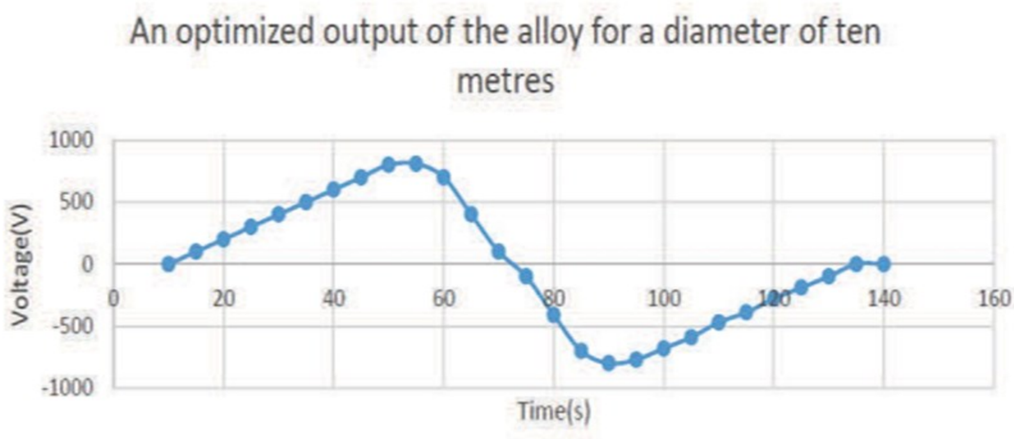


Figure 5: A graph of voltage against time during heating with steam and cooling in air.

The opening and closing of the steam valves is programmable in such a way that it allows the steam to flow through it in one minute and then closes to cutoff the steam supply and allow the alloy to cool as shown in figure 3 below.

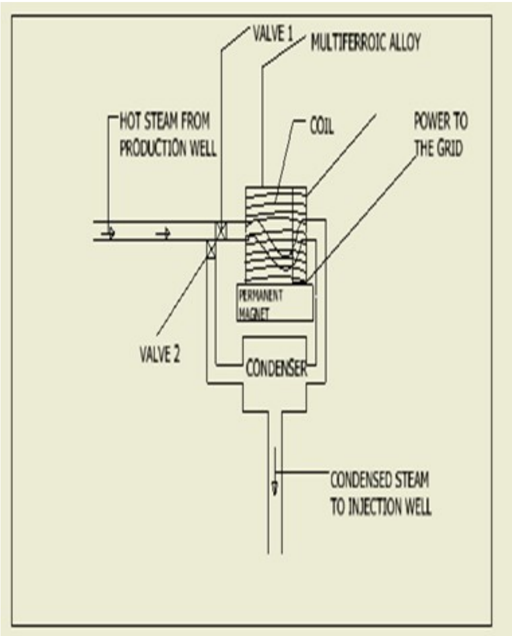


Figure 5.5: Figure above is showing valves 1 and 2 that controls the heating and cooling of the alloy

Where;

V_1 = valve 1

V_2 = Valve 2

V_3 = Valve 3

The steam is allowed to pass through the alloy until a temperature of 95°C is attained. Valve 1(V1) then closes while valve 2 and 3 opens for 60s, this prevents the steam from entering the alloy and allows it to cool through natural convection and conduction. After sixty seconds, valve 2 and 3 closes while valve1 opens for again sixty seconds to allow the steam to heat the alloy. The periodic heating and cooling of the alloy is therefore achieved through controlled opening and closing of the steam valves.

The dipolar relationship between the Magnetization **M,** magnetic induction **B** and magnetic field **H** is given by:

B = H + 4n**M**

From the above equation the rate of magnetic induction d**B/**dt is nonzero.

According to the Faradays law, the change in magnetic induction across a conductor induces electromotive force **E** into the conductor. This can be mathematically expressed as;

curl**E** = -1/c x d**B**/dt

Where c is the speed of light

For an assumed susceptibility x(t) and an axial demagnetization factor 0 < 6 < 4n, the following differential equation for the induced current is obtained

{[4nN(1 + (4n- 6)X(t)]/ c2Leff} I'(t) + [8rc /d2o + R/N + 4nAN(4n-6)/c2Leff] I(t) + [A(4n-6)X'(t)h0]/c = 0

Where A is the cross sectional area assumed to be $\pi D^2/4$

D= diameter of the alloy =100mm

N= number of turns in the coil

=2000

Ϭ = electrical conductivity of the copper wire= 5.4x 1017/s

d= diameter of the wire

R= external resistance = 10k ohm

h0= magnitude of the applied magnetic field

Leff= effective length of the coil

Considering the case where susceptibility is linear in time

X(t) = (t/t1) Xa+ (t1-t)/t1)Xm where Xm is the martensite susceptibility, the differential equation can be simplified to

(C1t + C2)I' (t) + C3 I(t) + C4= 0

Where;

C1= [4nAN (4n-6)(Xa-Xm)]/c2Leff C2= [4nAN (1 + (4n- 6)Xm)]/ c2Leff

C3=8rc/od2 + R/N + [4n (4n-6) AN (Xa- Xm)]/c2Leff

C4= [(4n-6) A (Xa-Xm) h0]/ct1

The general solution becomes

I(t) =(I0+C4/C3)(1 + C1t/C2)-C3/C1 - C4/C3

This solution has a short-lived transient solution followed by the saturation value I(t) =

-C4/C3 which gives a constant back field that opposes the field due to the permanent magnet.

Rapid heating through the phase transformation favors a big back field, and coupling with the large magnetization gives a higher power output.

5.3 Recommendable Specifications of the Design for Actual Geothermal Power Station

For an actual power station, a single alloy of 5m diameter, steam inlet diameter of 0.5 to 1m and 5000 to 10000 turns of coil are economical for maximum utilization of the waste heat from the steam. This is economically viable for medium geothermal wells.

Alternatively, several smaller units of 1m diameter may be installed in series where the quantity of steam coming from the turbine is insufficient. The output of each unit may then be combined to produce a substantial output. This is suitable for medium and small geothermal wells.

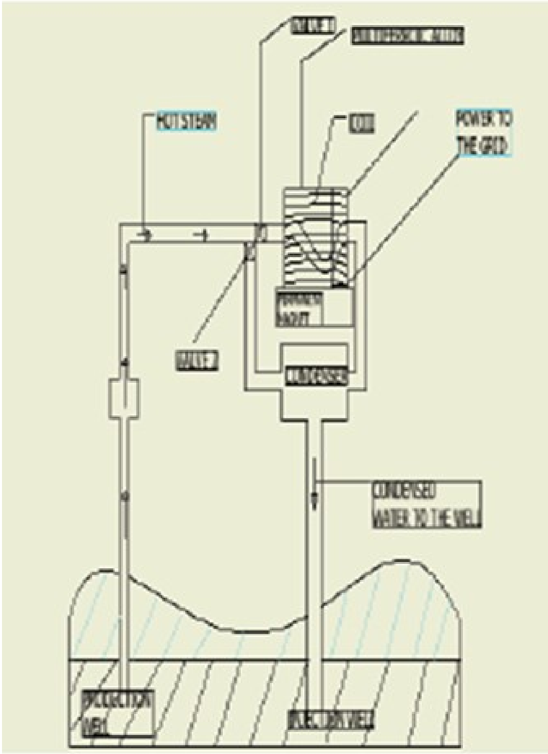


Figure 5.2: A multiferroic alloy incorporated in a non-commercial geothermal well.

The simulation of an optimized model that combines both heating and cooling processes at a periodic time of 60s, having 10m diameter alloy size and 10000 turns of coil produces 800V with a current of 1000 Amperes. Its transformation time is 5s with average susceptibility of the austenite as 0.1 emu cm-3Oe-1.The output of voltage at various times is shown in **table 4 below.**

5.4 The Voltage Output for an Optimized Model of 5m Diameter Alloy Size

Time(s)	10	15	20	25	30	35	40	45	50	55	60	65	70
Voltage(	0	100	200	300	400	500	600	700	800	810	700	400	100

Time(S)	75	80	85	90	95	100	105	110	115	120	125
Voltage(v)	-100	-410	-700	-800	-770	-680	-590	-470	-390	-280	-190

Table 4

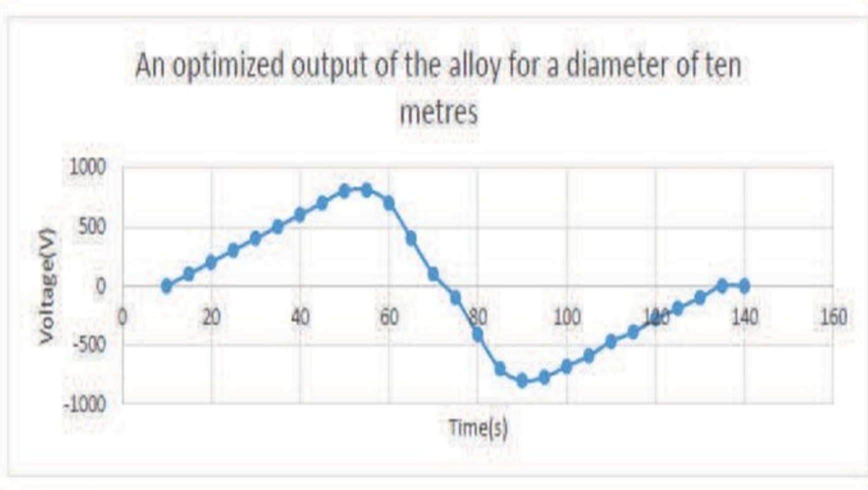


Figure 3: An optimized output of the alloy for a diameter of ten meters

The power produced = Voltage (V) x current (A)

= 800V x 1000A = **800,000Watts**

Assuming a power factor of 0.8,

Net power produced using a power factor of 0.8 = 800000 x 0.8 = 640,000Watts = **640kw**

Using 24 separate coils around the alloy to increase the frequency of power generation results to a total power of:- 640 x 24 = 15360kw = **15.36 MW**

Assuming hysteresis losses of 2% gives a net power output 0f **15Mw**

The power that can be produced from the waste heat in kilowatt- hour per year is given by:- 15,000kW x (365 x24)hr. = **131,400,000kWhr**.

The average urban residential power use in Kenya per household is

2501kWhr

The system can therefore serve approximately 131,400,000/2501 = **52,539** people in Kenya.

6. CONCLUSIONS

A rejected geothermal well can produce a power output of **15MW** through the adoption of this new technology of converting waste heat to electricity. This may contribute in reducing the huge energy shortage in developing countries and form a key economic driver that aids in industrial development.

Considering efficiency as the ratio of the work output to heat input, efficiency of power production is improved as the heat from steam that is otherwise wasted is converted into productive work. The technology that involves conversion of waste heat to electricity should be considered as the future for the geothermal industry in order to minimize wastage and improve the efficiency of power generation.

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