SUSTAINABLE ENERGY CENTER OF EXCELLENCE

Project Closure Report

CLIMATE COOKING STOVE PRODUCTION AND TEST

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EXECUTIVE SUMMARY

The solar-powered cooking stove project aimed to develop ten cooking stoves with three variations, designed to store heat using x-kg of magnetite (different mass size used) to enable cooking during periods without solar energy availability. The project was fully sponsored by the MECS program of the Loughborough University via Tridealhouse / ClimateStoven Social enterprise, with Director Michel Loots. The total grant was around 60.000£. Prototypes were constructed using a mix of imported and locally sourced materials while all electronic components were imported. Performance tests were conducted based on available standards to assess the effectiveness of the cooking stoves.

Despite the successful manufacturing of the ten (at the end twelve) prototype variants, the project had numerous technical challenges of which the three main were the heat transfer to the cooking pots, the insulation and the electrical components.

Heat storage and transfer. The heat storage capacity of magnetite fulfills the cooking energy needs. But the conductivity qualities of magnetite for thermal energy transfer to the cooking plate posed new challenges. Magnetite in itself does not transfer heat sufficiently rapidly to the cooking pot therefore it takes 45 to 90 minutes to reach 80 to 90 degrees. We solved this problem by integrating aluminum in the heat battery and increasing this aluminum content based on modelling. The last prototypes had an aluminum content of about 30% of volume of the heat battery and we have indications this will solve the heat transfer to the cooking pot. However, we did not get to the point of such tests because the stonewool insulation was not sufficient to retain the heat inside the heat battery.

Insulation. Even though the sides of all designed and produced samples were well insulated, controlling thermal heat loss, on all sides, but specifically at the bottom and top of all tested prototypes during charging and cooking were the most difficult issues. Our conclusion was that only a form of vacuum insulation would solve this problem.

Electrics and electronics. From AC/DC perspective, the technical challenges faced during prototype production and tests included issues like lack of optimized controlling mechanism for solar power DC conversion and heat charging. Many of the electronics used were designed for AC power while the solar system provides DC power. This led us to change power source to AC during the experiments. Another problem was the durability of the heating elements and of the thermostat

controlling the incoming power. Due to the constant working temperature around or above 200 degrees Celsius, plastics melted or charred. Sometimes aluminum melted.

From budgetary perspective 15,810 Euro have been initially allocated to AASTU for professional support and local material purchases, 22,900 Euro for materials and shipping of these materials to AASTU, about 11.000 Euro additional funds were invested in additional materials and tools in agreement with the project fund raiser. The balance was allocated to staff costs. The entirety of the MECS grant therefore was utilized to provide project input equipment, materials and tools from overseas, as well as buying required local consumable items to achieve the project objectives. Expert remuneration was also made in accordance to the approved proposal and consultation with the project work sponsor.

We were grateful to receive technical and in-kind support in materials from major industrial European companies of which our thanks go especially to LKAB Netherlands, Norsk Hydro Aluminum Netherlands, Rockwool Netherlands and Belgium, Xella Belgium, Va-Q-tec Germany and Pipelife/Wienerberger Belgium.

We believe our work has established a strong foundation for a structural solution to clean cooking through the development of a heat battery-based stove. Looking ahead, we have identified three key challenges that require focused attention: optimizing the performance and energy storage capacity of the heat battery combining magnetite with aluminum, developing a cost-effective vacuum insulation solution, and enhancing the durability and efficiency of the heating elements and electrical components. Addressing these challenges is essential for advancing this technology to the next level.

We are continuing on this path, and next steps are to improve the efficiency, reliability, and overall viability of solar-powered heat battery powered cooking stoves, bringing us closer to providing sustainable clean cooking solutions. We are actively seeking partnerships with universities, research institutions, industrial partners, funding organizations, and NGOs to co-develop and advance this vital research. Please do not hesitate to contact us.

1. BACKGROUND OF THE PROJECT

This research focuses on the creation of an innovative cooking stove that uses magnetite as a heat storing material. The main goal is to design a stove that can efficiently store heat and release it steadily for cooking.

1.1 The global clean cooking problem

Exposure to household air pollution from cooking with solid fuels causes over 3.5 million premature deaths annually, including half a million deaths from pneumonia among children under the age of 5 worldwide. HAP is the leading environmental risk factor globally. In contrast, the Sun is a vast, unlimited source of energy. The sun's power received by Earth is around 1.8 × 1011 MW, which are several thousands of times bigger than the current consumption rate on earth of all commercial energy sources. Food processing dates back to ancient times, when primitive processing involving various types of cooking, such as biomass burning, smoking, baking and steaming, fermenting, solar drying, solar cooking, and salt preservation, were practiced. Although biomass, such as wood, agricultural waste, and animal dung, has long been used to power cooking in many parts of the world, its use raises a variety of problems. One of the most serious concerns is indoor air pollution. Long-term exposure to these pollutants can lead to respiratory issues, particularly in women and children who spend a lot of time around the cooking area. Women and children bear an imbalance of the hardship of biomass collecting and cooking. This can worsen gender inequality and impede these populations' access to education and economic development. Improved cook stoves have been widely promoted as a way to reduce these challenges. The industrialization process accelerated the invention and availability of labor-saving cooking devices. This includes innovations such as cast-iron stoves, gas stoves, and ultimately, electrically powered appliances. These inventions increased cooking efficiency while reducing the time and effort required for cooking meals.

1.2 The clean cooking potential with solar energy in Ethiopia

There are a variety of sources that are used for cooking in the developing world, but still now most people in Africa cook with charcoal or fuel wood inside their home. Approximately 30% of Africans have access to electricity and 90% are dependent on traditional cooking fuels. This also applies to Ethiopia. Traditional cooking methods in many rural areas of Ethiopia rely heavily on biomass fuels, leading to deforestation, health issues, and inefficient energy use. The majority (96%) of Ethiopia's population still relies on polluting fuels for their cooking needs, with firewood most used (82%); (MECS-EnDev-Ethiopia-eCooking-Market-Assessment.pdf

At the same time, Ethiopia is endowed a great solar energy potential because of its proximity to the equator, which provides ample sunlight throughout the year. Ethiopia solar energy potential has the ability to generate between 3,000 and 5,000 kilowatt-hours (kWh) of solar energy per square meter per year in several regions.

Currently Ethiopia has embarked on a comprehensive national plan to promote green energy for cooking, aiming to reduce reliance on biomass fuels, improve public health, and mitigate environmental degradation. As part of its Climate Resilient Green Economy (CRGE) strategy, the government is actively investing in clean cooking technologies such as solar cookers, biogas digesters, and improved cook stoves. This initiative aligns with the Sustainable Development Goals (SDGs), particularly Goal 7, which advocates universal access to affordable, reliable, and modern energy services.

The Ethiopian government plan focuses on increasing renewable energy consumption in rural and urban homes, with the goal of reducing deforestation and indoor air pollution while also creating job opportunities in the clean energy sector. These activities help to achieve the government's aim of universal power access by 2030, with an emphasis on clean, renewable energy for cooking and general household use.

1.3 How this research project aims to solve clean cooking in Ethiopia

This project explores a novel energy-efficient cooking method using magnetite as a heat storage medium. The main objective of design and production of the ClimateStoven cooking stove is to allow rural households to cook without constant fuel input and reduce reliance on traditional biomass. The use of magnetite as a heat storage material has the potential to provide a more efficient, sustainable, and affordable alternative to traditional stoves that exhibit health, environmental and economic challenges.

The main objectives of this research were to develop an optimal clean cooking stove, manufacture ten prototypes with various geometries, and test these solar-powered cooking stoves. As part of a joint research initiative, Tridealhouse supplied clean cooking equipment, tools, and various materials for the development of a climate stove. AASTU's research team received financial support and materials from this MECS grant via Tridealhouse. AASTU conducted this study under the sustainable energy center of excellence for the development and manufacture of a heat battery based solar stove. With the support of Tridealhouse/ ClimateStoven project operating under Dr. Michel Loots, different types of cooking stoves were designed, manufactured and tested

This project status report discusses the project work from inception to this closure stage, including the different designs and prototypes that have been tested in the laboratory and the ensuing challenges and solutions.

2. DEVELOPING SOLAR HEAT BATTERY BASED COOKING TECHNOLOGY

2.1 Solar cooking technologies

Direct solar cooking technologies harness solar energy directly for cooking, typically using solar panels, parabolic reflectors, or evacuated tube collectors. These technologies focus on direct sunlight to heat cooking vessels, making them ideal for regions with high solar irradiance. Solar box cookers and parabolic solar cookers have been widely adopted for their efficiency and ability to reduce dependence on biomass fuels. However, direct solar cooking is limited by weather conditions and availability of sunlight, restricting its use during evenings and cloudy days (Kuhnke, 2014). Solar-thermal cooking has the drawback of strongly relying on the availability of direct sunlight. Depending on the global location, solar reflectors will not provide sufficient heat on a cloudy day, or in morning or evening hours.

Developing a heat battery based clean cooking stove.

The clean cooking stove under investigation can be an ideal intervention project to accommodate the mentioned limitation by Kuhnke, 2014. The stored energy made by DC solar or AC power source used as a cooking technology aims to overcome the limitations of direct solar cooking by transforming the electricity to heat and store this thermal energy for later use. Common thermal energy storage methods include phase change materials (PCMs), rock bed heat storage, and magnetite-based heat storage, where thermal energy is retained and gradually released during non-solar hours.

Studies have shown that magnetite offers high thermal storage capacity, making it a promising material for off-grid cooking solutions (Smith et al., 2016). However, the limitations such as heat retention losses and slow heat transfer rates are challenges that the current project investigation is aiming to address.

The combination of solar and stored energy cooking technologies holds potential for sustainable and reliable cooking solutions, especially in rural areas. Hybrid designs incorporating solar panels with thermal energy storage, such as using molten salts or magnetite, have shown promising results in increasing cooking capacity beyond daylight hours (Johnson & Patel, 2018). Future research should focus on optimizing materials, improving heat transfer mechanisms, and enhancing the affordability of such systems to promote wider adoption in low-resource settings.

2.2 Clean Cooking Technologies using heat storage

Solar energy cooking based on heat storage is one of the promising technologies in clean cooking. Thermal energy storage is already used on an industrial scale for energy generation.

"TES (Thermal Energy Storage) on an industrial scale in concentrated solar power (CSP) plants have proven to leveling off daily demand and supply of electricity. The simple concept that excess heat present at CSP plants during sunlight hours can be stored and transformed into electricity during nighttime or cloudy periods, is based on the properties of TES materials and architecture: thermal conductivity, high heat capacity and density, excellent stability, non-flammability, non-toxicity, availability, and low cost.

The current project aims to research a variant of TES for clean cooking. Heat storage with solar thermal of PV energy will be beneficial in extending cooking time even after the sun sets, providing flexibility and convenience. This is especially important in areas where cooking is done primarily in the evenings. If clouds block the sun for a period, the stored heat can still be used to finish cooking. Also, solar cookers can often generate more heat than is needed immediately. Heat storage allows for the capture and utilization of this excess energy, improving overall efficiency by regulating cooking demands and can fluctuate throughout the day. By having a backup of stored heat, solar cooking systems become more reliable and less susceptible to disruptions caused by weather or time of day.

2.3 The initiation of the Climate Stove Project:

The ClimateStoven Project was initiated by Tridealhouse under the management of Dr. Michel Loots. The project aimed to address the replacement of charcoal and fuelwood for cooking in urban slum situations. The reliance on biomass fuel sources significantly contributes to gender inequity, poverty, environmental degradation, and health issues. To combat this, Dr. Michel proposed a novel approach using solar-powered cooking stoves that harness thermal energy stored in magnetite for cooking.

The innovative design integrates a solar energy system with a thermal storage unit made from magnetite, a material known for its heat retention properties. The concept was brought to life by the Addis Ababa Science and Technology University (AASTU) research team, who meticulously designed and manufactured the stove's compartments to ensure effective heat storage and controlled energy release during cooking.

To ensure the feasibility and effectiveness of the Climate Stove, the AASTU research team developed multiple prototypes for performance testing. Each prototype varied in design and magnetite capacity, aiming to optimize heat retention and transfer. The testing process provided valuable insights into the design's strengths but also many challenges arose and identified areas needing improvement, particularly insulation techniques and heat distribution. The subsequent section of this report provides a comprehensive analysis of the design and manufacturing process for each prototype. It details the performance outcomes, highlighting successes and challenges faced during the project. These findings will contribute significantly to the advancement of clean cooking technologies and emphasize the importance of continued research and development in sustainable energy solutions. In order to start the project and understand the user needs, first a field study and visits were carried out by AASTU staff.

2.4 Results of initial field studies and rural site visits by AASTU University

Since the climate stove project inception, the Addis Ababa Science and Technology University (AASTU) research team was inspired and embraced the objective to introduce climate-friendly cooking stoves as a means to harness underutilized renewable energy resources. This initiative aligns with AASTU's mission to support national strategies focused on promoting green energy solutions and reducing the reliance on traditional biomass fuels.

To ensure the cooking stoves effectively meet the practical needs of the local community, the AASTU research team conducted a comprehensive site visit across several rural and semi-urban areas.

During this observational phase, researchers closely examined local cooking habits, materials commonly used for fuel, and household kitchen layouts. These critical insights revealed preferences for specific cooking pot types, heat intensity requirements for various dishes, and the average cooking duration for staple meals. By incorporating these findings, the design process prioritized user convenience and cultural compatibility. This community-oriented approach was aimed at maximizing adoption rates and ensuring long-term impact by aligning the product features with established cooking practices and energy availability patterns in the region.

The key findings from the site visit conducted in September 2023 include:

I. Types of Cooking Pots Used:

- **Traditional Clay Pots:** Still widely used in Sheger City, these pots are valued for their heat retention properties but are fragile. They are available in three forms based on household size:
    - Small size: Suitable for households with up to two people.
    - Medium size: Commonly used for households with up to five people.
    - Large size: Designed for larger families or communal cooking, serving up to 20 people.
- **Aluminum Pots:** A growing number of households have adopted aluminum pots due to their durability, affordability, and availability. These pots are easier to handle and more resistant to breakage compared to clay pots.

The observations from this site visit will directly inform the design of the climate-friendly cooking stoves, ensuring they align with local preferences and cooking methods while promoting energy efficiency and sustainability.

Figure 1: pictorial summary of site visits in Ethiopia by AASTU staff

II. Activities of People Using Open-Fire Cooking Systems:

We observed several activities related to open-fire cooking systems in the Sheger City area. These activities included:

- Gathering Firewood: Many individuals, mainly women and children, usually collect firewood from nearby forests and open areas.
- Gathering cow dung: some of the households use cow dung as a main source of heat in cooking related activities
- Food Preparation: A significant number of households were actively engaged in food preparation, chopping vegetables, and preparing ingredients for stew.
- Open-Fire Cooking: visited households using open fires for cooking stew. These fires were often located in outdoor kitchens or designated cooking areas.
- Smoke Exposure: It was noticeable that the use of open fires for cooking exposed individuals, especially women and children, to high levels of smoke, leading to health concerns.

III. Challenges Associated with Open-Fire Cooking:

During interviews and discussions with local residents, a team of AASTU researchers identified several challenges associated with the traditional open-fire cooking systems among that:

- Health Risks: Prolonged exposure to smoke while cooking leads to respiratory problems and eye irritation, especially among women and children.
- Environmental Impact: The widespread use of firewood contributes to deforestation in the region, leading to adverse ecological consequences.
- Inefficient Cooking: Open fires are often inefficient, leading to longer cooking times and increased fuel consumption.
- Safety Concerns: Open fires pose safety hazards, especially in households with young children, as accidental burns are common.
- Fuel Scarcity: Currently fuelwood, animal dung and charcoal are used as a common source of cooking energy. However, a lot of bio-mass waste and nearby availabilities and the rise of charcoal price were among the potential challenges observed by the research teams. The increasing demand for firewood has led to shortages and increased prices, causing financial strain for many families. Details are shown by picture in the appendix part.

2.5 Objectives of the Project

The primary objective of the project was to design and manufacture ten cooking prototypes compartments in three main design variations, incorporating magnetite as a thermal energy storage medium. The intention was to store heat generated from solar power in magnetite to ensure cooking capacity during periods without direct solar energy availability.

Specific objectives of the project were:

1. To design and install solar panels for use as energy source
2. To design and to manufacture ten cooking prototypes
3. To conduct cooking performance of user defined cook stove
4. To optimize the rock wool thickness for optimum insulation

Even if the scope of the project was to design and manufacture ten cooking prototypes, additional workloads were developed in consultation agreement of to the project sponsor in order to address the many challenges that came on our way.

3. MATERIALS, METHODS AND INDUSTRIAL PARTNERS

3.1 Project/Research Materials and import challenges

Tridealhouse provided project-oriented research input equipment, tools, and materials. The AASTU research team obtained all of the materials after they had been shipped. The table below shows most of the initial physical resources that were provided and used to produce and test the cooking stoves:

Table: 1 Trideal House initially purchased items and equipment (full list at Tridealhouse)

No.	Item name	(UOM)	Qty.	Unit Price (Euro)	Total (Euro)
1	Magnetite powder	Kg/Bag (15kg* 20bags)	320 kg	0.1	32
2	Electronic Temperature Sensor	Box	2		355.61
3	Ceramics for insulation	Box	1		421.21
4	Aluminum Box	Pcs	120		7892
5	Stainless steel sheet	Sheet	9		210
6	Circular Saw with accessories	Set	1		1123.61
7	Electricity testing Kit	Set	1		376.03
8	Volt craft CO2 Measuring devices	Pcs	1		90.9
9	LoRaWan air Quality tester	Pcs	1		499
10	Fluke Solar Irradiation measuring device	Pcs	1		342.98
11	Handheld thermal imaging camera	Pcs	1		320.99
12	Air Quality tester CO2 meter	Pcs			49
13	Cordless kit for drill, grinder & jigsaw	Set	1		139.67
14	Cordless drill driver	Pcs			123.14
15	RockWool Insulation	Packet	20		1069.2
16	Basalt Fiber	Packet	4		80
17	Aluminum Oxide	Bag	5		77.52
18	Vacuum chamber	Pcs	1		138.99
19	Jinko Solar Panel with accessories	Set	5		2396.21
20	Solar Panel (380) on honey comp structure	Pcs	8		1606
21	Meyer Burger solar Panel R white	Pcs	2		464.71
22	Bosch Temperature measuring devices	Pcs	2		65.96
23	Weight Balance	Pcs	2		65

24	Data acquisition module with accessories	pcs	1		531
25	Different electrical Stove as benchmark for test	pcs	5		234
26	High Temperature tape	pcs	5		65

Details of the items shipment and transfer process were shown in the picture below:

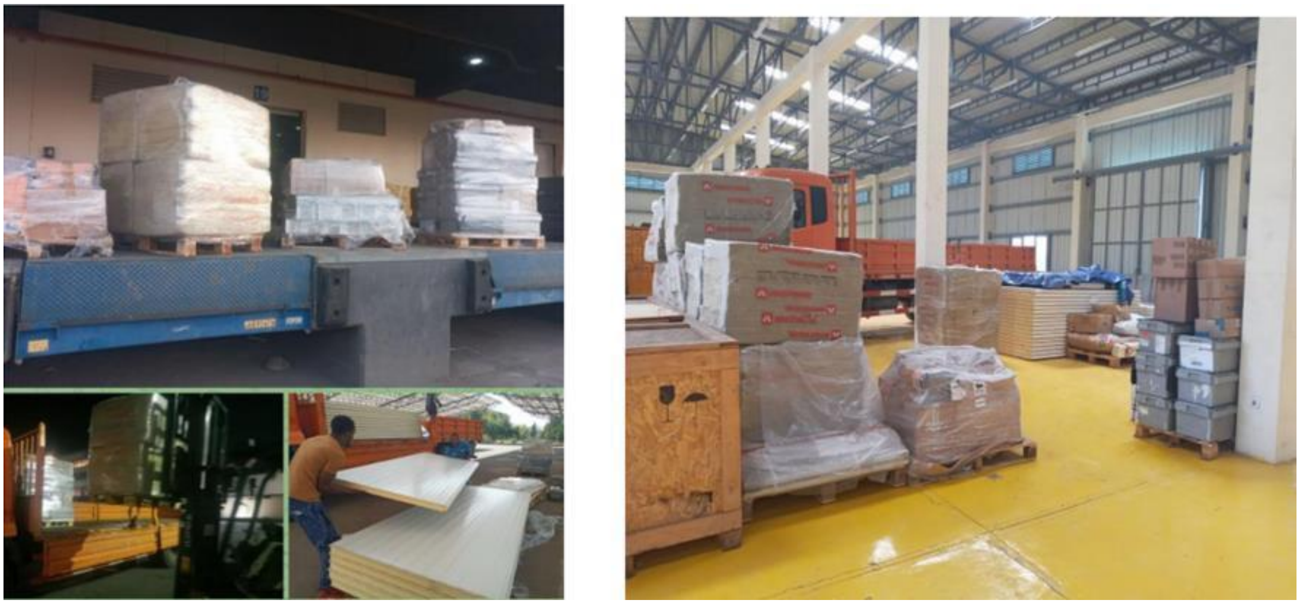


Figure 2: initially imported research items at AASTU main store

The shipment of all items from Trideal House in Belgium was needed but gave substantial custom delays. as crossing the Ethiopian customs process proved to be a substantial hurdle. The lengthy customs clearance period, spanning 51 days, significantly delayed the project's commencement by two months. Following this, the transfer of equipment from the Ethiopian Airlines warehouse to the AASTU main store took an additional 10 days, further extending the project's timeline.

To facilitate the release of these essential items, the university incurred significant expenses, exceeding 1.5 million Birr (around 22.000 Euro) in customs taxes. This substantial financial burden underscored the challenges associated with importing goods into Ethiopia. Despite these logistical and financial obstacles, the project team successfully navigated the customs process and secured legal ownership of all supplied items. This crucial step ensured that the university could utilize the equipment for research purposes and facilitated the commencement of project activities.

The successful release from customs and subsequent transfer of supplied equipment, while fraught with import challenges, laid the foundation for the project's implementation. This experience highlights the importance of careful planning and resource allocation when undertaking international collaborations and procuring equipment for research projects.

3.2 Industrial partners and support

We were grateful to receive technical and in-kind support in materials from major industrial European companies of which our thanks go especially to LKAB Netherlands, Norsk Hydro Aluminum Netherlands, Rockwool, Xella Belgium, Va-Q-tec Germany and Pipelife/Wienerberger Belgium.

3.3 Research Methods

The theoretical study by research papers review, analytical modeling and simulations as well as experimental test were used as research method of this project work.

First phase PV panel erection: Steel structure procurement, cutting and welding, civil work and assembly of the PV panel work were completed successfully, and 1600 watt were generated for further uses.

Figure 3: site work for PV panel installation

Installation of supplied solar PV panels was the primary task. The erection and installation of the solar panel system started with civil work. Site clearance, concrete preparation, steel structure preparation and assembly were implemented during this phase. A team of experts were involved in installing four solar panels that could generate up to 1600 Watts.

Second Phase Solar PV installation

In the second phase additional Solar PV panels were installed to provide 2.4 kW of solar power. This DC power electricity was then used as input energy for the magnetite.

Figure 4: second phase PV panel installation accomplishment

4. PRODUCTION AND TESTING OF CLIMATE STOVE PROTOTYPES

4.1 Encountered challenges

The performance testing of the prototype cooking stoves filled with magnetite revealed several significant challenges.

Managing the inlet solar based electrical power to effectively store heat within the chamber proved difficult. Precise control of the heating element's placement and capacity was necessary to ensure even heat distribution and prevent localized hotspots around the heating element. Achieving this balance was challenging during the tests.

Another major issue was the load-bearing capacity of the structure used to hold the magnetite chamber structure. The design needed to ensure that the structure could support the significant weight of the magnetite (up to 40 kg) without compromising its integrity of Rockwool insulator. The structure to keep the heat battery insulated from the bottom was adapted during testing. But as side effect, using steel structure or brick as support method was causing thermal loss.

Insulating the bottom of the compartment with Rockwool presented additional complications for easy maintenance and change of the heating elements. Effective insulation was required from the top and bottom of the cooking chamber to minimize heat loss. But excessive compaction of the rockwool damaged its insulator capabilities. This balancing act between achieving proper insulation at the bottom and maintaining the structural integrity of the magnetite heat battery remains a critical area for further design refinement and testing to ensure the creation of functional, reliable, and well insulated cooking stoves.

4.2 Installing an Omega Engineering 8 CH T/C USB Data Acquisition Module

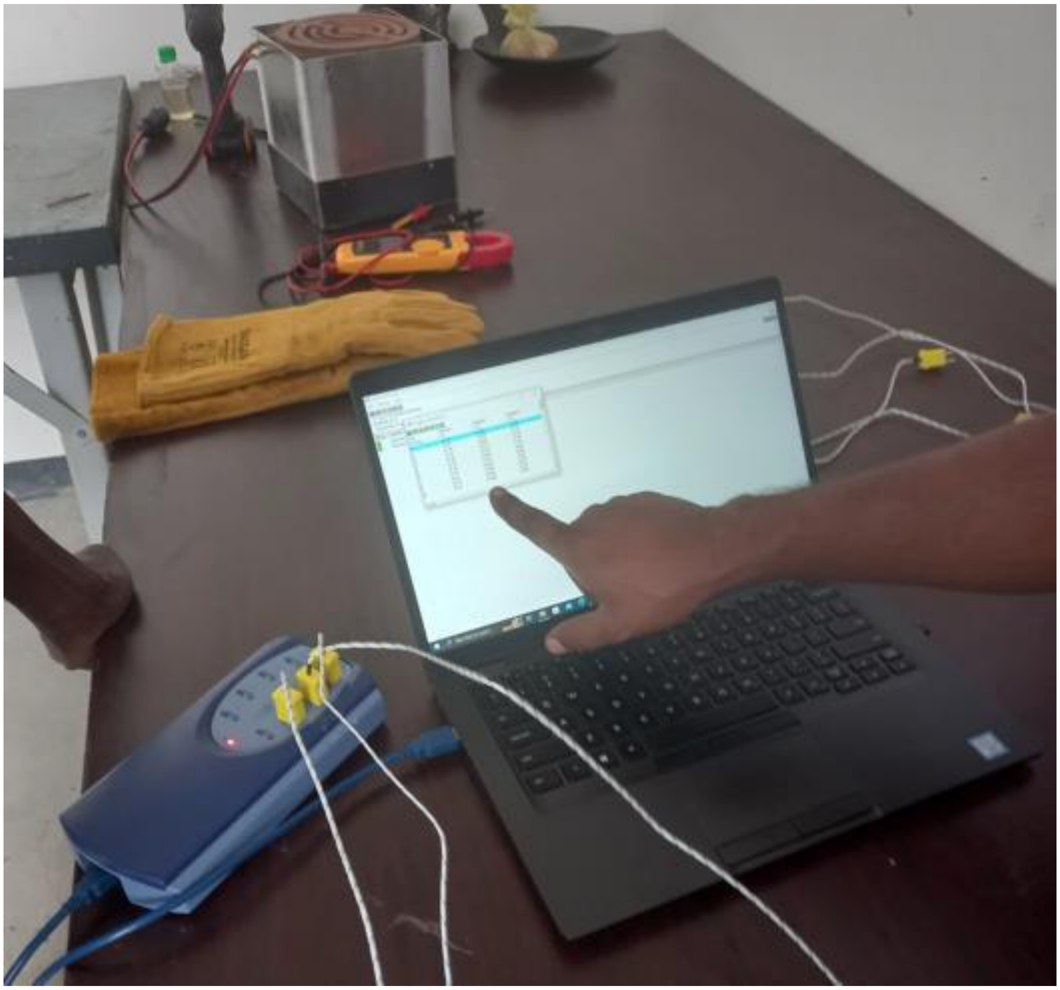


Figure 5: Omega Engineering Limited 8 CH T/C USB DATA ACQ MODULE

We installed the **Omega Engineering 8 CH T/C USB Data Acquisition Module** for our heat battery cooking experiments.:

1 We purchased the **Omega Engineering 8 CH T/C USB Data Acquisition Module** directly from Omega Engineering's website.

2 **Software Installation**: We downloaded the Omega DAQ software and drivers and installed them on our computer.

3 **Connecting the Module**: We connected the data acquisition module to the computer using the supplied USB cable. Once plugged in, the computer automatically recognized the device, which appeared under the connected hardware.

4 **Thermocouple Setup**: For temperature measurement, we connected 4 of up to 8 possible

thermocouples to the module's input channels.

5 **Channel Configuration**: Using the Omega software, we configured each channel to match the thermocouple type we used (Type K thermocouples in this case).

6 **Data Collection**: In the software, we set appropriate sampling rates and selected data logging parameters tailored to our cooking experiment. During the experiment, the software displayed real-time temperature readings from each channel, providing a clear visualization of heat variations.

7 **Data Analysis**: After the experiment, we exported the collected data in CSV format. This allowed us to analyze the temperature changes in the heat battery over time and identify patterns or anomalies that were critical for our findings.

4.3 Modelling and Simulation of heat storage using COMSOL Multiphysics software

Heat transfer is an exchange of thermal energy between two objects. The rate of heat transfer depends upon the temperatures of each entity and the medium through which the thermal energy is being transferred. In cooking, heat transfer refers to heating the food items through a cooking appliance, such as a stove, fryer, microwave, or oven.

Assumptions

- ➢ The discharging of heat from the heat storage system to the cooking pot is time-dependent and two dimensional.
- ➢ The modes of heat transfer within the system involves only conduction and convection, neglecting radiation heat transfer
- ➢ We assume the cooking system is on the ground level, and adiabatic
- ➢ The magnetite powder material is non-porous media

Boundary conditions and size of the first models

- ✓ Heat storage material = magnetite powder
- ✓ Insulation material Rockwool with thickness [0.3, 0.2, 0.15, 0.1, and 0.05 meters]
- ✓ Heat storage internal structural supporting material is aluminum
- ✓ Size of the alu storage box is 186*186*136 mm with storage thickness 2 mm

✓ Internal alu lattice with 44 mm spacing and 2 mm thickness

Thermal modelling of the system

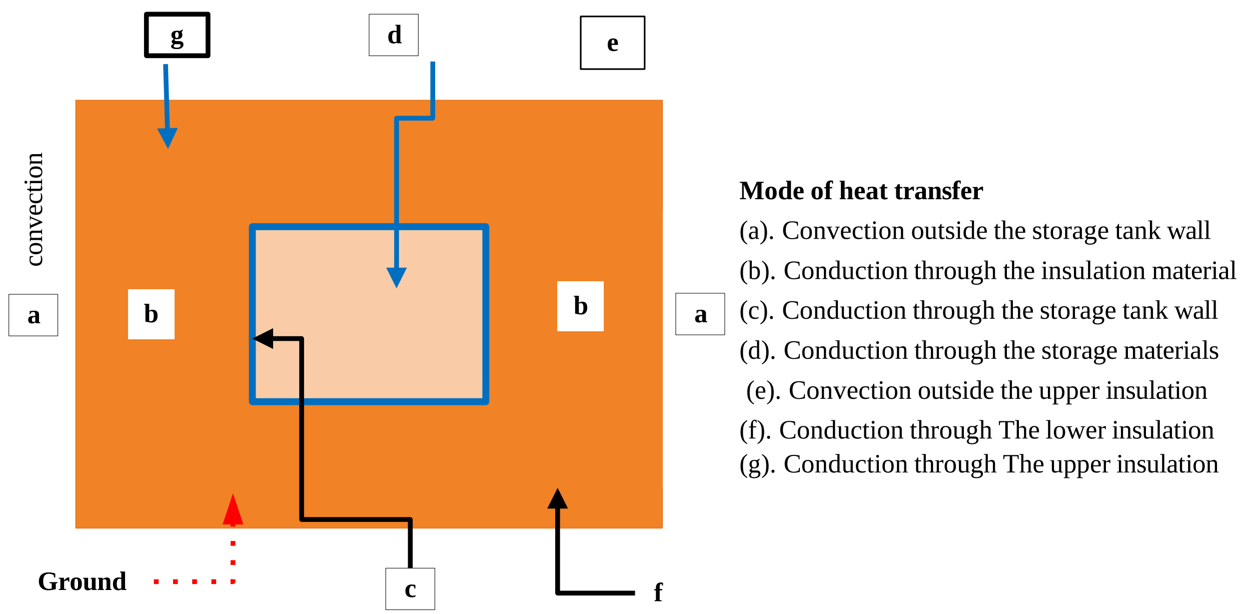


Figure 6: 2D section view of the heat storage system including mode of heat transfer

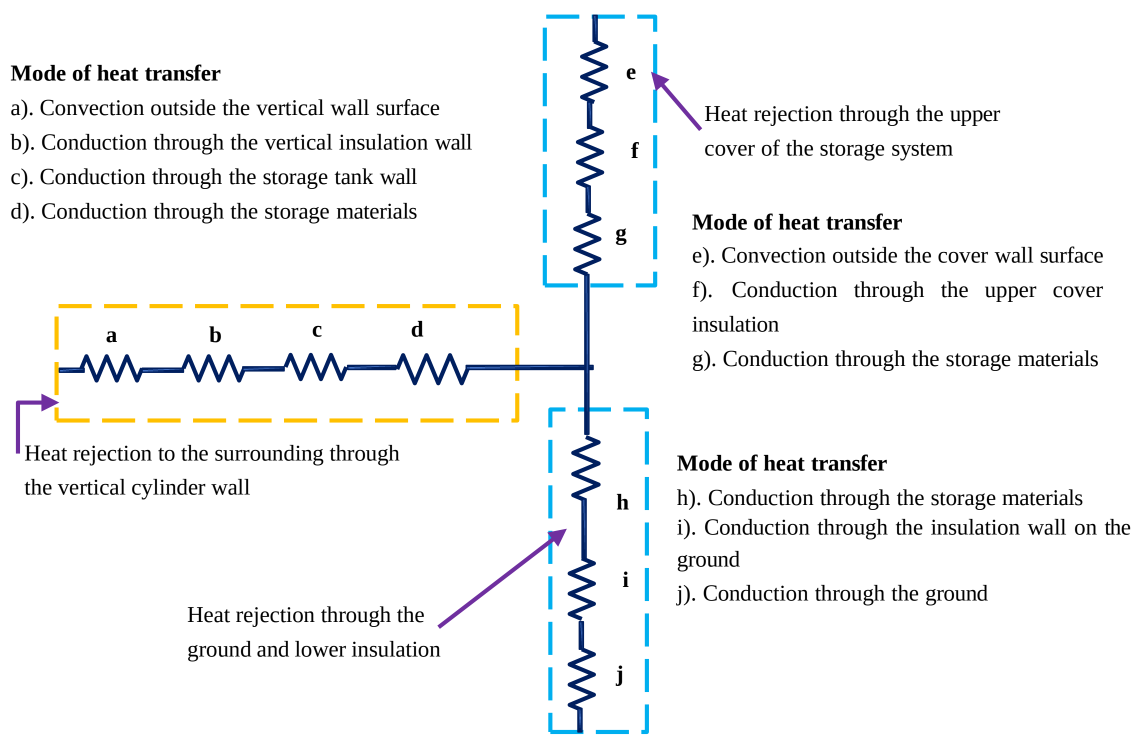


Figure 7: thermal network for the heat transfer processes

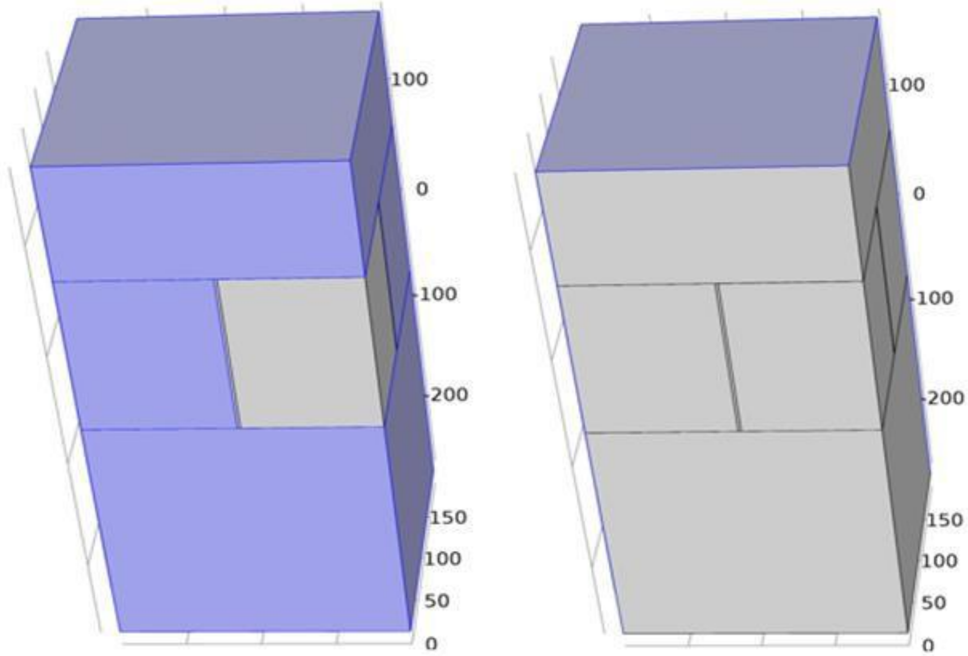


Figure 8: Schematic of Insulation and storage location

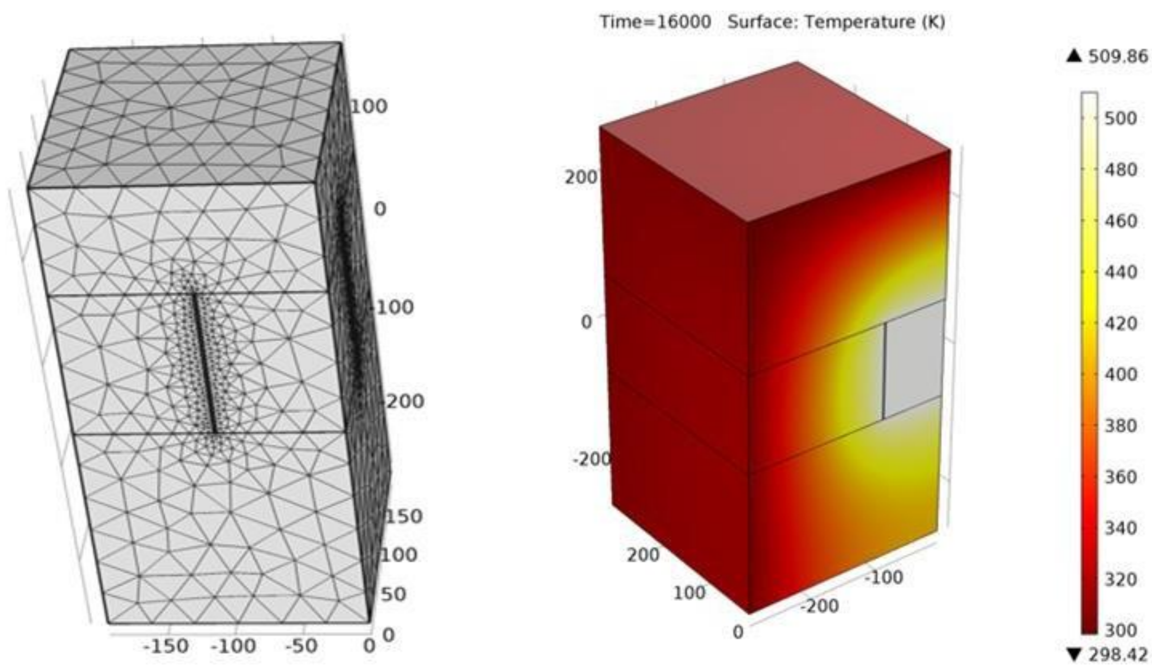


Figure 9: Schematic of model meshing and temperature distribution

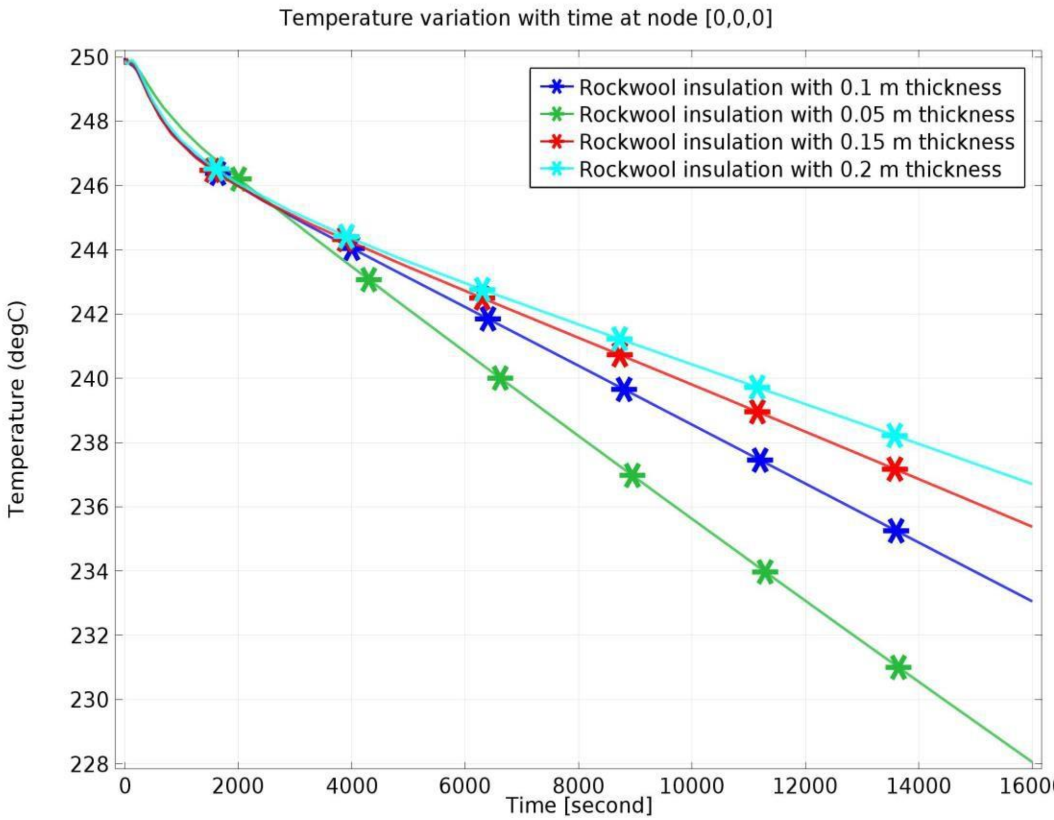


Figure 10: Temperature variation as a function of time at node [0,0,0]

Figure 9 shows the variation of the storage material (magnetite) temperature within four hours at the center of the heat storage system. In this case, COMSOL simulation was conducted using various thicknesses of the rockwool insulation materials, including 0.2, 0.15, 0.1, and 0.05 meters. After four hours, the storage temperature at the center becomes 237 ℃ for 0.2 m thickness, 235.5 ℃ for 0.15 m thickness, and 233 ℃ for 0.1 m thickness.

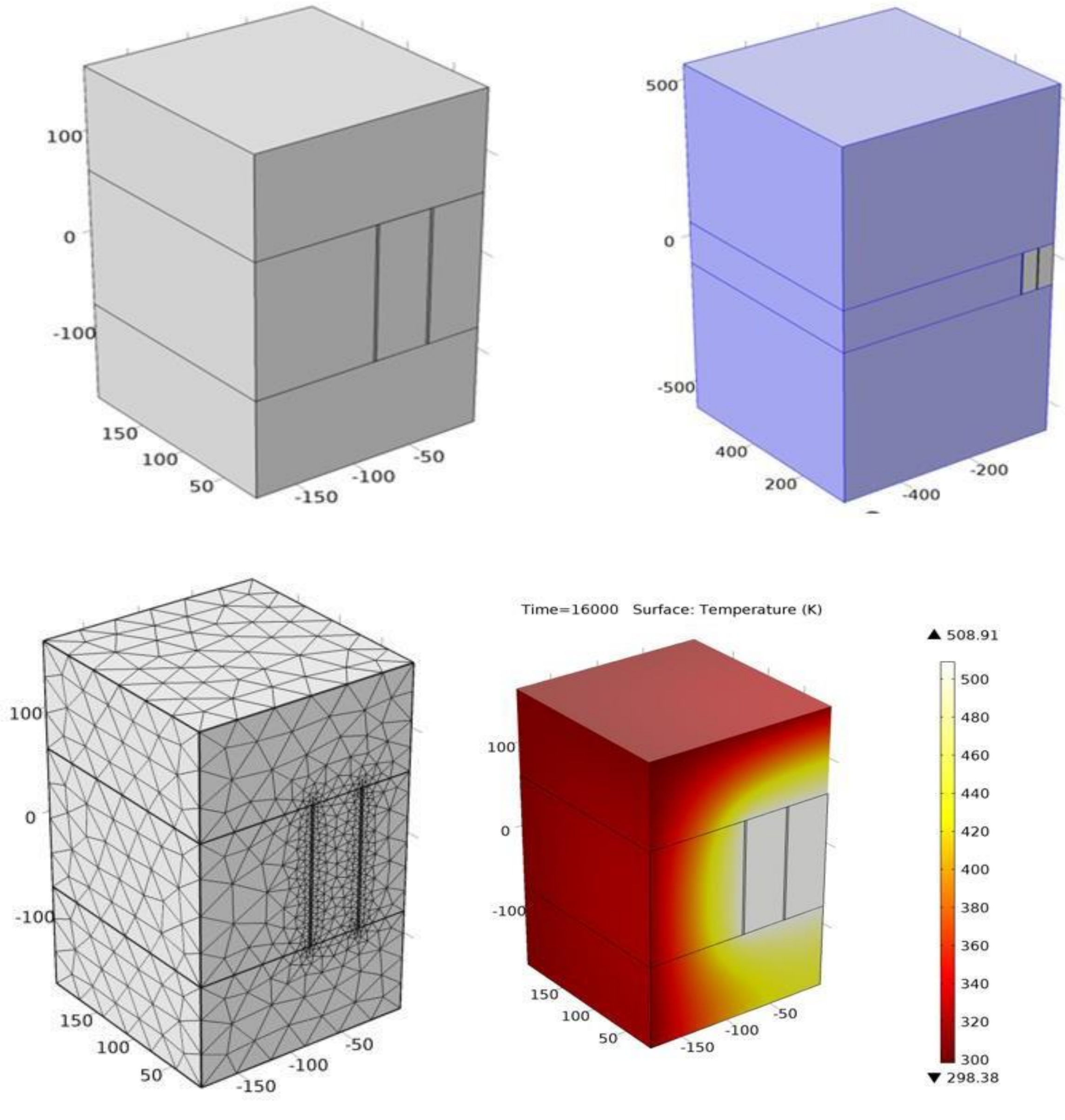


Figure 11: schematic of the model with maximum and minimum insulation thickness. Meshing and temperature

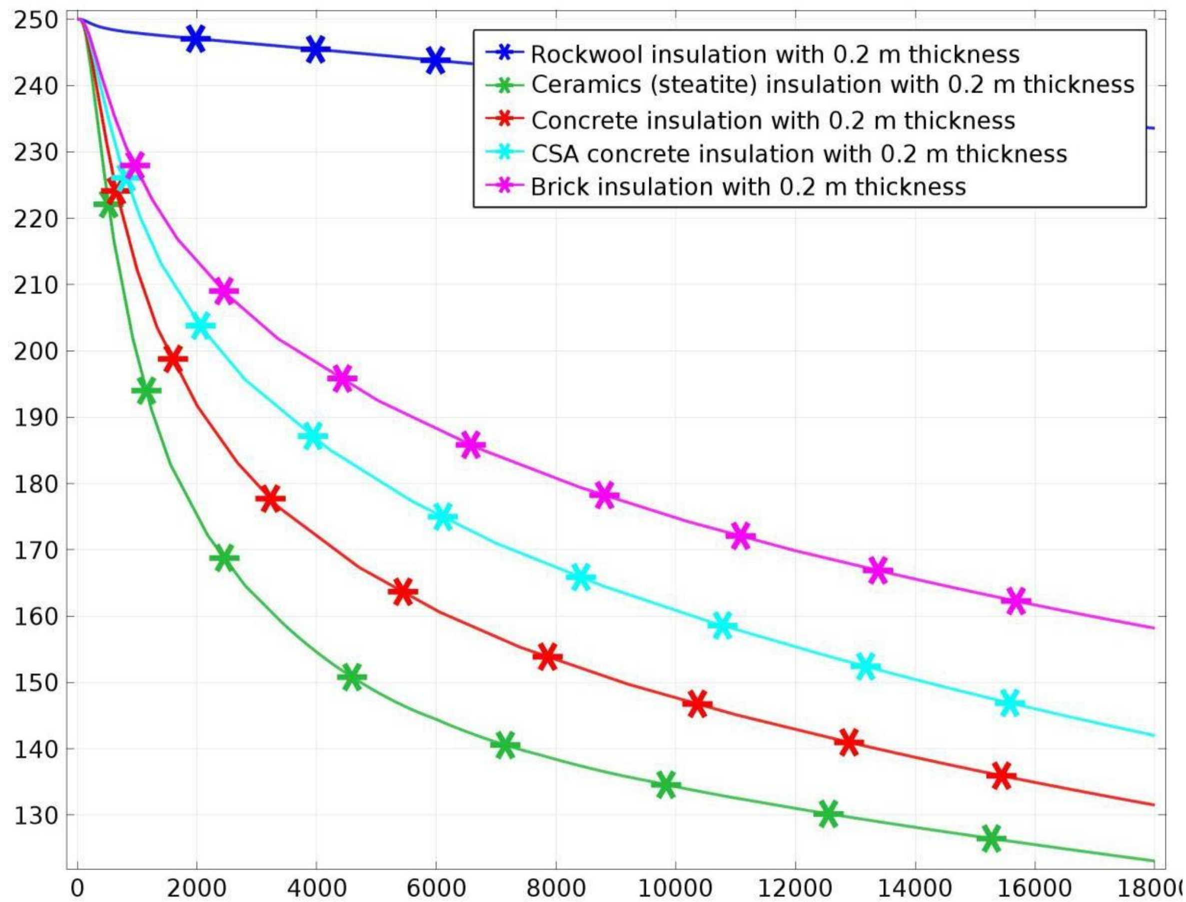


Figure 12: Temperature variation of heat storage material vs time using various insulation materials

Figure 12 illustrates the variation of the storage material (magnetite) temperature within five hours at the coordinates -10, 10, 0 of the storage system, utilizing various insulation materials. In this scenario, the Rockwool insulation material exhibited significant variation compared to others such as brick, CSA concrete, concrete, and ceramics insulation materials, all using a similar insulation thickness of 0.3 meters. Using a 0.3-meter insulation thickness resulted in a storage material temperature of 236 ℃ for Rockwool insulation, 160 ℃ for brick insulation, 148 ℃ for CSA concrete insulation, 138 ℃ for concrete insulation, and 129 ℃ for ceramics (steatite) insulation. In addition, using 0.2-meter insulation thickness (see Figure 11), the temperature of the storage material after five hours becomes 234 ℃ for Rockwool, 158 ℃ for brick, 142 ℃ for CSA concrete, 132 ℃ for concrete, and 122 ℃ for ceramics (steatite) insulations. Furthermore, using 0.1-meter thickness (refer to Figure 12) the result becomes 234 ℃ for Rockwool insulation, 148 ℃ for brick insulation, 128 ℃ for CSA concrete insulation, 120 ℃ for concrete insulation, and 110 ℃ for ceramics (steatite) insulation.

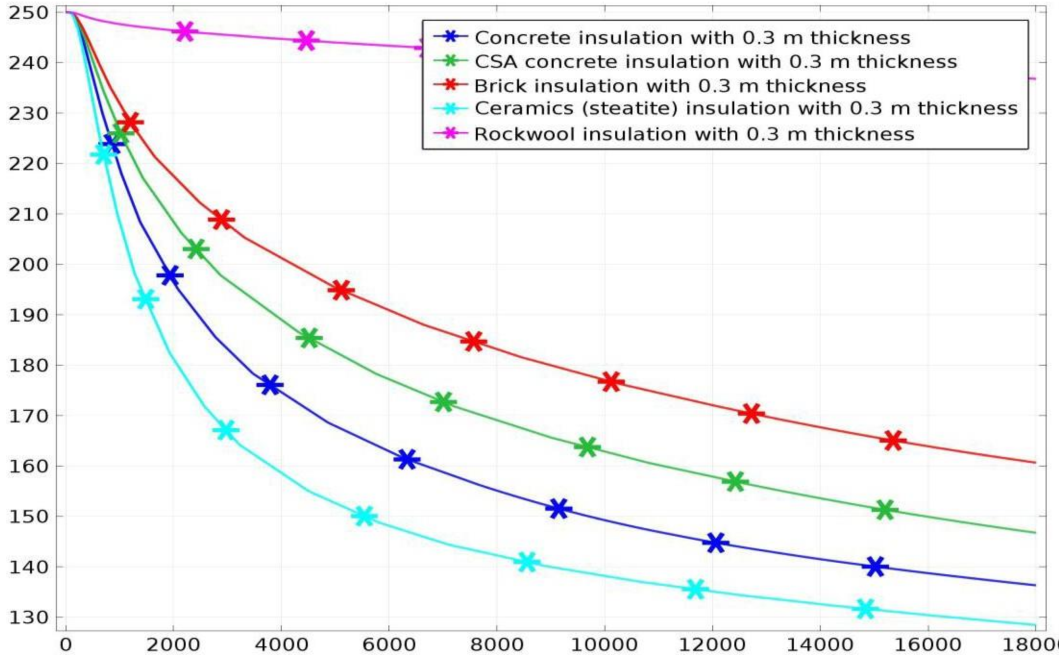


Figure 13: Temperature variation of heat storage material with time using various insulation materials

4.3 Key Findings on the modeling and simulation of insulator thickness optimization

The Rockwool as insulation material and first heat battery trial performance test were discussed below.

- ✓ Using Rockwool as insulator material was observed as potentially good material
- ✓ Using 20 cm thick rock was an optimum insulating material for prolonged heat retention.
- ✓ The modeling and simulation of insulator using magnetite as heat storage materials was confirmed experimentally.
- ✓ The use of DC power from PV panels as means of direct cooking was tested through water boiling but gave a long heating time, around 45 minutes was observed.
- ✓ The heat energy stored in the magnetite was a function of solar panel DC output wattages.
- ✓ The stored energy was observed as a function of insulation thickness. The thicker the insulator the better heat retention.

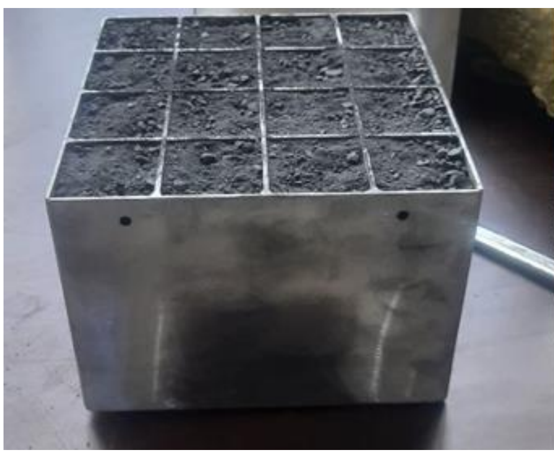
- ✓ All devices and tools like breakers and sockets and others used in the first compartment, were designed for AC power whereas the project main power source was DC power. The lack of DC type breaker and other controlling elements created a lot of complication like burning of the electric materials.

5. PRODUCT TEST AND RECORDED CHALLENGES FOR EACH OF 12 PROTOTYPES

5.1 Cooking Stove prototype-1: Single cell square box with control box

After successful installation of the Solar PV panel the first tabletop cooking stove design and production was made as open compartment to visualize the working system.

In the first prototype made as a cooking stove, a control box for heating element, 25 kg of magnetite, rock wool as insulator, and wood as external cover were used. After proper assembly of the cooking stove element, a 500-watt capacity heat element wase loaded with DC power to charge the 25kg magnetite on the box type cell compartment.



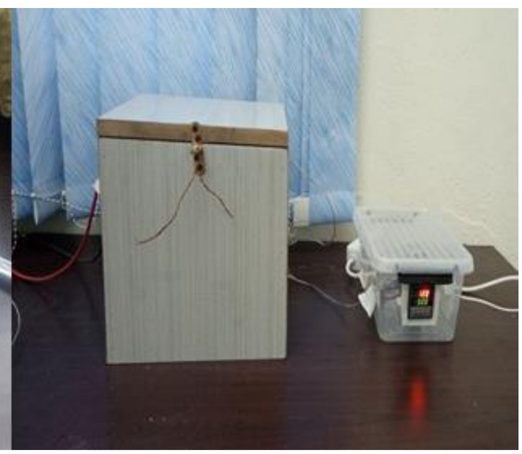


Figure 14: the first version Cooking Stove prototype model with 500-watt heater

The water boiling test by this Cooking Stove prototype takes 40-45 minutes to reach 75-80 degree centigrade, and excessive heat loss was also observed in the external body of the Cooking Stove prototype. According to the results the insulator thickness modeling and simulation work were done by thermal engineering expert. The heaters failed and the model stopped working.

5.2 Cooking Stove prototype-2: Single square box with multiple square cells

The magnetite holding box made of Aluminum and stainless steel were imported as research input, the electrical system installation, insulation, and external stove parts were made at the AASTU lab managed under the PI.

Following are the specifications of the design

- ✓ Dimension of compartment: 40*40*35 cm
- ✓ Magnetite in the chamber: 16Kg
- ✓ Heater: 1000 watt dry tube
- ✓ AC Breaker used
- ✓ Insulation material and thickness: 20 cm of rock wool

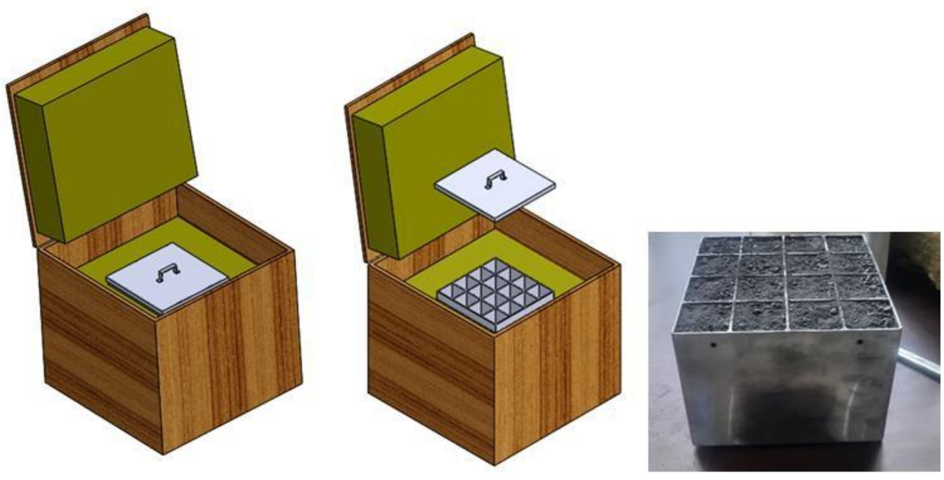


Figure 15: 2nd t version with 1kw heater

Observed result and challenges:

The top and side part of the cooking stove insulated the bottom part insulation were compressed due to the load by the magnetite that rest on it.

- ✓ Horizontal rested heater with the bottom heating system.
- ✓ The heat transfer from magnetite to cooking appliance was too slow.

- ✓ Extended heating of the magnetite resulted in the failure of the dry tube heating element as shown below.
- ✓ Built up or melting of magnetite in the dry tube and resulted failure of system.

5.3 Cooking Stove prototype-3: Single square box without internal cell

- ✓ Dimension of compartment: 40*40*35 cm
- ✓ Magnetite in the chamber: 19Kg
- ✓ Heater: vertical inserted 1000 watt dry tube
- ✓ Insulation material and thickness: 20 cm of rock wool

Figure 16: only magnetite without internal aluminums cells

Observed result and challenges

- ✓ Although the mass of magnetite in the compartment was increased, there is no significant heat retaining and efficiency change. The top and side part of the compartment insulated the bottom part insulation were compressed due to the load by the magnetite that rest on it.
- ✓ The heat transfer from magnetite to cooking appliance was too slow.

- ✓ Extended heating of the magnetite resulted in the failure of the dry tube heating element as shown below.
- ✓ Built up or melting of magnetite in the dry tube and resulted failure of system.
- ✓ Electrical power supply system burnout
- ✓ It takes 52 minutes to boil given amount of water

5.4 Cooking Stove prototype-4: Truncated box with 20 cm Rockwool insulation and heater control system

The third compartment's design and product manufacturing specifications, as well as performance test observations, are provided below.

- ✓ Dimension of compartment: 50*40*40 cm
- ✓ Mass of Magnetite in the chamber: 40Kg
- ✓ Used Heater: horizontal inserted 1000-watt dry tube
- ✓ Insulation material and thickness: all side 20 cm of rock wool, except bottom part (treated differently)

Figure 17: alternative design with 20 cm Rockwool

Observed result and challenges

- ✓ The change in magnetite mass brings some changes.
- ✓ The heat transfer from magnetite to the cooking appliance was too slow.
- ✓ Extended heating of the magnetite resulted in the failure of the dry tube heating element as

shown below

- ✓ Built up or melting of magnetite in the dry tube leads to the failure of the system.
- ✓ It takes 38 minutes to boil given the amount of water.

Figure 18: Heat coil failure and aggregation

5.5 Cooking Stove prototype-5: Adapted box with control system with 2kW heater

The truncated compartment was developed and built to test the effect of the truncated geometrical effect, and the water or cooking pane was insulated to decrease heat loss of the chamber system. The total mass of the magnetite used to retain the solar energy was 32 kg and 1000-watt dry tubes were used.

Figure 19: Alternative cooking stove design to stop upper heat loss

Observed result and challenges

- ✓ The top truncated part was observed as advantageous to slow the heat loss in the top part of the compartment and the change in magnetite mass brings some changes.
- ✓ The heat transfer from magnetite to the cooking appliance was enhanced graphite powder and some small change was observed.
- ✓ Repetitive use of the dry tube as a heating element resulted in the failure of the dry tube.
- ✓ It takes 48 minutes to boil the given amount of water.

5.6 Cooking Stove prototype-6: double heat box with 20 cm Rockwool insulation and 1 heater at the bottom

A series of interconnected square cell boxes were utilized to study the heat transfer effect among independent compartments. The setup involved using 32 kg of magnetite to collect and store thermal energy, with independent sensors and controllers installed to monitor heat distribution across the chambers. A 20 cm thick insulator was applied on all sides, including the bottom, to minimize heat loss and ensure efficient energy retention during the tests. 1000-watt capacity dry tube was inserted in the bottom part of the compartment. Accordingly, thermal energy was supplied from the middle.

However, significant issues arose with the bottom insulation system. The thermal power generated, combined with the substantial load of the magnetite, compromised the integrity of the insulation. This structural failure led to heat leakage and reduced the overall thermal efficiency of the system, highlighting the need for a more robust insulation design capable of withstanding both high temperatures and mechanical stress.

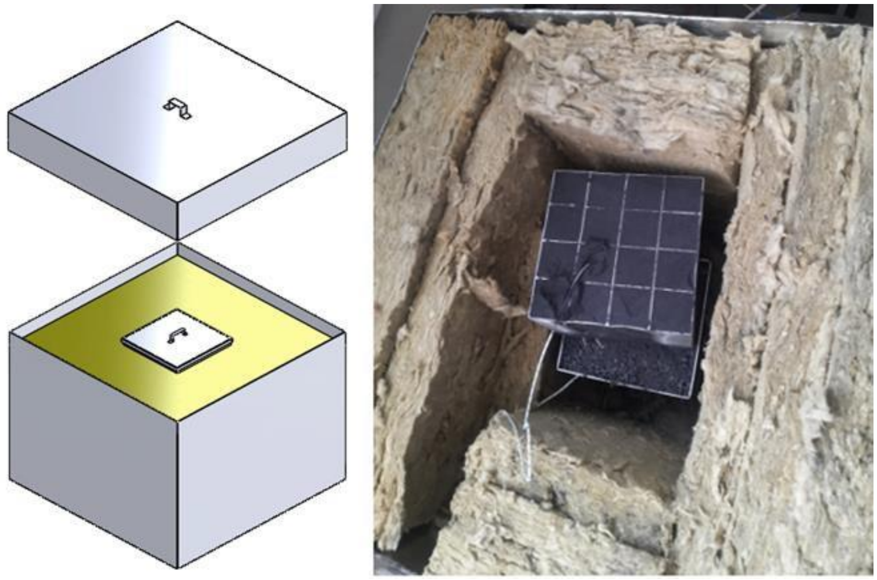


Figure 20: New version with upper insulated lid to contain heat loss

Observed result and challenges

- ✓ The heat transfer from magnetite to cooking appliance was too slow.
- ✓ The bottom compartment was damaged or destroyed, most probably due to heat energy from the top and bottom side.
- ✓ Repetitive use of the 1000 watt dry tube as heating element resulted in the failure of the dry tube

5.7 Cooking Stove prototype-7: triple box with 20 cm Rockwool insulation and 2 heater control system

A series of three vertically connected square compartments were used to investigate heat transfer efficiency using magnetite as a thermal storage medium. Two 1000-watt dry tube heating elements were positioned at the top and bottom of the setup, while the middle compartment functioned as the heat transfer medium. The structure was designed to hold 48 kg of magnetite for effective heat collection and retention. Independent sensors and controllers were integrated to monitor the heat distribution within the compartments. A 20 cm thick layer of insulation, including Rockwool at the bottom, was applied to minimize heat loss and improve thermal efficiency.

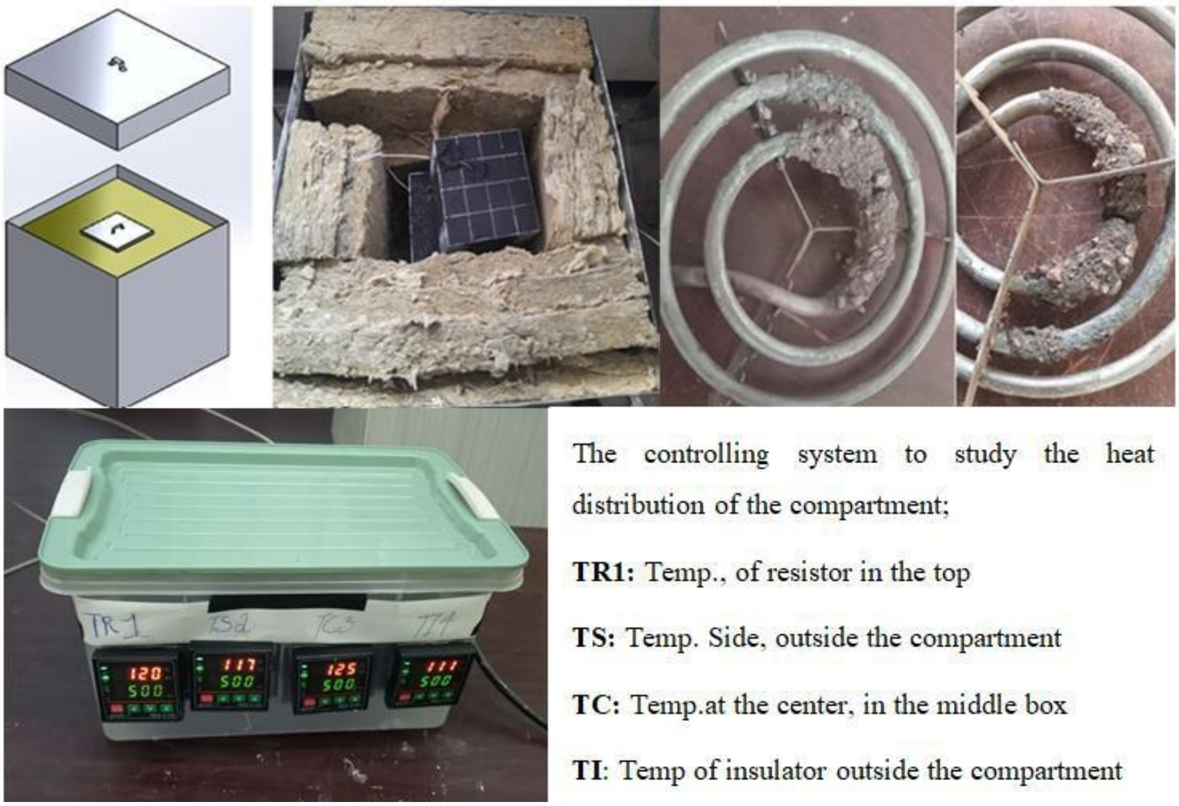


Figure 21: Previous version increasing magnetite content with 48 kg magnetite

However, significant challenges were observed during the testing phase. The heating element failed, and the Rockwool insulation at the bottom lost its structural integrity due to the combined effects of thermal stress and the heavy load of the magnetite. These failures compromised both heat retention and overall system efficiency, highlighting the need for improved heating element durability and more resilient insulation materials capable of withstanding both thermal stress and mechanical load.

5.8 Cooking Stove prototype-8: Multi-Purpose cooking, baking and water heater design

The multi-purpose cooking stove compartment was designed and manufactured to evaluate the effectiveness and efficiency of stored thermal energy for boiling water, cooking, and baking applications. The compartment featured an L-shaped geometry to accommodate multiple cooking tasks, including a baking oven with a sliding mechanism and a cooktop positioned at the leg of the structure. A total of 156 kg of magnetite was used as the thermal energy storage medium along with 5 liters of water. The heating system comprised a curved finger profile dry tube heater rated at 3000 watts, which was used to heat the magnetite inside the compartment effectively.

Significant positive results were observed during testing. The embedded water container efficiently absorbed heat, successfully boiling the water within a reasonable timeframe. The boiled water proved useful for secondary tasks such as preparing tea or enhancing cooking processes. Additionally, the oven section demonstrated the potential for effective bread baking, showcasing the stove's versatility. The ability to channel hot water through a galvanized steel (GS) pipe for other household purposes further highlighted the multifunctional nature of the cooking stove.

Despite the positive observations, several challenges emerged during the testing phase. The dry tube heating element failed under the performance test, compromising the system's reliability. Additionally, the design overlooked a proper pressure relief valve, which led to the loss of hot water in the form of steam, reducing overall efficiency. Another constraint was the weak transfer of thermal energy to the cooktop, limiting the stove's effectiveness for surface cooking.

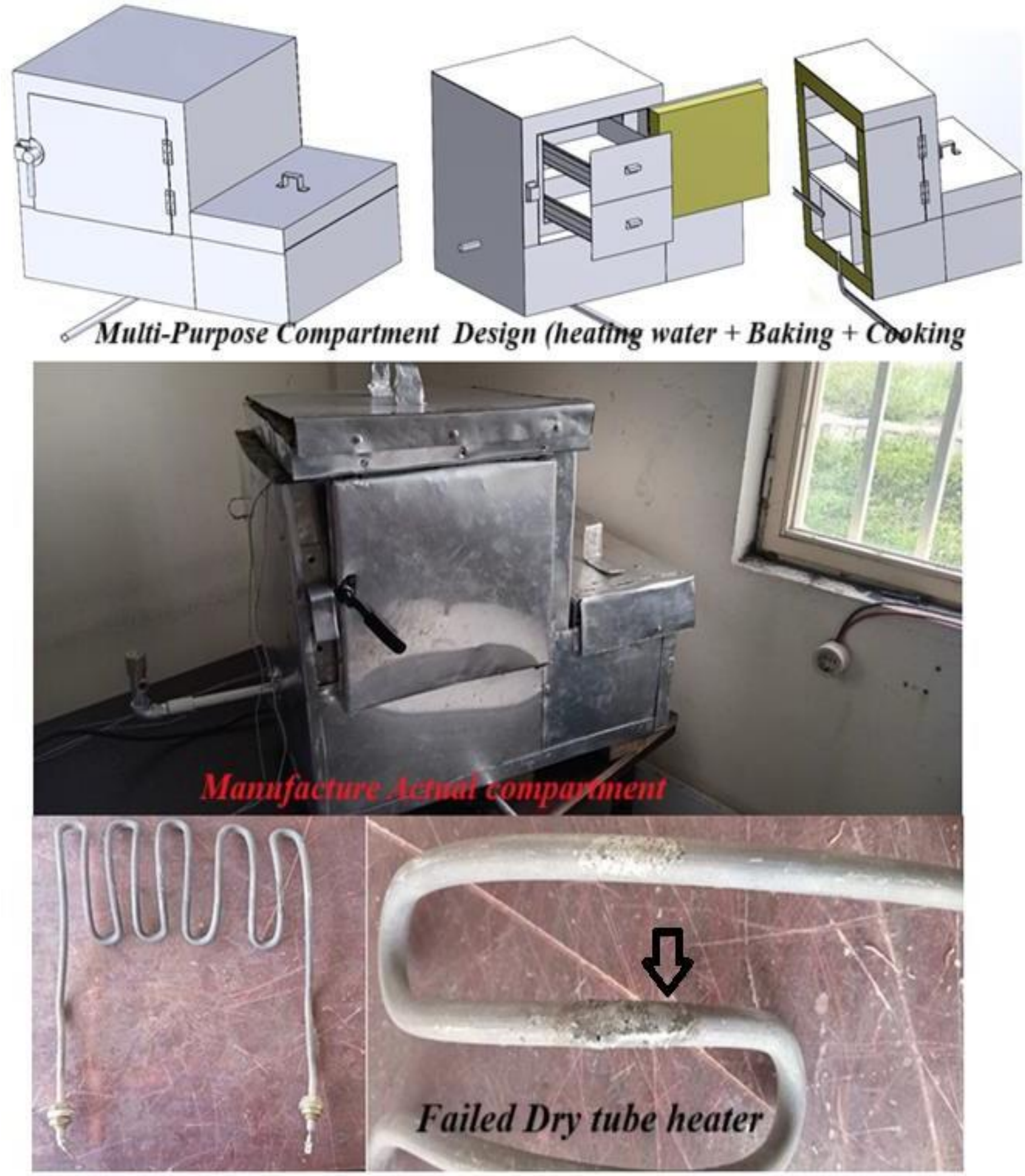


Figure 22: Multi-Purpose cooking, baking and water heater design and Product

To improve performance, key design optimizations are recommended. Selecting a more durable heating element capable of withstanding extended use is essential. Additionally, embedding the water container deeper within the magnetite mass could further enhance heat transfer efficiency and boiling rates. Incorporating multiple layers of insulation and refining the pressure relief system would also help reduce energy loss, making the stove a more reliable solution for cooking, baking, and water heating using stored solar power. This compartment is one of the successful trials in the process of making solar powered cooking stoves. Many novel ideas also assisted the cooking process and diverse use of the store energy. The following picture depicts the phenomenon design, production and performance testing.

5.9 Cooking Stove prototype-9 for baking Inghera

By this compartment setup and production, direct solar power usage for daytime cooking has proven to be an effective and efficient method for harnessing renewable energy. Even though the primary objective of this project was to collect and store solar energy in a given mass of magnetite for use during the absence of direct solar power. Scholars researched solar cookers, such as parabolic reflectors and solar box cookers have demonstrated the ability to cook food quickly under sufficient sunlight by concentrating solar radiation onto a cooking vessel (Kuhnke, 2014). However, a major limitation of direct solar cooking is its dependency on sunlight availability, making it ineffective during nighttime or cloudy conditions. This limitation has driven research into thermal energy storage (TES) systems to extend the usability of solar energy for cooking beyond daylight hours. Magnetite, a dense iron oxide mineral, was selected due to its high heat retention capacity and ability to store thermal energy for extended periods (Smith et al., 2016). This approach aims to combine the efficiency of direct solar cooking with the flexibility of stored energy, offering a more continuous and reliable clean cooking solution.

Such an intervention holds significant potential for off-grid rural areas where access to conventional energy sources is limited. Stored thermal energy cooking systems can help reduce reliance on biomass fuels, which are often linked to deforestation and indoor air pollution (Johnson & Patel, 2018). Additionally, the ability to rapidly cook meals using direct solar energy set up makes this compartment as a technology suitable for communities with high cooking demands. However, further research is needed to optimize the DC power generated heat supply to the cooking appliance and transferring media controlling leads to ensure the direct use of solar energy usage as cooking technology with minimal damage to the cooking appliance.

Figure 23: Small test version and bigger full size Inghera version

5.10 Cooking Stove prototype-10: Glazed Ceramic Clay tube and external brick support

The newly developed cooking prototype consisted of a 24 cm diameter, 60 cm long glazed ceramic tube/ cylinder designed to hold 46 kg of magnetite for thermal energy storage. The ceramic material served a dual role as both a heat storage medium and a partial insulator. During the trials, it was observed that heat insulation occurred on the sides of the ceramic cylinder, confirming ceramic's natural insulating properties. However, a considerable amount of heat is lost through the bottom of the structure, highlighting a key issue in heat conservation. To counteract this, a perforated 5 cm thick brick was introduced for structural load support, with the aim of minimizing direct heat loss and ensuring stability for the vertical-standing cylinder containing magnetite.

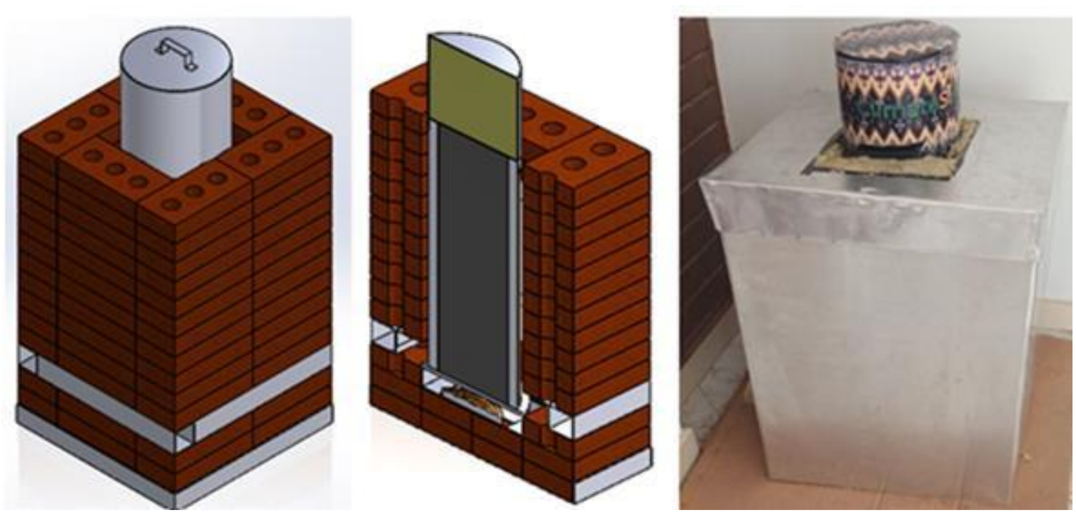


Figure 24: Using vitrified clay tube to hold magnetite, and external brick construction versus rockwool and stainless-steel casing used earlier

The top section of the heat battery was insulated with a 20 cm thick cover designed to minimize heat loss further. To improve heat transfer efficiency, an aluminum C-section profile was embedded within the top cover, facilitating faster heat transfer from the magnetite to the cooking surface.

Despite incorporating several design concepts from previous trials, the water boiling tests still did not meet performance standards.

While the heating element itself did not fail, a significant heat absorption by the brick base was observed, reducing the overall efficiency of the system. This heat absorption issue indicates a need for further optimization in both heat insulation strategies and load-bearing material choices.

Figure 25: Repositioning PV panels on the purpose-built green lab house

After the university management decided to build a sustainable bio block house that will also act as lab and demonstration of new technologies, the previously installed solar panels were relocated to the rooftop of the bio block structure. This relocation enabled an integrated setup where both the cooking stove and the bio block house could be tested together by allowing residents to use the system for real-life trials, contributing to a deeper understanding of the projects' practical performance and energy efficiency.

5.11 Cooking Stove prototype-11: re-designed model and assembly

New improved design of casing

Figure 26: New design to solve the upper insulation during and after cooking

ClimateStoven provided a new external casing shape and design, that was manufactured externally at the Bole Industry Park by Prof Tsegaye of Healthy Fires company. The finishing, internal part production, and system assembly were completed at AASTU under PI supervision. The following part discusses the performance test of the Cooking Stove prototype 11 manufacture and testing.

The materials used in this stove design focused on maximizing heat retention and transfer efficiency. Magnetite (Fe_3O_4) was used as the primary heat storage medium due to its high heat capacity, with 25 kg of the material used in the setup. The magnetite was contained within a ceramic cylinder with a diameter of 15 cm and a height of 45 cm, chosen for its thermal stability and insulation properties. To improve heat conduction, a 1 cm thick aluminum cover was placed on top of the cylinder. The heat storage compartment was carefully designed to ensure effective containment and transfer of heat. The ceramic cylinder, filled with magnetite, was central to the system's ability to store thermal energy. The aluminum top cover was connected to a series of inserted aluminum rods, which were strategically placed to enhance heat transfer from the magnetite to the cooking surface. This design aims to ensure steady heat availability for cooking purposes.

The heat transfer mechanism relied on the thermal storage capacity of magnetite. Once heated, the magnetite gradually released stored heat to the aluminum top cover. The aluminum rods embedded within the structure further improved heat distribution, ensuring the heat was conducted effectively from the magnetite to the cooking surface. This approach was intended to maintain consistent cooking temperatures during use.

The testing procedure involved heating the stove until the magnetite reached its thermal capacity. Temperature probes were positioned at the bottom, middle, and top of the ceramic compartment to monitor heat transfer and distribution. Cooking tests were conducted, including boiling 0.6 liters of water and cooking a single egg, while the time required reaching sufficient cooking temperatures and completing the tasks was recorded for performance evaluation.

Table 1: **Pre-heated Test at Day-2**

Record Time	**Aluminum Rod Temp (^oC)**	**Maximum Top Plate Temp (^oC)**

8:20AM	70	60
9:20AM	75	69
10:20AM	83	92
11:20AM	91	103
12:20PM	103	117
1:20PM	109	124
2:20M	119	132
3:20PM	125	140
4:20PM	136	152
5:20PM	151	158

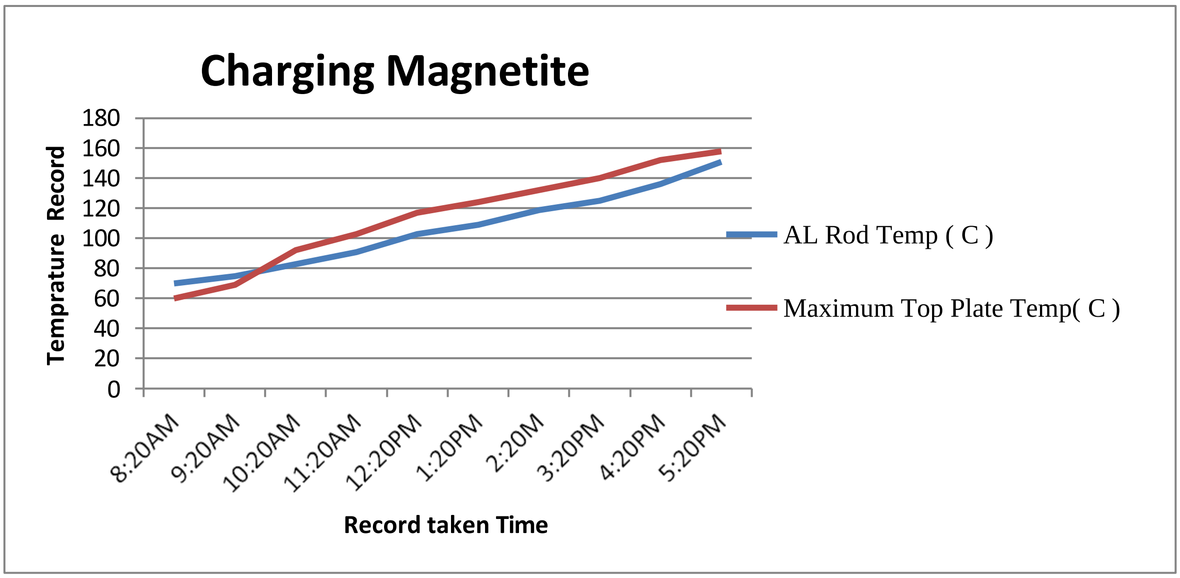


Figure 27: Prototype load charging process

1st phase of charging the heat battery:

- ✓ The temperatures of both the aluminum rod and the plate begin to rise significantly from the morning (8:20 AM), where the aluminum rod starts at **70°C** and the cooking plate at **60°C**. Since the system was exposed to heat a day before the record setup, the record was started from non-room temp.
- ✓ By **10:20 AM**, the aluminum rod temperature has increased to **83°C**, while the plate temperature rises to **92°C**. This sharp increase suggests that heat transfer efficiency improves as the aluminum rod and plate warm up.

2nd Phase of charging, rapid increase:

- ✓ As the day progresses and supplied energy intensifies, the temperature increases rapidly. By **12:20 PM**, the aluminum rod reaches **103°C**, while the top plate reaches **117°C**. The temperature differential between the rod and plate indicates that the plate absorbs heat more efficiently, most likely because it is in close contact with the inserted aluminum rods and U-channel section, which accelerates heat transmission due to aluminum conductivity qualities.
- ✓ By **2:20 PM**, the aluminum rod reaches **119°C**, and the cooking plate reaches **132°C**, indicating continuous heating. This time period seems critical as the system is nearing its peak temperatures, with efficient heat absorption.

3rd phase of charging - peak temp:

- ✓ The temperatures continue to rise in the afternoon. By **3:20 PM**, the aluminum rod reaches **125°C**, and the cooking plate reaches **140°C**. This sustained high temperature is crucial for ensuring that the magnetite inside the system absorbs enough heat to store for later use.
- ✓ By **5:20 PM**, the aluminum rod achieves **151°C**, and the cooking plate reaches **158°C**, marking the peak temperatures of the day. At this point, the heat battery has absorbed a significant amount of heat in the magnetite for later use.

In conclusion, the stove design demonstrated a promising approach for heat retention and transfer using magnetite as a thermal storage medium in combination with aluminum rods. While the aluminum components effectively enhanced heat transfer, further optimization was required to improve heating efficiency and cooking performance. The testing highlighted the system's potential for sustained heat release, but refining insulation and heat transfer pathways could further improve results.

Water Boiling Test Result: 35 minutes to get to 81 degrees

The water boiling test is a crucial step in assessing the effectiveness, sustainability, and safety of cooking technologies, particularly for regions where clean cooking solutions are necessary. The results can guide the improvement of stove designs. The cooking prototype developed 189 degrees centigrade as a maximum temperature of test-1 set up. We unplugged the power source for the water boiling test with the collected thermal heat loaded in the magnetite. As shown in the image below, the water boiling test uses magnetite thermal energy to raise the temperature of water from room temperature to 85 degrees centigrade in about 35 minutes and continues steadily. Yet, since the built-up thermal energy in the magnetite remained unable to boil water in the given time frame, the design has to be explored further with an improved test setup.

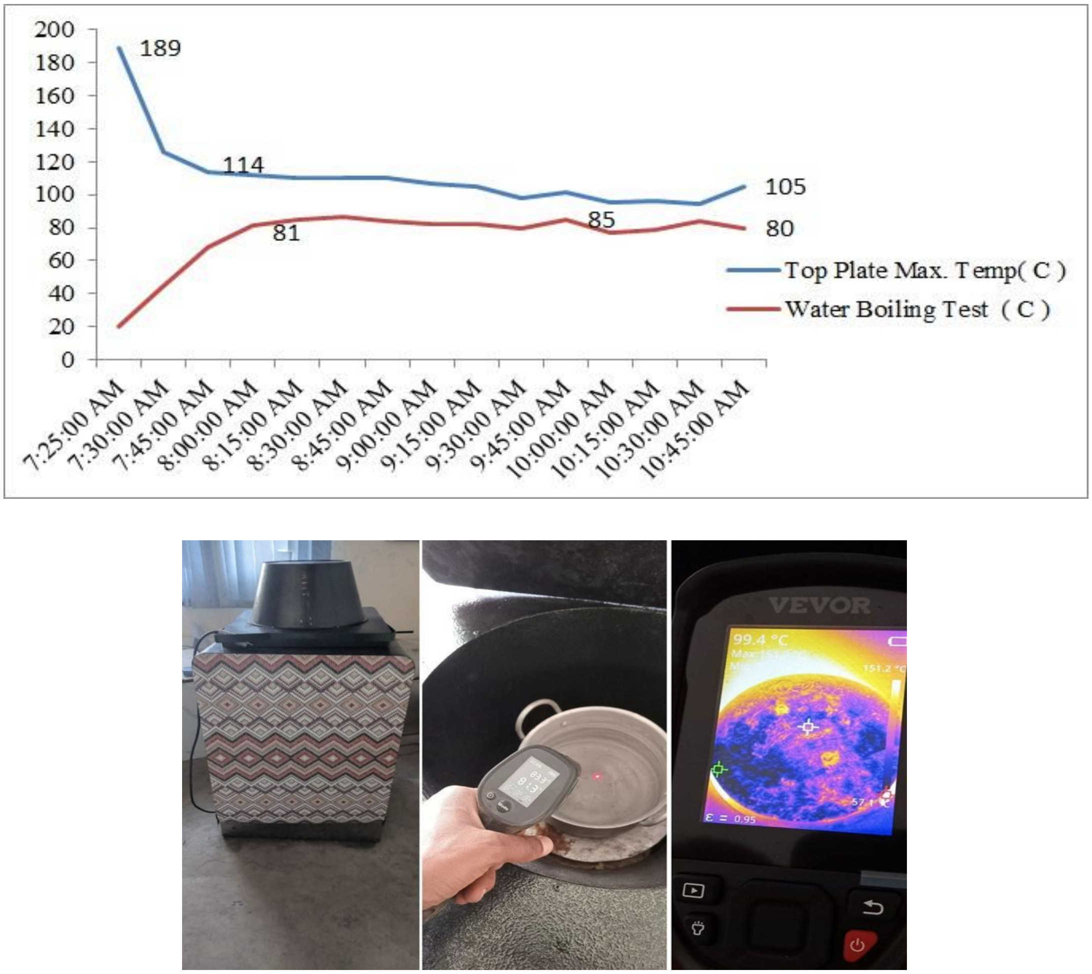


Figure 28: Water boiling test

Cooking Test: Cooking Scrambled Eggs

A simple cooking test is used to evaluate the performance and efficiency of a cooking appliance or stove by measuring the energy consumption, time, and heat required to cook a specific type of food—in this case, a scrambled egg was used as first simple test.

To scramble an egg, the following basic steps are involved:

- **Ingredients:** One egg, oil and salt were ready for further steps.
- **Cooking Method:** The egg is beaten, then cooked in a heated aluminum pan with some oil and stirred until firm but not dry.
- **Target Temperature:** Since scrambled eggs are cooked at a medium-low heat, with the target internal temperature of the egg reaching around 70°C to ensure food safety without

overcooking.

Hence, the existing cooking test setups were applied for determining the capacity of the cooking stove prototype. For this test, there were 60 grams of egg. The designed prototype cooked the scrambled eggs in 13 minutes, utilizing 10.4kJ of heat energy stored by magnetite. The inserted aluminum rods proved effective in speeding up the transfer of heat from the magnetite to the top cover. Heat retention remained consistent, allowing stable cooking temperatures over time.

Figure 29: Scrambling egg using stored heat by magnetite

Observed Result and Challenges by Cooking Stove prototype 11

- ✓ Magnetite demonstrated strong heat retention and gradual heat release, confirming its suitability for thermal energy storage in cooking applications. The ability to maintain a high temperature for extended periods without additional energy input would be a significant advantage for rural cooking, where fuel is often scarce or expensive
- ✓ Using Aluminum or another good thermal conductive metal looks feasible for fast transmission of stored heat. The fact that the system reaches temperatures exceeding 189°C suggests that the magnetite can be heated to a certain energy level rapidly.
- ✓ Increasing the number of aluminum rods or beams will increase the high temperature and thermal conductivity that will facilitate rapid heat transfer from the magnetite to the cooking plate contact surface area.

- ✓ The combination of a vitrified clay tube in which the heat battery with magnetite, aluminum rods and aluminum top disk provides an effective way to store and transfer heat. However, the design should be optimized further for heat loss prevention, and additional insulation may be added to improve efficiency.
- ✓ The current stove's performance in cooking an egg within 13 minutes shows promise for other basic cooking tasks, such as boiling water or preparing stews. The ability to maintain a cooking temperature for this period without fuel input highlights the stove's potential for efficient energy use.
- ✓ In the current cooking configuration, there is a heat loss through the top surface of the compartment, it needs major design revision to insulate the excess heat loss.
- ✓ The heating element/resistor repeatedly broke failed to perform for sustained period of time and it needs major technical revision to use it as continual heat supplier.
- ✓ The aluminum rod used to enhance the heat transfer partially melted away from the bottom cover as illustrated.

Figure 30: Aluminum disks and rods, melted aluminum at bottom near heating

In conclusion, the stove design demonstrated a promising approach for heat retention and transfer using magnetite as a thermal storage medium in combination with aluminum for sustained heat release. Refining the diameter of Aluminum rod as a heat transfer path and controlling the bottom temperature could further improve cooking time results.

5.12 Cooking Stove prototype-12: Vacuum insulated cooking stove model

The prototype was designed to store thermal energy using 44 kg of magnetite contained within a cylindrical sheet metal structure with an 18 cm diameter. At the core of the design, a 1.5 cm thick aluminum plate was positioned inside the cylinder to aid in heat transfer. Four aluminum bars extended upward from this plate, transferring heat from the magnetite to the top aluminum plate, which was 3 cm thick. Beneath the aluminum plate, a 1 mm stainless steel sheet was added to further facilitate heat transfer. Surrounding this setup was a ceramic cylinder with an outer diameter of 24 mm and an inner diameter of 20 mm, filled with perlite insulation between the ceramic and sheet metal. A stainless-steel stand was used to hold the entire structure, with the heating element placed inside the stand. To minimize heat loss further, a vacuum insulation layer was applied around the ceramic cylinder, with all insulation components forming a triangular top cover.

The heat transfer process started from the heater, which initially transferred heat to the 1 mm stainless steel sheet. This heat was then conducted into the magnetite via the bottom 1.5 cm thick aluminum plate. As the magnetite absorbed heat, the aluminum bars in contact with the magnetite were also heated. The heat was further conducted upward to the top 3 cm thick aluminum plate, ensuring heat distribution for cooking purposes.

During prototype testing, significant challenges arose related to the heating elements used. The initial heating element chosen was a spiral heater. However, it failed due to excessive heat stress and direct contact with the ceramic insulator, which compromised its structural integrity and operational capacity. This failure prompted the team to replace it with a mini electric cooking plate as an alternative heating element.

Unfortunately, the mini electric cooking plate also failed to perform effectively. It was unable to raise the temperature of the top aluminum plate to the desired level, significantly limiting the efficiency of heat transfer. The failure was primarily attributed to overheating within the heating element itself, which was unable to sustain consistent energy transfer throughout the cooking process.

Figure 31: Improved Aluminum heat transfer structure and vacuum panel use. Failed electric plate

The challenges observed in the prototype highlight the need for more durable and efficient heating elements capable of withstanding high thermal stress. Future improvements should focus on heat-resistant materials for heating elements, better heat distribution strategies, and enhanced insulation techniques to reduce heat loss and improve overall efficiency. Addressing these issues will be crucial to the success of the magnetite-based thermal storage cooking stove.

6 LESSONS AND RECOMMENDATIONS

6.1 Lessons

Solar-powered cooking stoves that utilize magnetite as a thermal energy storage medium offer a unique approach by harnessing the sun's energy to heat the magnetite, which can store and release heat over an extended period to cook. Magnetite's high specific heat capacity with a high density and therefore small volume allows to retain heat for long durations, making it an ideal material for such applications. This method offers an environmentally friendly alternative to traditional cooking methods and reduces the reliance on fuel wood.

Initial tests for this project were done with DC from solar panels, as this project emphasizes the use of solar (DC) power for charging the magnetite. But many electronic components for testing the heat battery were tailored to AC electric power to charge the magnetite. Therefore, there is a need to develop or source/ adapt industrial strength electric and heat components that can withstand permanent heat at 200 degrees and are adapted to transform DC current into heat for the specific application of heat batteries for cooking.

The solar PV panels at Addis Ababa Science and Technology University (AASTU) have provided up to 4kW of peak electricity to power a part of our clean cooking heat batteries prototypes. The initial trials with this system have proven promising, with magnetite successfully storing heat for use in cooking. Research continued to explore how to enhance heat transfer efficiency to cook and improve the cost-effective conductive architecture of the heat battery that can optimize the cooking process, notably by using aluminum lattices, beams and top disks.

The development and testing of various magnetite-based cooking stoves led to incremental improvement of the heat battery over the various phases. More than 12 different stove models with varying geometries were developed, each with specific design objectives and heat capacities in mind. While many of these designs showed potential, only a few met minimal usability and cooking performance thresholds. The challenge with magnetite alone is the insufficient heat transfer towards the cooking pot. We tested and gradually added more and more aluminum to transfer the heat from the magnetite column towards the cooking plate. Of the models tested with increasing aluminum content, five were deemed promising.

Even if the model of magnetite and aluminum that came out in the last prototypes looked the right solution, there was still a problem of insulation. We did not succeed in heating the magnetite above the threshold of 140 to 150 degrees. The rockwool of 20 cm which had a thermal conductivity of about 40 W/mk at room temperature, has a much bigger thermal conductivity at 200 degrees of around 0.01 W/mw, and was much less effective. In addition, the thermal expansion and contraction of the surrounding air led to bellow effect and suction/ exchange of cold air. Our conclusion was that only vacuum insulation could solve this problem. We therefore started cooperation with VaQtec company to supply heat resistant vacuum panels. These were already tested in our version 12, and we will continue to develop vacuum solutions in next phases of our R&D journey.

All these lessons were crucial to move the project forward to the next phase, which will involve testing improved stove designs with optimized magnetite/aluminum batteries, better insulation efficiency and adaptability to different cooking environments.

6.2 Recommendations and next steps

1 First the heat transfer to cooking pots has to be optimized for cooking and baking. Our research and iterations show that combining magnetite with aluminum looks like a way to develop performant heat batteries. We will need much more aluminum than our first prototypes, probably around 25 to 30 volumes %.

2 Second, the insulation has to be much more effective. Rockwool loses insulation capacity as temperatures increase, but most other insulators are losing insulation efficiency at higher temperatures as well. Therefore, only vacuum insulation looks like a feasible option. Our findings suggest we should try to develop a low-cost vacuum envelope for the heat battery. We are thinking about combining VaqTec panels with our own vacuum tube system using vitrified clay tubes.

3 Third, investment in robust AC and DC electrical components capable of converting the DC current into heat and withstanding high continuous temperatures will be essential for the stove’s durability

Solving these three challenges, which is doable, will allow us to build the next generation heat battery-based cooking stoves that will conform to standard cooking lab tests under controlled conditions.

6.3 Special thanks

Many thanks to the MECS/ University of Loughborough team that were always there to support and encourage us and allow time extensions.

Special thanks to our industrial partners/ supporters LKAB Netherlands, Norsk Hydro Aluminum Netherlands, Pipelife/Wienenberger Belgium, Rockwool Netherlands and Belgium, Xella Belgium and Va-Q-Tec Germany. Without their technical guidance and in-kind support with materials and/or access to tailored samples we could not have performed all the experiments needed to get into the right direction.

6.4 Contact and cooperation:

Addressing the global clean cooking crisis, which impacts millions of people, requires the collaboration of many stakeholders. Developing an innovative solar PV and heat battery-driven cooking stove is a complex challenge that calls for expertise, resources, and collective effort. We are actively seeking partnerships with universities, research institutions, industrial partners, funding organizations, and NGOs to co-develop and advance this vital research.

Our goal is to design and refine heat battery-powered cookstoves that are effective and efficient but also capable of being produced locally to ensure sustainability and affordability. By working together, we can drive meaningful progress toward providing clean cooking solutions and improve lives in underserved communities worldwide. We welcome all like-minded partners to join us in making this vision a reality.

Please do not hesitate to contact us:

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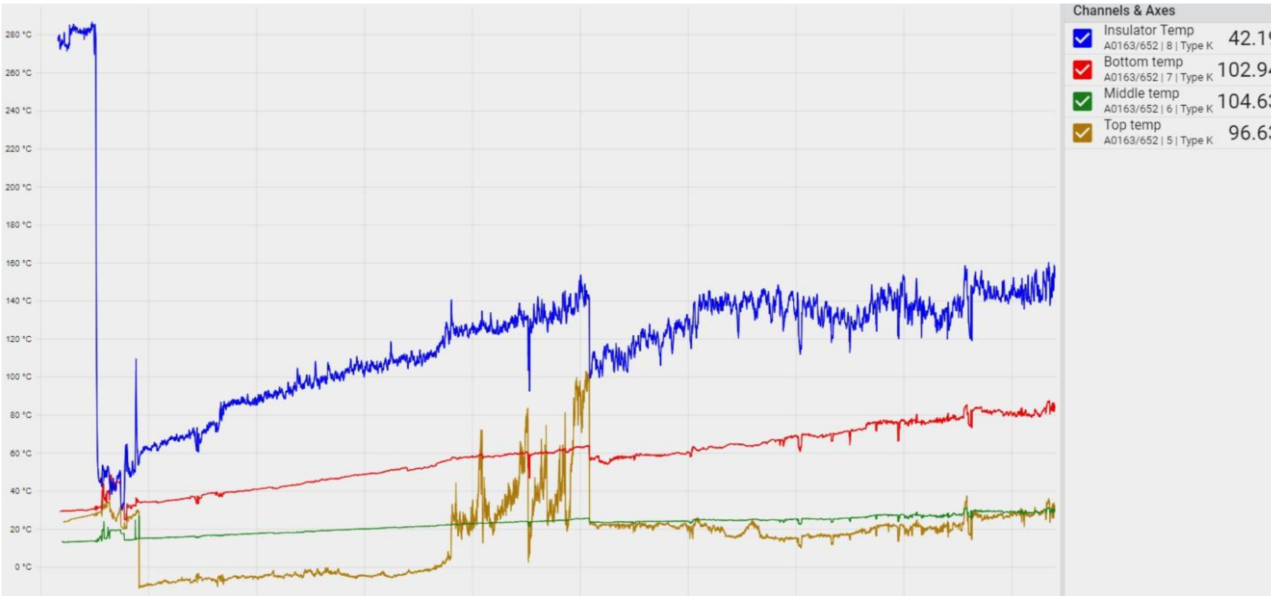
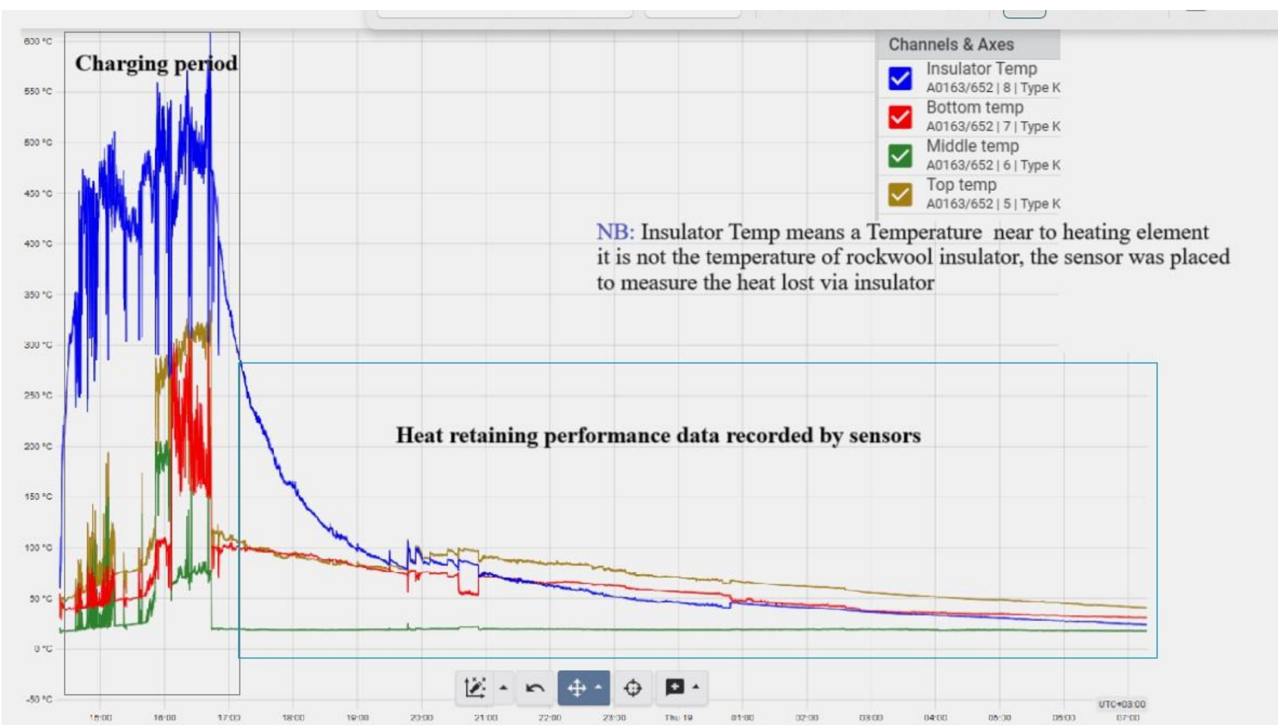
For Tridealhouse / ClimateStoven (Belgium): Dr Michel Loots, mloots@tridealhouse.com

APPENDIX

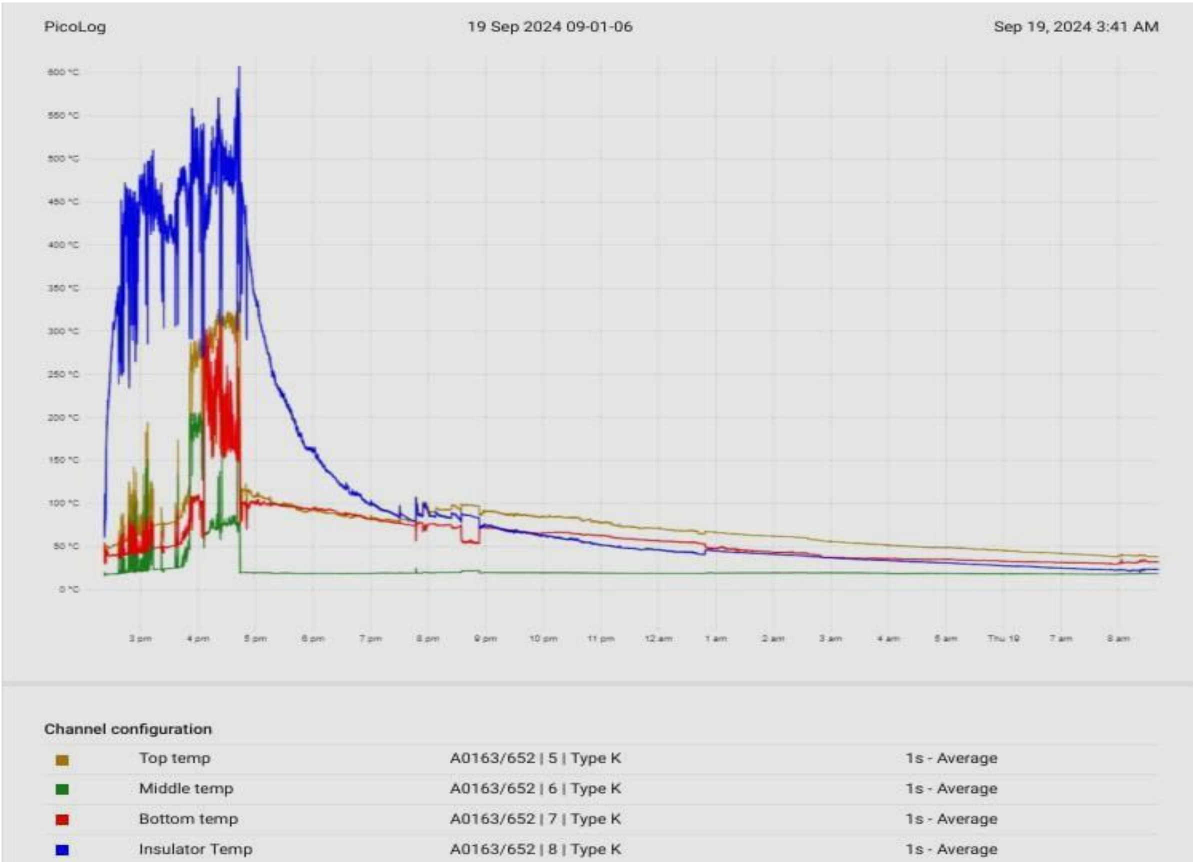
Sensor outputs for Compartment 5, 6, 7 and 8 for charging time set-ups



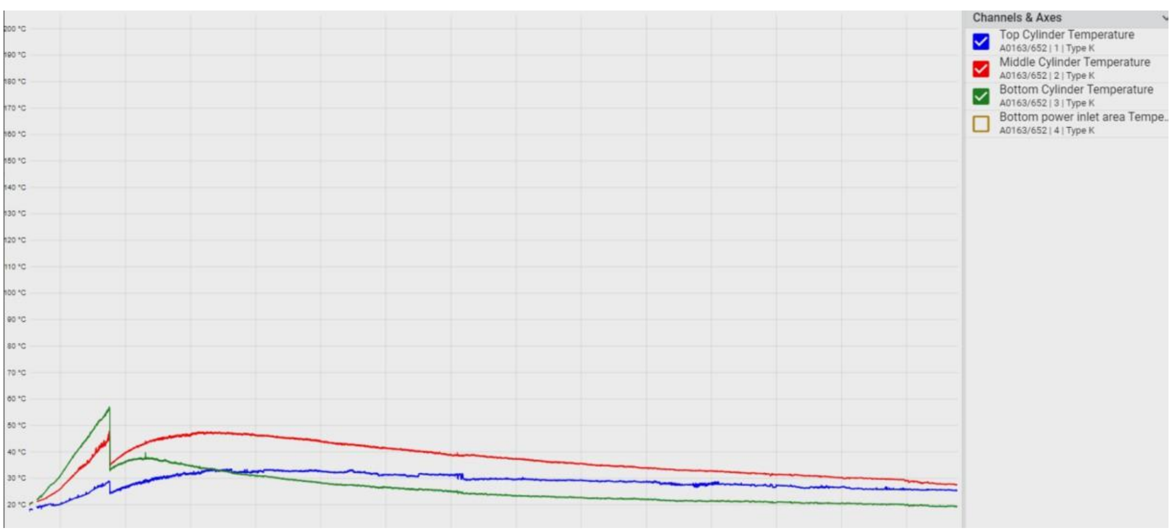
Compartment Heat supply and Retaining test set up-1



Charging and Heat retaining performance test set up-2



Charging and Heat retaining performance test set up-3



Charging and Heat retaining performance test set up-4