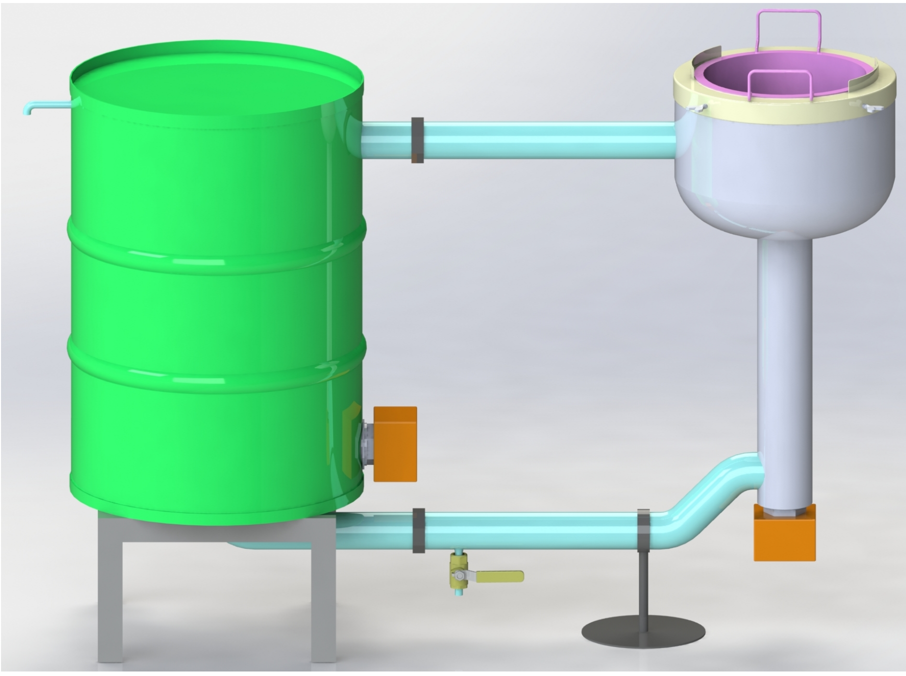
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Alexander Peter Olsen

Design and testing of a natural-circulating heat storage for cooking

Master's thesis in Mechanical Engineering
Supervisor: Ole Jørgen Nydal
June 2022



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NTNU
Kunnskap for en bedre verden

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Abstract

The world has seen significant improvements regarding access to electricity in recent years. Still, approximately 770 million people do not have access in 2021, according to a report by the World Energy Outlook, with the majority living in Sub-Saharan Africa. The lack of electricity causes food to be cooked traditionally, using biomass or other solid fuels as an energy source. Traditional cooking can be highly polluting and unclean and contributes to deforestation and the subsequent degradation of the environment. It is estimated in the same report that health risks associated with air pollution from burning these materials, as well as kerosene, cause 2.5 million premature deaths annually.

Several clean cooking solutions have been designed and developed to combat unclean cooking, but many lack the possibility to store energy, resulting in limited use if powered by intermittent energy sources such as solar or wind power. Their use can be extended if implemented with a storage solution to store energy over time. Therefore, the thesis investigates the design and testing of a natural-circulating heat storage solution for cooking to be implemented in rural areas of southern Africa.

The system consists of two tanks filled with oil, connected to each other through piping, where one tank serves as a sensible heat thermal energy storage, SHTES, and the other as a cooker. The cooker is a smaller tank containing a heating element and a pot that can be used for cooking. This design allows for only heating a small volume of oil which, through natural circulation, can charge the SHTES or allow cooking directly. The SHTES can later be discharged through reversed natural circulation to allow cooking, even when power to the heating element is not available. Temperatures and the flow of oil are regulated through a valve concept.

A system has been designed, built, and tested to demonstrate and further develop the concept described above. The emphasis during testing was on the efficiency of the natural circulation to provide adequate cooking power and on methods for controlling the cooker temperature. Through a preliminary set of experiments, the system was tested with varying success. When powering the heating element, natural circulation occurred, which charged and thermally stratified the SHTES while maintaining adequate temperatures in the cooker. When discharging, adequate natural circulation to sustain cooking only occurred when the system was fully charged, leaving a significant amount of energy in the SHTES when this was not the case. Remediation methods were therefore proposed and tested. These consisted of a new type of valve, allowing the user control of the flow from outside the system, and a manual pump to assist in fully discharging the SHTES of usable energy. Through a set of final experiments, the effect of the modifications was tested. Experiments showed that the displacement valve provided similar control, with only minor differences to the previous solution, but was safe and easier to regulate. The pump allowed the extraction of usable energy even when the SHTES was not fully charged, however, further optimization is required before implementation. A cooking test of 2kg of kidney beans from stored energy also showed that the system is proficient in cooking wet foods for a substantial amount of people. When fully charged, the prototype can store 6.8 kWh of usable energy, and through testing, it has been proved to store usable energy for over 16 hours.

Based on results from testing and other considerations, the system is deemed ready for testing under real-life conditions in rural areas of southern Africa.

Sammendrag

De siste årene har verden gjennomgått betydelige forbedringer når det gjelder tilgang til elektrisitet. Likevel manglet fortsatt omtrent 770 millioner mennesker tilgang til elektrisitet i 2021, ifølge en rapport fra World Energy Outlook. Flertallet av disse bor i Afrika sør for Sahara. Mangelen på elektrisitet gjør at mat tilberedes tradisjonelt, med biomasse eller annet fast brensel som energikilde. Slik tilbereding kan være svært forurensende og gir et miljøproblem som følge av avskoging i tett befolkede områder. Det anslås i nevnte rapport at helserisikoen forbundet med luftforurensning fra forbrenning av disse materialene, samt parafin, årlig forårsaker 2,5 millioner premature dødsfall.

For å bekjempe uren matlaging, har det tidligere blitt utviklet flere rene matlagningsløsninger. En utfordring med disse er imidlertid at mange av menneskene løsningene er tiltenkt mangler muligheten til å lagre energi. Det resulterer i begrenset bruk hvis løsningene drives av intermitterende energikilder som sol og vindkraft. Bruken av disse systemene kan dermed utvides hvis de implementeres med en lagringsløsning for å lagre energi over tid. Derfor undersøker denne oppgaven design og testing av et naturlig sirkulerende varmelager for matlaging som kan implementeres i Afrikanske omgivelser.

Systemet består av to tanker fylt med olje, koblet til hverandre gjennom rør. Den ene tanken fungerer som et lager for energi i form av varme, og den andre som en koker. Kokeren er en mindre tank som inneholder et varmeelement og en gryte som kan brukes til matlaging. Denne utformingen gjør det mulig å kun måtte varme opp et lite volum olje, som gjennom naturlig sirkulasjon, kan varme opp lageret eller tillate matlaging. Naturlig sirkulasjon kan også muliggjøre å senere tappe lageret for energi for å tillate matlaging, selv når elektrisitet fra energikilden ikke er tilgjengelig. Temperaturer og strømmen av olje i systemet reguleres av en ventil.

Et system er designet, bygget og testet for å demonstrere og videreutvikle konseptet beskrevet ovenfor. Under testingen ble det lagt vekt på effektiviteten til naturlig sirkulasjon for å gi tilstrekkelig kraft til matlaging og på metoder for å kontrollere kokerens temperatur. Gjennom et innledende sett med eksperimenter ble systemet testet med varierende suksess. Når energi ble tilført systemet gjennom varmeelementet, oppsto naturlig sirkulasjon, som ladet og termisk stratifiserte lageret samtidig som det opprettholdt tilstrekkelige temperaturer i kokeren. Når systemet ble tappet for energi oppstod tilstrekkelig naturlig sirkulasjon for å opprettholde matlaging bare når systemet var fulladet, og etterlot en betydelig mengde energi i lageret når dette ikke var tilfellet. Utbedringsmetoder ble derfor foreslått og testet. Disse besto av en ny ventil, som tillot brukeren å kontrollere strømmen av olje fra utsiden av systemet, og en manuell pumpe for å hjelpe til med å fullstendig tømme lageret for brukbar energi. Gjennom ett sett med senere eksperimenter ble effekten av modifikasjonene testet. Eksperimentene viste at fortrengningsventilen ga tilsvarende kontroll, med kun mindre forskjeller fra forrige løsning. Løsningen var imidlertid trygg og lettere å regulere. Pumpen tillot utvinning av brukbar energi selv når lageret ikke var fulladet, men ytterligere optimalisering er nødvendig før implementering. En matlagingstest av 2 kg kidneybønner fra lagret energi viste også at systemet er tilstrekkelig til å tilberede mat til et betydelig antall mennesker. Fulladet kan prototypen lagre 6,8 kWh med brukbar energi, og gjennom testing har den vist seg å lagre brukbar energi i over 16 timer.

Basert på resultater fra testing og andre hensyn, anses systemet som klart for testing under virkelige forhold i det sørlige Afrika.

Contents

List of Figures

List of Tables

Nomenclature

q”	Local heat flux	[W/m^2]
k	Thermal conductivity constant	[W/mk]
T	Temperature	[^oC]
x	Distance	[m]
h	Heat transfer coefficient	[W/m^2k]
U	Overall heat transfer coefficient	[W/m^2k]
Q	Heat	[KJ]
A_s	Surface area	[m^2]
R	Thermal resistance	[K/W]
η_{dis}	Discharging efficiency	[$-$]
m	Mass	[kg]
C_p	Specific heat capacity	[kJ/kgK]
T_0	Ambient temperature	[^oC]
T_m	Average temperature	[^oC]
ω	Mass fraction	[$-$]
E_x	Exergy	[KJ]
H	Height	[m]
z	Vertical length	[m]
T_e	Equivalent temperature of fully mixed	[^oC]
F_b	Buoyancy force	[N]
g	Gravitational acceleration	[m/s^2]
ρ	Density	[kg/m^3]
V	Volume	[m^3]
R_h	Hydraulic resistance	[m^{-4}]
$\dot{m}$	Mass flow	[kg/s]
P	Pressure	[Pa]
Re_D	Reynolds number pipe flow	[$-$]
D_h	Hydraulic diameter	[m]
μ	Kinematic viscosity	[m^2/s]
f	Darcy friction factor	[$-$]
$x_{fd,v}$	Entry length velocity boundary layer	[m]
u_m	Mean velocity	[m/s]
$\eta_{cooking}$	Cooking efficiency	[$-$]

List of abbreviations

SSA	Sub-Saharan-Africa
PV	Photo-voltaic
NORHED	Norwegian Programme for Capacity Development in Higher Education and Research for Development
Norad	The Norwegian Agency for Development Cooperation
SHTES	Sensible heat thermal energy storage
TES	Thermal energy storage
PCM	Phase changing materials
LHTES	Latent heat thermal energy storage
HTF	Heat transfer fluid
CSP	Concentrating solar power
TC	Thermocouple

1 Introduction

The world has seen significant improvements regarding access to electricity in recent years [1]. More and more people in different parts of the world have access to electricity. Still, approximately 770 million people do not have access in 2021, according to a report by the World Energy Outlook, with the majority living in Sub-Saharan Africa, SSA [1]. This poses significant challenges for these areas and people affected, particularly for cooking food. Without proper access to electricity or other necessary utilities, the cooking of food is done traditionally, using biomass, or other solid fuels as an energy source. Figure 1.1 shows a map of the proportion of the population with primary access to clean cooking.

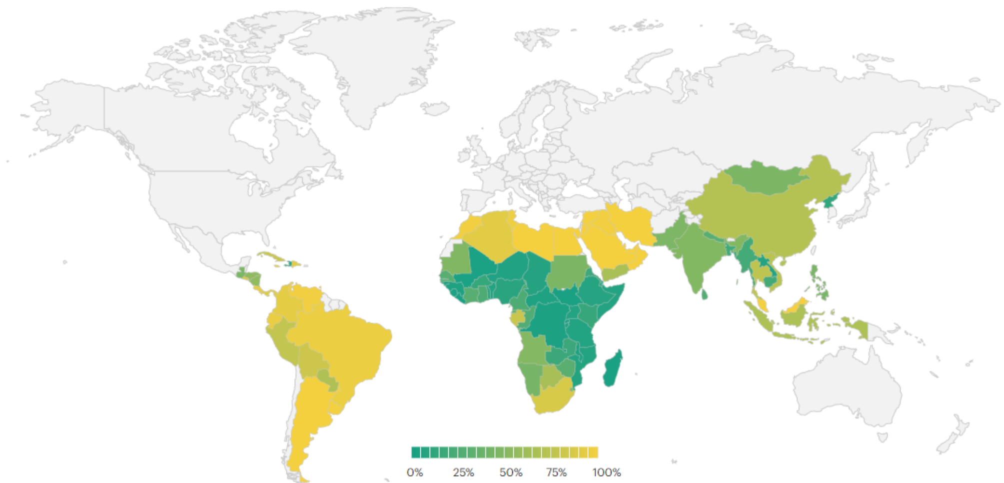


Figure 1.1: Proportion of population with primary access to clean cooking facilities, 2018 [2]

The same report by the World Energy Outlook estimates that 2.5 million premature deaths are caused annually due to cooking with biomass, coal, and kerosene [1], with a majority in developing economies. This is due to the health risks associated with air pollution from burning these materials. The use of biomass for cooking has also led to deforestation in the affected areas [3]. It is estimated that 1/3 of the world's population still will not have access to clean cooking fuels in 2030 [4]. Therefore, new cooking solutions utilizing clean energy sources could have a considerable positive impact. Under the COVID-19 pandemic, 30 million people lost access to clean cooking due to the pandemic diminishing their means to pay [1]. Therefore, these cooking solutions need to be low cost so that they can be available to as many people as possible.

A possible clean energy source for cooking is small-scale decentralized renewable energy. Energy sources such as hydro, wind, and solar power all have the potential for implementation. SSA, which is one of the most affected areas by unclean cooking, has a large potential for the use of solar power. The practical solar photo-voltaic, PV, power potential, regardless of any limitations to the development and operation, is shown in figure 1.2. PV solar panels installed in SSA will therefore produce high amounts of energy compared to installed PV capacity, thus showing potential for implementation with cooking.

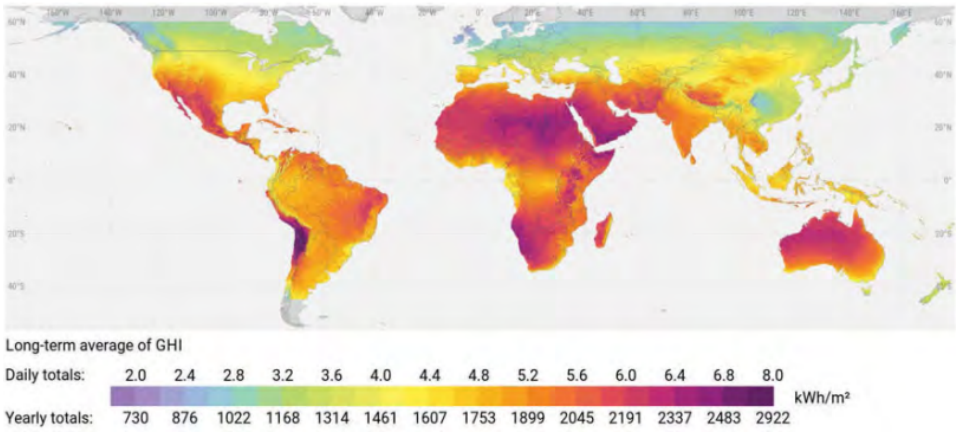


Figure 1.2: Practical solar power potential world map [5]

1.1 Background

In 2012 the NORHED project was launched by Norad, the Norwegian agency for development cooperation. The goal of the project is to "strengthen the capacity of higher education institutions in developing countries" [6]. Through NORHED, several cross-continent research projects between universities have been started. One project is the solar energy research collaboration between NTNU and a group of African universities in Tanzania, Ethiopia, Mozambique, and Uganda. Through this research project, several solar cookers have been developed to provide clean cooking in regions relying on the use of unclean fuels. Research has been done using direct solar cookers, which utilize the energy of direct sunlight to cook food, and solar cookers using PV solar panels to heat a thermal energy storage used for cooking.

In spring 2021, a heat storage for cooking was developed by Olsen [7]. This is a clean cooker consisting of a sensible heat thermal energy storage, SHTES, which is warmed by a heating element powered by an energy source of choice. By heating a thermal energy storage, instead of heating a pot directly, aims to allow consistent cooking using an intermittent energy source such as solar power or other renewable energy sources. The system, which is named the Dual Tank System, is based on a system developed by Bjørshol and Nylund in the MSc "Single Tank Oil Based Heat Storage for Cooking" but aims to solve issues in regards to upscaling and cooking with low power energy sources [8]. The system has only reached the design phase, but shows promise with testing required. A similar concept has been numerically studied in the MSc by Fjeldsæter and Stordal [9].

The Dual Tank System consists of two tanks connected through pipes at the top and bottom of the tanks. The largest tank is used as a SHTES, which can be filled with oil or a mixture of rocks and oil as the heat storage medium. The smaller tank contains the heating element and a pot at the top that can be used for cooking. Ideally, by supplying power to the heating element, the oil in the smaller tank will become warmer, causing thermal expansion. This will make the liquid column expand, causing hot oil to flow from the small to the larger tank through a pipe at the top, and cold oil to be sucked in at the bottom of the small tank. This in turn initializing natural circulation. If the system functions as intended, the SHTES will be thermally stratified, and food can be cooked through heat transfer between the oil and pot. When external power is no longer available, the system should discharge and provide energy from the SHTES to the pot through natural circulation.

1.2 Objective

The main objective of this thesis is to arrive at a heat storage concept for cooking, which can be applied in a rural African environment. A heat storage for cooking based on the natural circulation of hot oil between a cooker part and a storage part has earlier been designed. The specific objectives are to review the system, build it, and test its performance in a laboratory setting. Emphasis is in particular on the efficiency of natural circulation to provide adequate cooking power and on methods for controlling the cooker temperature. In case of low circulation efficiencies or lack of temperature control, remediation methods shall be proposed and tested. The system should be cheap to manufacture, safe to operate and simple so that it can be constructed by local work forces.

1.3 Scope

Developing and testing a working prototype includes various work tasks and focus areas. This thesis includes design, 3D-modelling, construction, and experimental work to reach the objectives listed above. Still, several areas, that could be beneficial for a working heat storage for cooking, have been excluded due to time limitations, which are listed below:

- As the system is to be implemented in a rural African environment without or limited access to electricity or utilities, various small-scale renewable power sources should be tested.
- In the thesis, several designs are presented that should be experimentally tested, but due to time limitations, could not. This is the case for the use of a secondary heating element, the use of rocks in the SHTES, and the implementation of spacers on the cooker top.

1.4 Citation

As this thesis is a continuation of the project work "Heat Storage For Cooking" by Olsen, parts of the text have been modified and reused in the current thesis [7]. The sections in which text has been reused are listed in table 1.1.

Section	Type
1.0	Recited
1.1	Recited with alterations
2.1	Recited
2.2	Recited with large alterations
2.4	Recited
3.1	Recited with alterations

Table 1.1: Recited sections [7]

2 Theory

The following section forms the theoretical foundation used in this thesis.

2.1 Heat transfer

A general definition of heat transfer is: "Thermal energy in transit due to a spatial temperature difference" [10]. Three modes of heat transfer exist: Conduction, convection, and radiation. Radiation will not be described in this thesis.

2.1.1 Conduction

Conduction is a heat transfer mode due to temperature gradients in either solids or fluids. Where temperature gradients are present, conduction will exist. Conduction through a medium is described by Fourier's law given by:

$$q"_{cond} = -k \cdot \frac{dT}{dx} \tag{1}$$

Fourier's law states that the heat flux, q", is a product of the thermal conductivity, k, and the temperature gradient in the medium. k is the thermal conductivity of a medium and describes its ability to transfer heat.

2.1.2 Convection

Convection is a heat transfer mode due to bulk fluid motion and random motion of particles, either due to diffusion or conduction [10]. Convection occurs when the heat transfer fluid comes into contact with either a solid surface or another fluid with a temperature difference. The heat transfer is described by Newton's law of cooling:

$$q"_{conv} = h \cdot \Delta T \tag{2}$$

Where h is the heat transfer coefficient. The heat transfer coefficient is affected by several factors, one of which is the fluid motion which increases the heat transfer coefficient [10]. The fluid motion is either induced by force or internally in the fluid itself. This is described respectively as forced or natural convection. Forced convection often induces a higher heat transfer coefficient due to higher velocities, but natural convection also needs to be taken into account.

2.1.3 Overall heat transfer coefficient

A system with a different surface temperature than the surroundings will experience heat transfer due to the processes described above, along with radiation. The magnitude of heat loss is determined by the amount of thermal resistance in the system together with the difference in surface temperature in regard to the ambient. The heat transfer of a system consisting of several materials with varying thermal resistance can be determined using the overall heat transfer coefficient, U. The heat transfer, Q, can be expressed by equation (3) [10]:

$$Q = U \cdot A_s \cdot \Delta T \tag{3}$$

Where A_s is the total surface area, and U is given by equation (4), where R_{tot} is the sum of thermal resistances in the system.

$$U = \frac{1}{R_{tot}} \tag{4}$$

The primary method for lowering the heat exchange between an object and the environment is wrapping the system in thermal insulation with low thermal conductivity. This serves three purposes. Adding a layer of insulation with low thermal conductivity increases the thermal resistance of the system. It hinders the movement of gasses around the system, decreasing the heat transfer coefficient. Finally, it decreases heat loss to radiation due to lowering the temperature of the surface area exposed to the surroundings.

2.2 Thermal Energy storage

Thermal energy storage, also known as TES, is a technology that has received much attention in recent years. In a TES, energy is stored either as sensible, latent, or thermo-chemical heat. Each comes with advantages and disadvantages, but this thesis will only focus on sensible heat storage. A TES system allows the user to store energy for either short or long durations of time, depending on its design and use. This makes the system optimal for shaving down peak loads and reducing the discrepancy in energy demand and production [11]. This allows for the use of smaller equipment, which in turn can reduce costs. TES systems can either be used for heating or cooling, depending on the application.

The complete storage process of a TES system is shown in figure 2.1. The cycle consists of the charging process where heat or cooling is added to the system. This energy can then be stored for a given amount of time, depending on the system, before being discharged in the final step. Here the stored heat or cooling can then be supplied to the intended process. Many TES systems involve charging and discharging continuously.

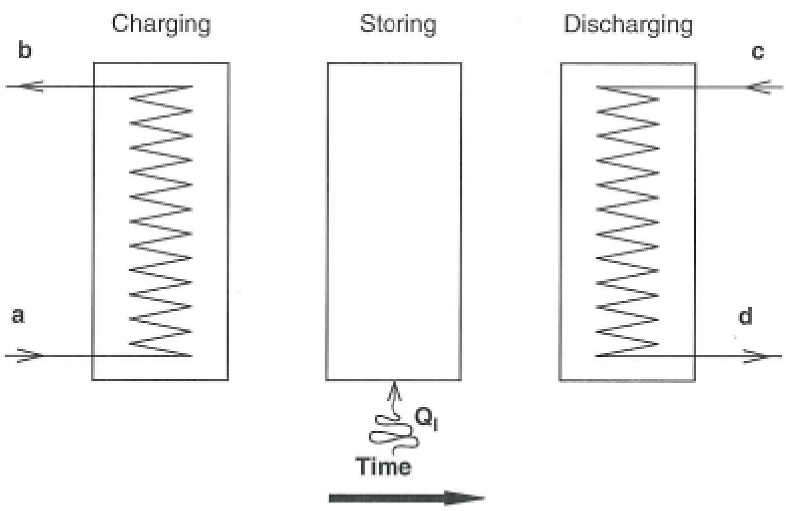


Figure 2.1: TES charging and discharging cycle [12]

The discharging efficiency, η_{dis}, of a SHTES can be expressed by equation (5) [13]:

$$\eta_{dis}(\%) = \frac{Energy\,output}{Energy\,input} * 100 \tag{5}$$

2.2.1 Sensible heat storage

SHTES, is a TES system that stores energy due to a temperature difference of its storage medium with the surroundings [11]. The system utilizes either solids or liquids as the storage medium or a combination of the two. The amount of energy stored depends on the mass of the storage material, m, specific heat capacity, C_p, and the average temperature difference of the system with its surroundings. This is shown in equation (6), where T_m is the average temperature of the system, and T_0 is the ambient temperature. T_m is calculated based on equation (8).

$$Q = (T_m - T_0) \cdot C_p \cdot m \tag{6}$$

For mixtures, this can be found by utilizing the average specific heat capacity. For a mixture of component 1 and component 2, with ω being the mass fraction m_1/m_{total}, this is given by the relationship:

$$C_{p(mixture)} = \omega \cdot C_{p(1)} + (1 - \omega) \cdot C_{p(2)} \tag{7}$$

When selecting the heat storage material for a SHTES system, other factors such as the working temperature of the system and lifespan of the medium need to be considered. Some storage mediums such as water will start to boil at low temperatures under atmospheric pressure. This eliminates water as a storage medium for several industrial processes that require high-temperature systems [12]. Other materials such as rocks can experience thermal stresses under high temperatures causing them to crack due to differential expansion of mineral grains [14]. Selection of the proper storage medium is therefore important for the functionality of a SHTES system.

2.2.2 Thermal stratification

SHTES systems of equal storage capacity can vary significantly in the amount of usable energy. Depending on local temperature variations in the system compared to the environment, the amount of usable energy can change [15]. SHTES can either store energy with a fully mixed storage, meaning of uniform temperature, or with thermal stratification. A thermally stratified storage stores energy with a temperature gradient in the storage, meaning with non-uniform temperature. The process of achieving thermal stratification is described later on. The study of usable energy in a system is described by the exergy content, E_x, and exergy is defined as the maximum useful work possible during a process that brings the system into equilibrium with its surroundings [16].

The exergy content of a SHTES can be calculated using the calculation method described by Rosen [17], where only a summary will be shown here. The calculation method is based on the assumptions of a SHTES of height H, with one-dimensional temperature variation with height z in the vertical direction and constant cross-sectional area. The C_p and T_0 are assumed constant over the entire temperature range of the system. The average temperature of the system can be expressed as equation (8), while T_e in equation (9) represents the equivalent temperature of a fully mixed SHTES that has the same exergy content as the stratified equivalent SHTES.

$$T_m \equiv \frac{1}{H}\int_0^H T(z)\,dz \tag{8}$$

$$T_e \equiv exp\left(\frac{1}{H}\int_0^H ln\,T(z)\,dz\right) \tag{9}$$

The exergy content of the storage can be expressed as equation (10).

$$E_X = Q - m \cdot C_P \cdot T_0\,ln\left(\frac{T_e}{T_0}\right) \tag{10}$$

As the stored energy of a SHTES is calculated using T_m, the stored energy of a fully mixed and a stratified SHTES is equal. However, based on equation (10), the exergy content of a thermally stratified SHTES will always be higher than for a fully mixed storage. The available energy is, therefore, higher for a stratified SHTES [17].

Thermal stratification is the process of separating the storage medium into layers with different temperatures. The process is driven by the change in buoyancy due to variations in density of fluids at different temperatures described in section 2.3. This will cause hot fluids to rise upwards, while colder fluids will move towards the bottom of the storage. The layer that separates the hot from the cold medium is referred to as the thermocline. This layer has an abrupt temperature gradient steeper than layers above and below. The thinner the thermocline, the more thermally stratified the tank is. For a SHTES illustrated in figure 2.2, thermal stratification can be achieved and maintained by minimizing mixing of the storage medium and insulating the tank [12]. Mixing is kept to a minimum by only adding or removing cold medium at the bottom of the storage and hot at the top carefully through diffusers. Eventually, without the supply of energy, the stratification in the tank will diminish due to internal conduction and heat loss to the surroundings.

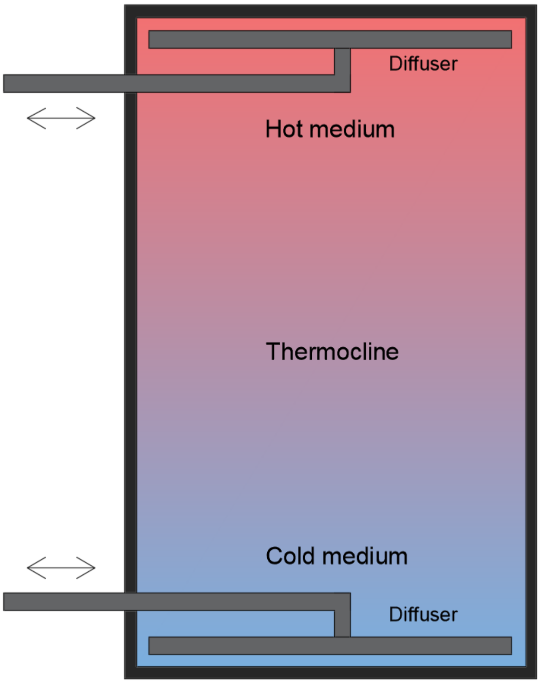


Figure 2.2: Thermally stratified SHTES

2.3 Natural circulation loop

Natural circulation loops have received significant attention in recent years due to their ability to convey heat without the use of pumps, and therefore low energy use [18]. Natural circulation is a fluid flow induced by density changes, much in resemblance to natural convection, but the heat transfer coefficient is not studied. Natural circulation can occur in a system consisting of a heat source and sink connected through pipes or open pools and can therefore convey heat passively. A simplified natural circulation loop is illustrated in figure 2.3.

The natural circulation process is driven by thermally induced density gradients of the fluid in the loop [19]. The supply of energy through the heat source heats the fluid, causing it to expand. This, along with the effect of gravity, induces buoyancy forces, F_b, in the fluid. The induced buoyancy force can be expressed as shown in equation (11) [20], with g being gravitational acceleration, andΔV given by equation (12). The equation shows expansion as a result of change in temperature, with ρ_{old} and ρ_{new} being the density before and after expansion. The induced buoyancy force, forces hot fluid upwards while cold fluid downwards. The density difference, as well as height for open systems between the two liquid columns, is what induces natural circulation. Therefore the taller the system is, the larger the induced forces will be. The induced mass flow rate, $\dot{m}$, due to natural circulation under steady-state conditions can be determined from the retarding pressure drop in the system and the thermal driving forces. This can be expressed through equation (13) [21], where R_h is the hydraulic resistance consisting of pressure loss through pipe flow and loss in single components.

$$F_b = \rho \cdot g \cdot \Delta V \tag{11}$$

$$\Delta V = V_{initial} \cdot \left(\frac{\rho_{old}}{\rho_{new}} - 1 \right) \tag{12}$$

$$\int -g \cdot \rho \, dz = \frac{R_h \cdot \dot{m}^2}{2 \cdot \bar{\rho}} \tag{13}$$

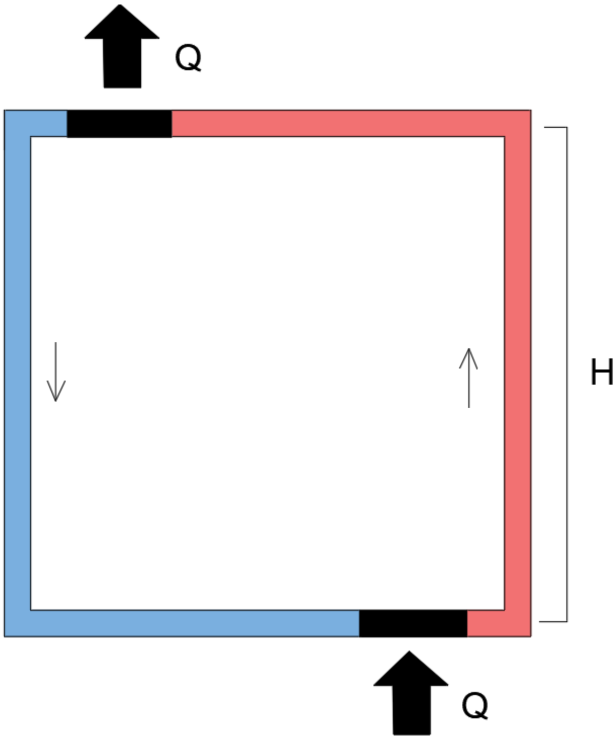


Figure 2.3: Simplified natural circulation loop

2.4 Pressure

The pressure, P, in a stagnant liquid, is dependent on the height of the liquid column, the density of the liquid, and gravity. This is given by equation (14):

$$P = \rho \cdot g \cdot z \tag{14}$$

The volume change due to the thermal expansion of a medium is proportional to the change in density, as shown in equation (12). In a closed container of constant cross-section, thermal expansion of a medium will therefore not result in a change of pressure, due to the change in height equalizing change in density.

2.4.1 Pressure loss pipe flow

A fluid flowing in a pipe will experience pressure loss due to friction forces acting on the fluid. The pressure loss is highly dependent on the velocity of the flow, the flow regime in the tube as well as the roughness of the pipe. The flow regime in the pipe can be described by the Reynolds number, Re_D. For fluid flow in a pipe of constant diameter, this is given by:

$$Re_D = \left(\frac{4 \cdot \dot{m}}{\pi \cdot D_h \cdot \mu} \right) \tag{15}$$

Where D_h is the hydraulic diameter of the pipe, and μ the kinematic viscosity of the fluid.

Depending on the Reynolds number, we can categorize the flow into three different regimes as given in table 2.1. For pipe flow with Reynolds number below 2300, we can assume it to be laminar. Here there is little mixing of the fluid, and the flow will experience the least pressure loss [22]. At Reynolds number above 10 000, the flow can be assumed to be fully turbulent.

	Laminar	Transition	Turbulent
Internal flow	< 2300	2300 - 10 000	10 000 <

Table 2.1: Critical Reynolds number internal flow

As pressure loss is induced by velocity gradients along the surface of the pipe, the development of the velocity boundary layer is important. After the flow's velocity boundary layer is fully developed and properties assumed constant, the pressure loss will be constant. The development of this boundary layer is shown in figure 2.4. This is for laminar flow, as the boundary layer for turbulent flow can often be assumed fully developed at pipe entry due to good mixing in the fluid [22].

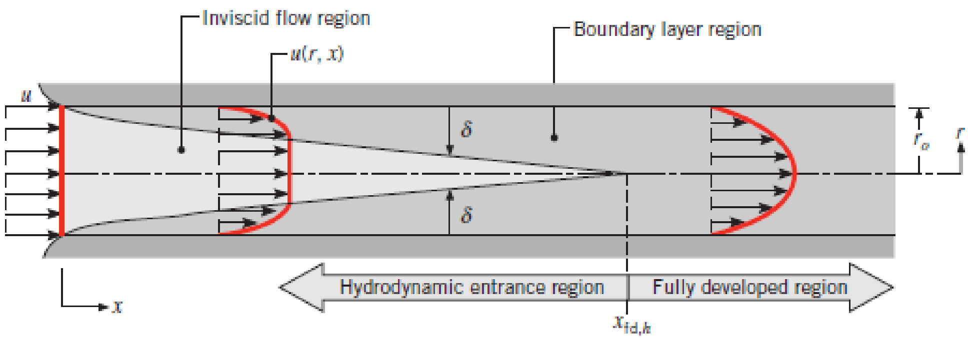


Figure 2.4: Laminar, hydrodynamic boundary layer development in a circular tube [10].

The entry length, $x_{fd,v}$ for the velocity boundary layer to fully develop for laminar flow is given by the equation below [10].

$$x_{fd,v} = 0,05 \cdot Re_D \cdot D_h \tag{16}$$

Pressure loss for fully developed flow in a pipe of a given length is given by equation (17), where u_m is the average velocity of the fluid.

$$\Delta P = f\frac{\rho u_m^2}{2D_h}(x_2 - x_1) \tag{17}$$

The Darcy friction factor,f , is a dimensionless parameter. Depending on the flow regime, this can be calculated using various formulas. For the laminar fully developed case, this is given by:

$$f = \frac{64}{Re_D} \tag{18}$$

2.5 Review of TES for cooking

Several clean cooking solutions have been designed and developed to combat unclean cooking for regions with limited access to electricity and utilities, in particular solar cookers. These can be divided into direct and indirect solar cookers based on their working principle [23]. Direct solar cookers include the box, panel and concentrating type, while indirect the flat plate, evacuated tube and concentrating type [24]. These solar cookers are able to use renewable energy from the sun instead of non-renewable alternatives in the affected areas such as charcoal, kerosene and other harmful fuel sources. Direct solar cookers concentrate sunlight directly onto the cooking vessel, while indirect using a fluid to transfer heat from a collector to the cooking vessel [25]. Due to their working mechanism, they are still limited to operating when direct sunlight is present, limiting them for use during the daytime on sunny days [26]. It is, therefore, necessary to include a TES in the systems to provide cooking in periods of the day with limited sunlight and during nighttime to further improve solar cookers [27, 28].

During the past years, many different solar cookers with TES systems have been investigated. This includes both TES systems based on phase-changing materials, PCM, known as latent heat thermal energy storage, LHTES, and SHTES. Of the LHTES type, a direct box type solar cooker was investigated by Sharma et al. in 2000 [29], an evacuated tube solar collector, ETSC, system by Sharma et al. in 2005 [30], and the implementation of a PCM container with a parabolic type solar cooker by Lecuona et al. in 2013 [31], to mention a few. Several SHTES systems have also been investigated with an indirect SHTES parabolic solar cooking system by Mbodij and Hajji in 2017 [32], and a high temperature combined SHTES and LHTES parabolic solar cooker by Mussard et al. in 2013 [33]. A common factor for most of the systems mentioned above and solar cookers with TES in general [28], is the relatively low working temperature of the systems. Solar cookers can be divided into different categories based on their required temperature range, which is listed in table 2.2. Only the system by Mussard et al. had working temperatures within the frying range of food, with the rest only able to achieve cooking or boiling. It is therefore interesting to further research high-temperature solar cookers able to achieve frying or even grilling, and reduce cooking times.

Use	Temperature range [^oC]
Cooking	[85, 90]
Boiling	[100, 130]
Frying	[200, 250]
Grilling	[300, $->$]

Table 2.2: Temperature range solar cookers [32]

Developing low-cost systems is a significant part in the large scale use of solar cookers [25]. The implementation of TES in solar cookers, therefore, seems counterintuitive due to increased costs due to the added parts and complexity. The implementation of TES is still a significant improvement due to the added function of cooking during non-sunshine hours [34]. Selecting the correct TES materials is therefore important for keeping costs low and increasing the efficiency of the systems. PCM used for LHTES are often of high cost, and SHTES mediums are therefore an attractive option due to being more economical [34]. Further research of high-temperature SHTES for solar cookers could therefore be beneficial.

2.6 Review Oil Pebble SHTES

A topic of interest for use in solar cookers is oil-packed bed TES systems utilizing pebbles as the heat storage medium. Such systems can allow high-temperature SHTES with relatively low costs due to the use of an abundant resource, rocks. The use of oil as the heat transfer fluid, HTF, instead of more commonly used HTF as air or water, can provide higher temperature and more effective systems due to fewer constraints as the difficulty of containment and low boiling temperatures [35]. In the following sections, a brief review of such systems and current research will be given and will provide parts of the foundation of later system design.

Three different SHTES was investigated by Lugolele et al. concerning the performance of charging and discharging cycles, respectively [36, 37]. The experiments compared a TES tank filled with sunflower oil with equivalent tanks of sunflower oil/pebble bed TES tanks. The rock type used was granite with an average particle diameter of 10.5mm and 31.9mm, respectively. The system was charged using an electrical heater and discharged with a heat exchanger, both together with a circulation pump. The maximum temperatures achieved in the systems was 260^oC. The systems were tested with different flow rates for charging and discharging cycles, while studying exergy and energy rates, stratification profiles and more. Results from charging experiments showed that the large pebble TES showed the slowest drop in stratification number for all flow rates, while oil was the largest, suggesting the large pebble TES stores more useful energy than the other systems. Still, the best overall thermal performance for charging was the small pebbles TES system [36]. Results from discharging experiments were highly dependent on flow rates from the storage, resulting in the systems having varying performance compared to each other. The results still showed an enhancement in TES capacity, and the efficiency of a sunflower oil TES tank with the inclusion of a rock bed of 31.9mm granite [37].

Different rock types have been experimental and numerically investigated by Grirate et al. for filler materials for thermal oil thermocline storages [38]. Here six different local rock types from Morocco were investigated being quartzite, basalt, granite, hornfels, cipolin and marble. The study focused on comparing the rocks against each other based on their properties and efficiency for storage, together with thermocline performance. The rocks were compared for temperatures between $T \in [250,\ 350\ ^oC]$, meaning high-temperature systems that can be used for concentrating solar power, CSP, plants and for the lower temperature range, solar cookers. Results showed that basalt appears to be the best storage material for CSP plants due to, amongst others, its large volumetric heat capacity. Still, basalt could not be recommended due to corrosion problems in contact with thermal oil. The study, therefore, concluded that cipolin and quartzite were the best candidates for storage in direct contact with thermal oil [38] .

Several attempts have been made to simulate the behaviour of oil-packed bed TES utilizing pebbles to help aid in the design of SHTES. Mawire et al. have made such an attempt and developed a model with the goal of accurately simulating the axial temperature distribution of a vertical SHTES with small sandy stones during charging and discharging [35]. The model was created using Simulink, utilizing a modified Schumann model. The results from the simulation model were compared to experimental results from an equivalent system powered by a variable heat source with a constant temperature. The storage tank is of 20 l capacity. Comparing results from the simulation model and experimental data showed explicit agreement for the charging process, especially in the range from $T \in [20,\ 140\ ^oC]$, with more significant deviations above 140 ^oC. Discharging results were found comparable with experimental results. It was, therefore, demonstrated that simulation models in Simulink can ensure realistic predictions of TES performance with real experimental data [35].

3 System description

In this section, a description of the Dual Tank System developed in the project "Heat storage for cooking" will be given, together with a description of its ideal behaviour [7]. This is followed by a design review of the system, where the system will be further refined for testing purposes. Finally, the built system will be presented.

3.1 Previously designed Dual Tank System

The Dual Tank System, a clean cooking system, was based on the use of a SHTES as intermediate storage for generated energy to be used for cooking. The size of the SHTES can be varied based on application, but an oil tank of V=0.216m^3 with an internal height of 850mm and a diameter of Ø567mm is selected as the design foundation. The tank can be filled with a liquid heat storage medium of choice or a mixture of solid and liquid medium, with only a few adjustments required based on the selection to account for change in properties. The heat storage medium selected as the basis for the system is a mixture of mineral oil of type Duratherm-630 due to its non-toxicity and thermodynamic properties, and the rock type Chert. From the literature review in section 2.6 it was found that a suitable rock type for an oil-pebble SHTES was quartzite. This is a rock type predominantly consisting of quartz. Chert was selected due to its high quartz content to mimic the quartzite properties, and it is a typical rock type found in SSA [39]. The oil volume displaced in the barrel by rocks depends on the size and shape of the rocks. A displacement of 60% per volume has been used as the base for the design of the system. The oil barrel will be filled to z=750mm with the heat storage medium at an ambient temperature of 20 ^oC. This allows room for the thermal expansion of oil due to the temperature increase when the system is in operation. The Dual Tank System is illustrated in figure 3.1 and 3.2, with the SHTES shown in blue on the left-hand side.

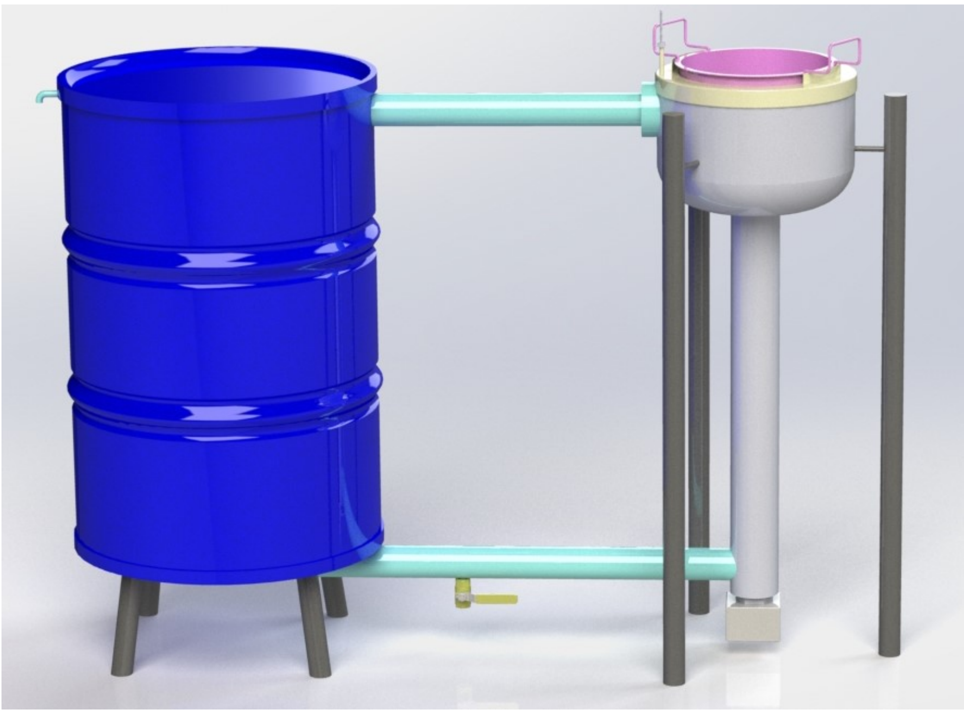


Figure 3.1: Overview of the Dual Tank System

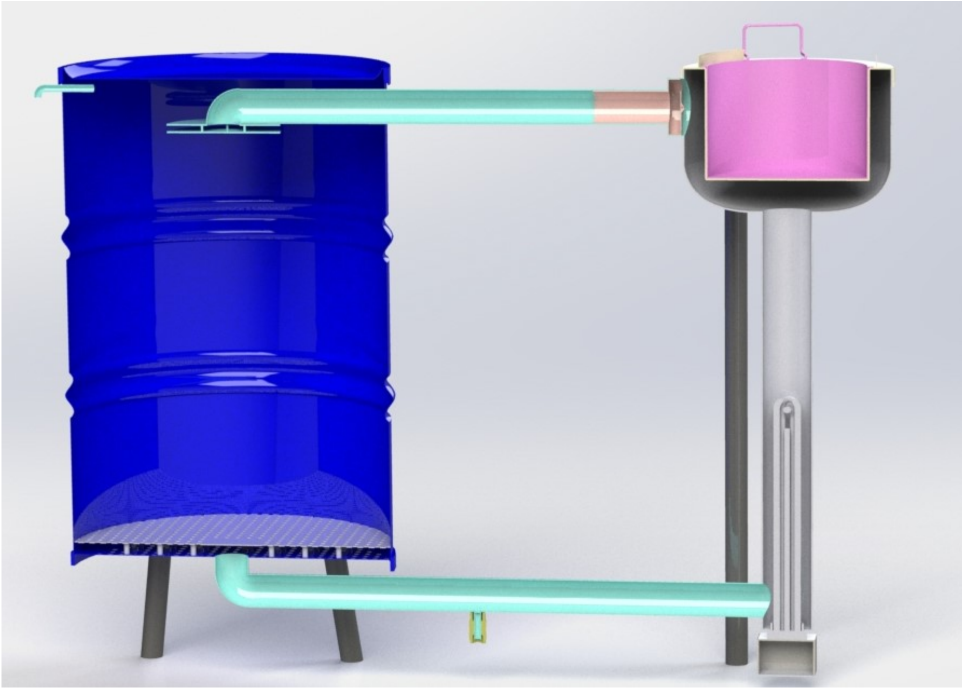


Figure 3.2: Half view of the Dual Tank System

The second tank of the Dual Tank System is the cooker. The cooker is connected to the SHTES through two pipes of Ø60.3x2mm at the top and bottom of the system. The bottom pipe is always open, resulting in the cooker being filled with the same initial oil level as the SHTES. The lower part of the cooker is a tube containing the heating element. The tube has an internal diameter of Ø83mm, and the heating element is 400mm in length with a 1800W capacity. The height and capacity of the heating element can easily be altered if required. The heating element can be connected to an external power source of choice. The tube containing the heating element is welded to the bottom of a standard end cap and has an internal diameter of Ø350mm, with a wall thickness of 3mm. The end cap is 89mm tall and has a ring of 167mm height welded to the top to increase its length. This allows for placing a cooking pot at the top where food can be cooked or water boiled. The pot at the top is a pot in pot solution, with the outer pot in direct contact with the oil in the cooker at all times. The outer pot is welded to a lid attached to the extended end cap. This forms a mechanical barrier between the cooker and potential water that could enter the system, drastically reducing the possibility of injury. The outer pot is Ø280mm in diameter and 193mm deep. The inner pot is made to a tight fit inside the outer pot and has an internal volume of 10.9L. Between them, a small amount of oil is added to increase the heat transfer coefficient by replacing otherwise present air between the pots. Both the cooker and the SHTES are supported by stands of Ø40mm pipe. The final height of the cooker is 1090mm, and the cooker can be seen on the right-hand side in figure 3.1 and 3.2.

The Dual Tank System allows cooking through natural circulation due to thermal expansion of oil. When heat is added to the system, the oil on the cooker side will start to expand. The oil will expand by approximately 18.7%, over a temperature range of 200 ^oC from ambient temperature based on data from Appendix A4 and equation (12). This results in the oil height in the cooker will increase by 53mm. As heat is only added to the cooker side of the system, the heat storage medium in the SHTES will not expand as of yet. Therefore, when the oil level is high enough to reach the entry of the top pipe, the oil will start to flow from the cooker to the SHTES. As the top pipe is placed 18mm above the initial oil level in the system, this will first occur at approximately 100 ^oC due to thermal expansion. Due to overflow, the pressure in the cooker inlet, which is where the bottom pipe enters the cooker, will decrease. This is due to a reduction in height of the liquid column, in turn reducing pressure as described by equation (14). Pressure at the SHTES outlet in the bottom pipe will increase for the same reasons due to the added liquid volume. This, in turn, forces cold oil into the cooker to be heated, initializing natural circulation as described in section 2.3. This process heats the tank and is therefore charging the SHTES.

In periods where there is a need for energy, but the heating element is not receiving sufficient power, the SHTES will be discharged. Here the process will reverse. Oil will be cooled at the interface between the oil and pot due to heat exchange. This causes the oil to contract, increasing its density and reducing the height of the liquid column. The colder oil will start to flow downwards towards the bottom of the cooker, while hot oil from the SHTES flows in at the top. This, in turn, induces natural circulation also while discharging. When the SHTES is fully charged at a uniform temperature of 220 ^oC, the oil level will be at 806mm. This is due to the thermal expansion of the oil and the rocks remaining at approximately constant volume independent of temperature. The ideal charging and discharging process of the system are illustrated in figures 3.3 and 3.4, with the arrows illustrating the oil flow.

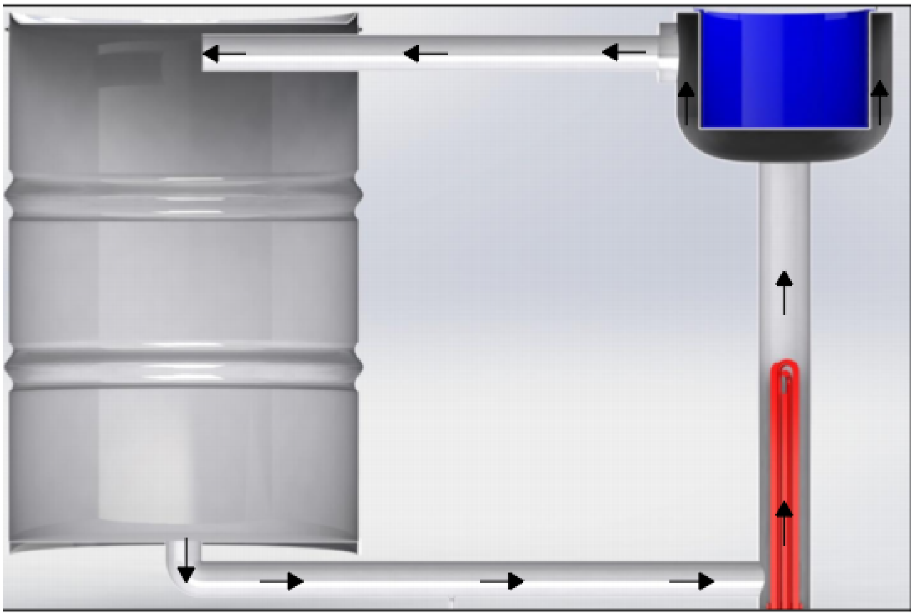


Figure 3.3: Ideal flow during charging

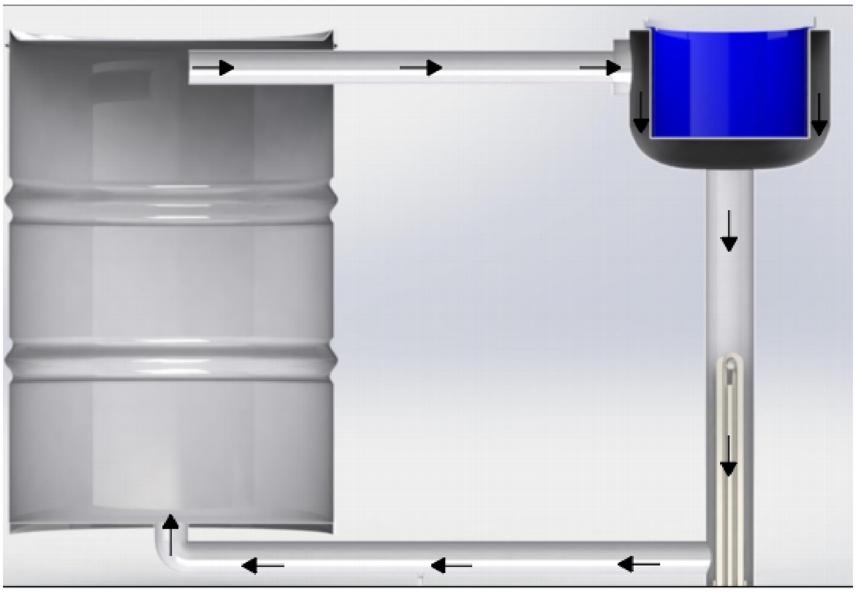


Figure 3.4: Ideal flow during discharging

To improve the thermal stratification in the SHTES, the pipes can both be connected to diffusers to limit mixing. These can be seen in figure 3.5. The bottom diffuser consists of a perforated plate with Ø567mm diameter, placed 20mm above the bottom of the barrel held up by spacers. In the centre of the plate, a 160x160mm area is not perforated, with the bottom pipe entry placed directly underneath. The bottom plate serves two purposes. It protects the pipe from rocks entering it and potentially clogging the system and limits flow from the storage directly above the plate and, therefore, pipe entry, in turn reducing mixing. A top diffuser limits flow in the axial direction, only allowing oil to flow radially into the SHTES.

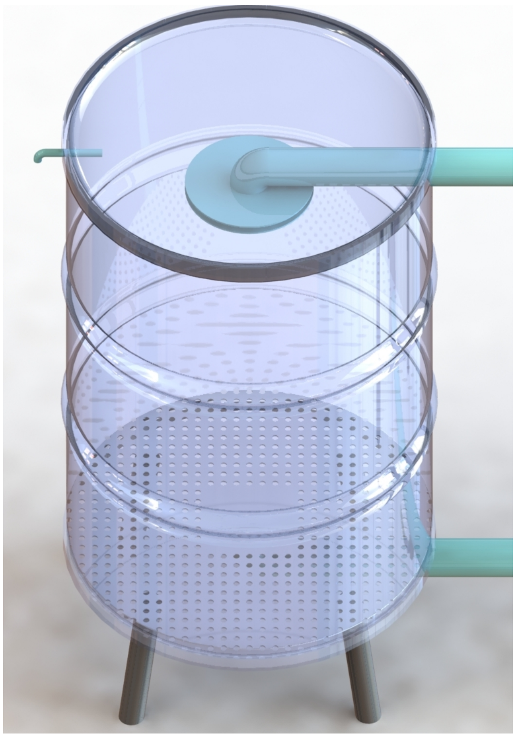


Figure 3.5: Diffuser placement in transparent SHTES

To control circulation in the system, in turn controlling temperatures in the system, a valve was designed to regulate the flow. A drawing of the valve is shown in figure 3.6. The valve consists of two pipes inserted into another, creating a tight fit. An outer pipe is connected to the top pipe between the cooker and SHTES and transitions into a 100x1.5mm pipe welded directly to the end cap. Inside, a smaller pipe with outer dimensions to tightly fit is inserted. The inner pipe is a total of 150mm long, and the tight fit will create a seal to stop oil from flowing between the two pipes due to friction forces overcoming the fluid motion. The inner pipe can be rotated freely, and due to a plate welded to the front, the fluid level can be controlled. This is due to a cut-out in the top, allowing oil to flow in at different heights when rotated. The valve allows for 74 mm control over the height level in the cooker and 57mm from the pipe. It is adjusted by turning a bolt connected to a threaded rod exiting the lid of the cooker. This is shown in figure 3.7 on the left-hand side. The threaded rod is inserted into a slot on the front of the valve. By turning the bolt, the rod moves up or down, in turn rotating the inner pipe by dragging it up or down. The turn rate is limited to 90^o to ensure the valve operates as intended, and it is held in place by two small plates attached to the outer pipe.

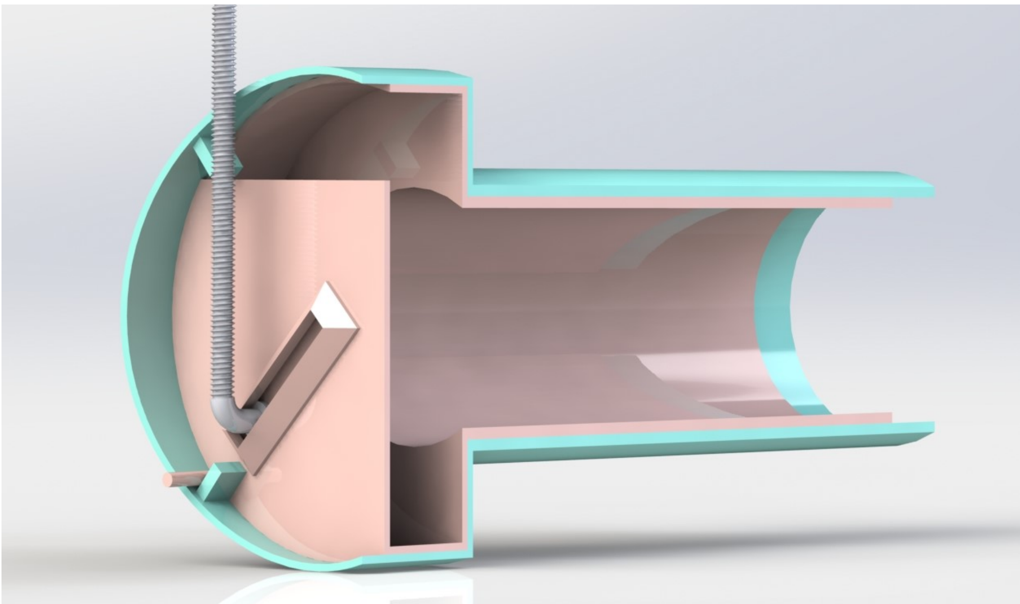


Figure 3.6: Half view of pipe in pipe valve

To further control the heat transfer to the cooking pot, a lifting device for the inner pot has been designed. This is a simple spacer of 20mm height that the handles of the pot can be placed on. This lifts the pot from the bottom of the outer pot, eliminating direct contact with the oil, in turn reducing heat transfer. The pot is lifted manually by the user of the system and placed on the spacers when needed. A closeup of the spacers can be seen in figure 3.7 showing the top of the cooker.

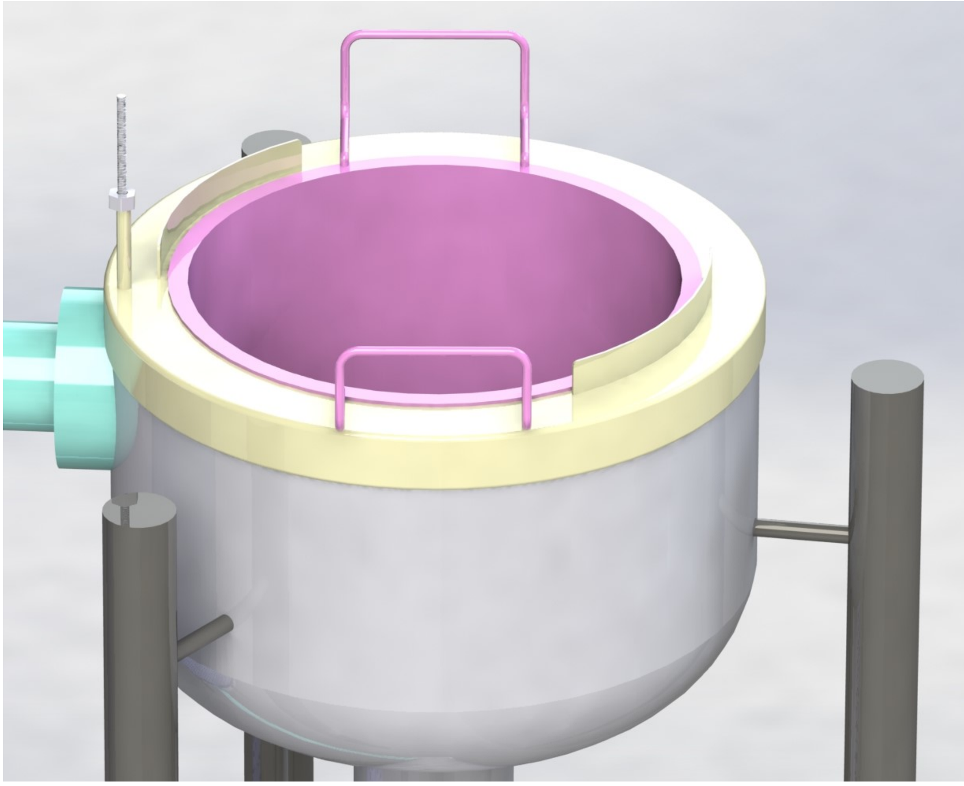


Figure 3.7: Top view cooker

The thermal energy stored in the Dual Tank System determines the amount of food which can be cooked in periods with little to no available power. The stored thermal energy depends highly on the temperature and material used for the heat storage medium. Assuming food can be prepared at heat storage temperatures between [100, 220] ^oC, the amount can be calculated based on the selected heat storage mediums. The density of Chert is 2648 [kg/m^3], with a specific heat capacity approximated to that of rocks with high quartz content at 0.870 [kJ/kgK] [39]. The specific heat capacity of rocks is assumed constant within the working temperature of the Dual Tank System. The entire system contains a total of V=0.114m^3 of rocks and V=0.088m^3 of oil at an ambient temperature of 20 ^oC. This amounts to 300.8kg of rocks and 76.6kg of oil. The specific heat capacity of Duratherm-630 is linear within the temperature range of [100, 220] ^oC, with an average specific heat capacity of 2.39 [kJ/kgK] [40]. Utilizing equation (6) and (7) the available energy can be estimated. This results in a total of 14.8kWh available energy between [100, 220] ^oC assuming the storage is uniformly charged. In a study conducted by Kajumba et al., it was discovered that to cook for one day for an average family of five in rural areas of Uganda requires 2.27kWh of energy using a hot plate [41]. By assuming a similar efficiency for the Dual Tank System, the stored energy in the SHTES would enable the daily cooking for approximately 32 people neglecting losses if fully charged.

The system also contains other features that are important to its functionality. The entirety of the system is insulated to reduce heat loss to the environment and contribute to thermal stratification as described in section 2.2.2. The required thermal resistance by the insulation is to be determined through testing. At the lowest point in the system, which is the bottom pipe, a 1/2 inch ball valve has been implemented. This allows for draining the system of oil to ease transport or maintenance. This can be seen in figure 3.1 in the middle of the bottom pipe. To increase the safety of the system, an overflow pipe of 12x1mm diameter has been placed in the SHTES to reduce the dangers of over-expansion. If the system is initially overfilled with oil, the oil could expand to volumes higher than the system can handle. The overflow pipe ensures the oil is drained from the system in a safe manner if this were to happen.

3.2 Design review

A review was carried out for the pre-designed system. The review focused on several aspects of the system, with the following four points.

- Potential errors which could endanger the safety or functionality of the system.
- Changes that could simplify the system to lower costs and production time.
- Aspects were also reviewed to assist in creating a prototype for testing purposes.
- Adding functionality to the system.

The size of the SHTES in the Dual Tank System was reduced based on testing criteria. The Dual Tank System consists of a SHTES to store generated energy to be used for cooking. The tank size determines along with other factors such as heat loss, the amount of food which can be cooked while discharging the system. Increasing its size results in increased cooking potential, but comes at the cost of increased charging time. The heating element in the system is of limited capacity, and the charging time, therefore, increases linearly with the storage size. The pre-designed Dual Tank System requires 24.2 kWh to fully charge to a temperature of 220 ^oC from ambient, neglecting heat losses. The heating element selected supplies a maximum of 1.8 kW of energy, the charging time is, therefore minimum 13.4h, an inconveniently long time for testing purposes. As a result, the size of the SHTES is reduced to a 100L oil tank. The system is also only filled with oil, removing rocks to ease the potential process of implementing changes to the system. The system will be filled to a height of approximately z=0.52m with oil, which results in a total of V=0.098m^3. The new tank size will therefore result in a charging requirement of approximately 10.7 kWh and a usable amount of stored energy of 6.8 kWh between [100, 220] ^oC based on equation (6). The charging time is thereby reduced to a minimum of 5.9h, which is better suited for testing. By reducing the size of the SHTES, the height of the liquid column of oil is reduced. This, in turn, will reduce the thermal expansion of oil, reducing the driving forces of natural circulation as explained in section 2.3. Therefore if this version of the system achieves cooking through natural circulation, it is expected that the larger version will as well due to larger driving forces. The new SHTES, as well as other changes, can be seen in figure 3.8.

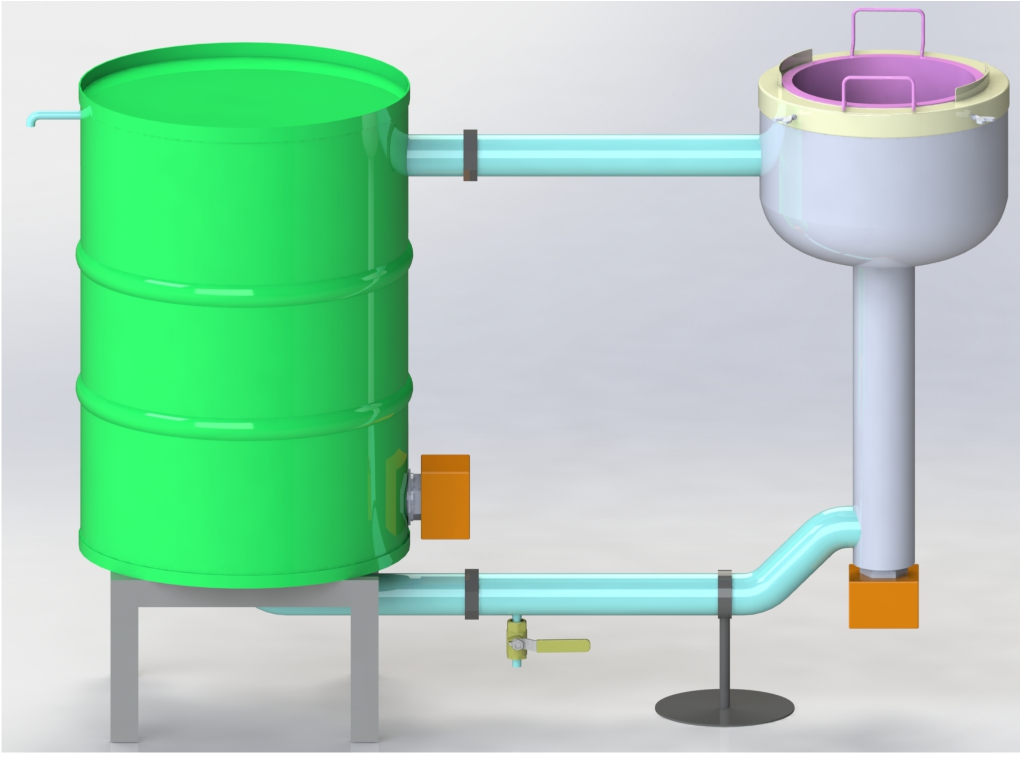


Figure 3.8: Reviewed system overview

The bottom pipe connecting the SHTES and cooker has been redesigned to reduce unwanted oil migration. When energy is supplied to oil in the cooker, the oil will thermally expand with the temperature increase. This induces buoyancy forces causing the oil to flow upwards. The straight pipe connecting the SHTES and cooker shown in figure 3.2 could therefore allow hot oil to flow into the SHTES through the bottom pipe. This is due to heated oil from the lower parts of the heating element could reenter the bottom pipe due to buoyancy forces. This would reduce the thermal stratification of the SHTES due to the mixing of hot oil in the lower layers of the barrel and could negatively affect the natural circulation of the system. The bottom pipe has therefore been redesigned with an angled pipe entering the cooker as shown in figure 3.8. This provides a height difference of Δz = 100mm, and in turn, when hot oil enters the pipe, it should flow back into the cooker for the same reason mentioned above.

A secondary heating element was designed to be implemented in the system to allow for the simultaneous use of multiple energy sources. This results in a decreased charging time due to the added capacity of the secondary heating element. It would also allow for continuous charging even during the night if an energy source such as wind power is utilized. Placement of the heating element in the system causes difficulties due to space requirements and the thermodynamic effect on the system. Space requirements determine the heating element to be placed directly into the SHTES. This will potentially destroy thermal stratification if placed at a low height due to internal circulation as an effect of buoyancy forces, or cause local overheating if placed high when the cooker is not under load. The heating element is selected to be implemented at the lowest point in the SHTES to reduce the risk of overheating, with the effect on the thermal stratification to be further studied. The placement has caused the bottom diffuser to be extended to z=100mm to protect the heating element from the potential use of rocks if utilized as part of the heat storage medium. The placement of the heating element is as shown in figure 3.9.

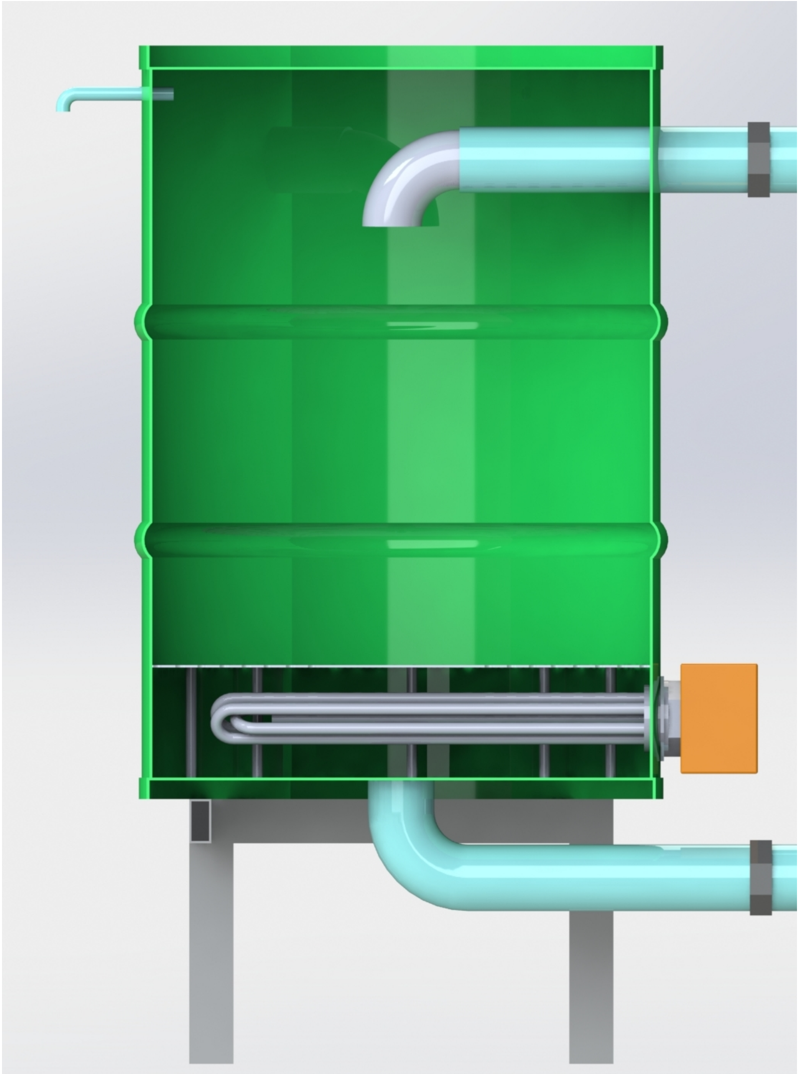


Figure 3.9: Heating element placement SHTES

The system has been simplified to ease production requirements for a working prototype. The Dual Tank System contains a valve connected to the cooker as shown in figure 3.6. Removing the more complicated valve system and replacing it with a simpler but less controllable valve lowers production requirements. This is done by installing a new valve named the turning valve in the top pipe, which is based on a tightly machined fit between two pipes, but with the valve placed directly into the SHTES. The valve is a 90^o pipe bend that, when turned sideways, controls the height level oil is allowed to escape or enter. The valve provides 100mm of controllable height and is illustrated in figure 3.10. To turn the valve, the SHTES needs to be opened and manually rotated. This new valve is therefore not viable for the final system as it severely compromises safety. As an effect of the new valve, the top diffuser in the SHTES has been removed.

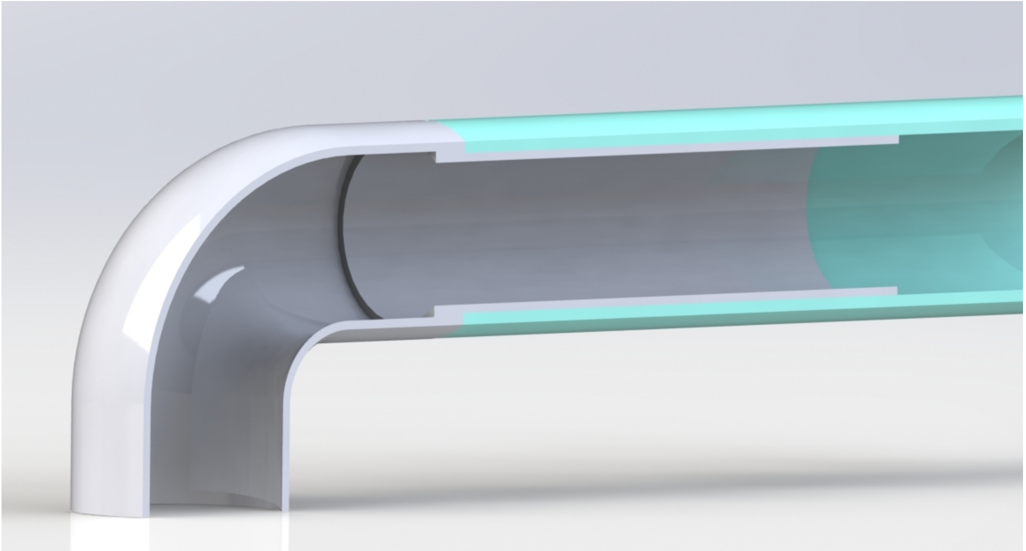


Figure 3.10: Half view turning valve

Technical drawings of the reviewed system and its components is in Appendix A3.1, with dimensions listed in mm.

3.3 Built Dual Tank System

The built Dual Tank System was in its entirety thermally insulated using two different insulation materials. The insulation materials used were ISOFRAX®1260 FILT of 18mm thickness and Fyrewrap of 50mm thickness. The respective U-values are 4.44 W/m^2K and 0.64 W/m^2K [42, 43]. These insulation materials were selected based on their fire resistance within the temperature range the system operates within. ISOFRAX®1260 FILT was used to insulate the cooker top externally. The top and bottom of the barrel were insulated using both a layer of ISOFRAX®1260 FILT together with Fyrewrap, and the rest of the system was insulated using a single layer of Fyrewrap. A thin layer of insulation was also added between the stand and cooker to break the thermal bridge that would occur if the two metals were in contact. The average overall heat transfer coefficient of the system is experimentally determined in section 4.4.

The completed Dual Tank System can be seen in figure 3.11, 3.12 and 3.13. The orange compound around the top pipe in figure 3.12 is a sealant capable of withstanding high temperatures. The insulation of the system, together with the thermocouples, which will be referred to as TCs, placed throughout the system is shown in figure 3.12. The orange straps around the insulation serve the purpose of holding the insulation in place. The system was constructed without the spacers at the top of the cooker and without the secondary heating element, as this is not the main focus of testing.

Figure 3.11: Completed Dual Tank System left view

Figure 3.12: Completed Dual Tank System right view

Figure 3.13: Completed Dual Tank System with insulation without the barrel lid

4 Preliminary testing

In the following section, a description of the experimental setup, results, and discussion of preliminary testing of the Dual Tank System will be given. The experiments are grouped into tests regarding charging, storage, and discharging of the system.

4.1 Objective

To validate and understand the Dual Tank System, thorough testing is required. Based on the results from testing, the system can be further developed and improved to provide clean cooking as efficiently as possible. A set of preliminary experiments was therefore completed with the configuration described in section 4.1.1. Through experiments, the following were to be tested for the simplified Dual Tank System:

- Can the SHTES be charged through natural circulation by supplying power from the heating element
- Does the SHTES thermally stratify and remain stratified through charging, discharging, and storage
- Can cooking be achieved from different power levels using the heating element
- Is the insulation sufficient to maintain temperatures usable for cooking over time
- Is sufficient natural circulation achieved to sustain cooking while discharging the SHTES
- Can the Dual Tank System and cooking be regulated through the valve

4.1.1 System configuration

To test the Dual Tank System, the oil level was filled to z=0.52m, amounting to a total of V=0.098m^3 of oil in the system. To easier observe changes in heat transfer to the cooking pot during experiments, a single pot solution was chosen instead of the pot in pot solution. This significantly decreases the thermal resistance between the oil and what is being cooked, and makes it easier to observe the temperature distribution in the cooker top.

4.2 Definition of Terms

In the following sections, a list of terms will be used to describe the experiment course. Below is a list of these terms together with their definition.

- **High power**: 1800W of power supplied to the heating element
- **Low power**: 580W of power supplied to the heating element
- **Overflow**: When oil is allowed to flow between the two tanks through the top pipe. This is illustrated by the oil level in figure 4.1, and can occur in both directions.

The remaining terms are the turning valve position, which is described in the following list.

- **Fully upwards:** Valve is turned to its highest point, resulting in the highest overflow temperature, and can hinder overflow in its entirety.
- **Fully downwards:** Valve is turned horizontally, removing the valve as a barrier, resulting in the lowest overflow temperature.
- **Middle:** Valve position is between Fully upwards and Fully downwards
- **Turned upwards:** Valve is turned further upwards from its current position, resulting in higher overflow temperature or hindering overflow.
- **Turned downwards:** Valve is turned further downwards from its current position, resulting in lower overflow temperature.

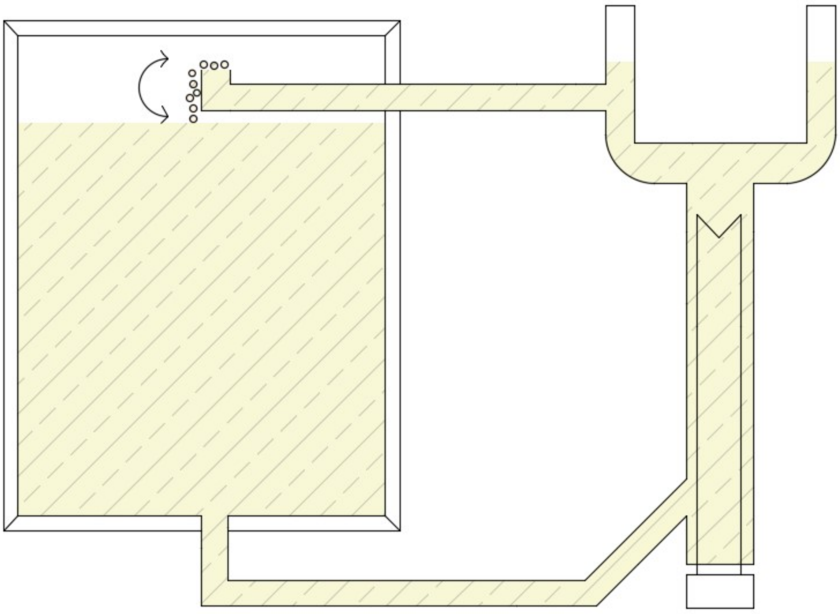


Figure 4.1: Simplified system overview, demonstrating overflow and valve position

4.2.1 Calculations

In the following sections, the energy content and other parameters have been calculated for the Dual Tank System. The definition and method for these calculations are described below.

Extracted energy: Amount of energy extracted from the system through heating water. This has been calculated based on equation (6), using the average specific heat capacity of water within the temperature range.

Total energy: Total amount of energy in the system above ambient temperature. This has again been calculated using equation (6), but is derived by dividing the system into individual zones, calculating the energy content of each zone and then summing them up for the total energy content. The zones are assumed uniform in temperature, with temperature based on TC data. The energy content has been calculated using the average specific heat capacity within the temperature range. The system is divided into nine zones, seven in the SHTES, one in the bottom pipe, and one in the cooker. The distribution of oil is assumed constant through the experiment.

Usable energy: Energy content of oil above T=100^oC in the system. This is calculated in the same manner as the total energy but only accounts for the energy above T=100^oC in each zone.

Cooking efficiency: This is defined as the amount of energy extracted in the cooker compared to the amount of usable energy stored in the system. It is therefore calculated using a modified version of equation (5), shown in equation (19):

$$\eta_{Cook}(\%) = \frac{Extracted\,energy}{Usable\,energy} * 100 \tag{19}$$

4.3 Method

4.3.1 General procedure

Experiments conducted to test the Dual Tank System followed a standard procedure. To regulate the overflow temperature, the valve position was altered in several of the experiments. Due to the expansion of oil with temperature, the valve position also needed to be gradually adjusted to maintain constant overflow temperature when discharging, although rarely. This was done by removing the lid of the SHTES and by using a pipe wrench manually turning the valve. This caused minor local spikes in the temperature measurements from the SHTES as the TCs was disturbed in the process. When the valve had been adjusted, the lid was placed back on the SHTES and reinsulated.

During testing, temperatures in the system were kept below T=229^oC to stay below the flash point of Duratherm-630, drastically reducing the risk of fire. This upper-temperature limit was still briefly exceeded for a few experiments to examine if temperatures would drop due to heat transport from natural circulation.

All experiments conducted to test the cooking capabilities of the system were completed using water as the medium to be heated. This was done to standardize testing, as the exact energy required to boil water could be calculated and compared to other tests. A standardized amount of V=5L was used for every test. All boiling tests were conducted with a lid placed on the pot to reduce heat losses to the environment. When boiling occurred, it was either left to boil or replaced with V=5L of cold water.

When the pot was not used for boiling, the pot was insulated for all experiments with the exception of experiment A1. The insulation consisted of three layers of stacked 50mm Fyrewrap insulation contained by aluminium foil placed into the pot, together with a lid to mitigate air circulation. This was done to reduce heat loss from the system and replicate how the system would be used in real life.

All electricity supplied to the heating element during testing was supplied from the Norwegian electrical grid. This was done to make experiments conducted on the system with the same configuration comparable, as the power delivery would be constant and not vary if energy sources such as wind or solar power was used. Electricity was connected to the system through a variable output transformer, able to alter the voltage supplied to the heating element, in turn altering the delivered power to the system. The transformer is shown in figure 4.2, and has a range between [10-230 V]. At 230V, the heating element delivers a total of 1800W of power, while at 130V, the power supplied is 580W.

When conducting discharging experiments, the SHTES was initially charged and then unplugged from the power source for the entire duration of the experiments. The valve was then turned to a position where oil could flow from the SHTES into the cooker when discharging began. To test discharging, boiling tests were completed for each experiment where 5L of cold water was added to the pot, left until boiling, and replaced with 5L of new cold water, repeating the process until the storage could no longer sustain boiling.

Figure 4.2: Variable voltage transformer used for testing

4.3.2 Experimental setup

To closely monitor the system, the Dual Tank System was fitted with an array of TCs. The TCs used were of type K, and were connected to a pico logger. The pico logger allows for the logging of temperatures in the system based on the change in electrical resistance of the TCs with temperature. The pico logger was of the type TC-08 [44], and PicoLog 6 software was used to plot the temperatures [45]. Figure 4.3 shows a simplified system view with the installed TCs marked in blue and the corresponding vertical height shown in table 4.1. The colors visualized in the table correspond with the color of the TC it represents in later graphs.

The TCs installed in the Dual Tank System served different purposes for monitoring the system. TC 1-7 was installed for monitoring the temperature distribution within the SHTES. These allow for the calculation of the energy content and to monitor the thermal stratification of the tank. The amount of measuring points control the resolution of the data and, therefore, the accuracy of the calculations. TCs 4, 4' and 4" were installed to observe any radial differences in temperature in the SHTES. TC 4' was placed at the center of the tank while 4 and 4" 0.11m to each side. TC A and B were installed to monitor natural circulation as an effect of temperature changes in the bottom pipe. TC D, E, and F were installed at the top of the cooker to monitor temperatures around the cooking pot, which determines the amount of energy that can be supplied for cooking. The reason behind installing three TCs around the cooking pot was to unveil potential issues with flow distribution as an effect of natural circulation. A thermocouple, TC W, was also placed in the pot itself to monitor the temperature of water but was first installed after experiment A5 was conducted. Finally, TC C was placed directly onto the heating element to monitor potential overheating of oil as this is assumed to be the hottest point in the system. Values from this TC will not be displayed in figures as it is only used for safety monitoring.

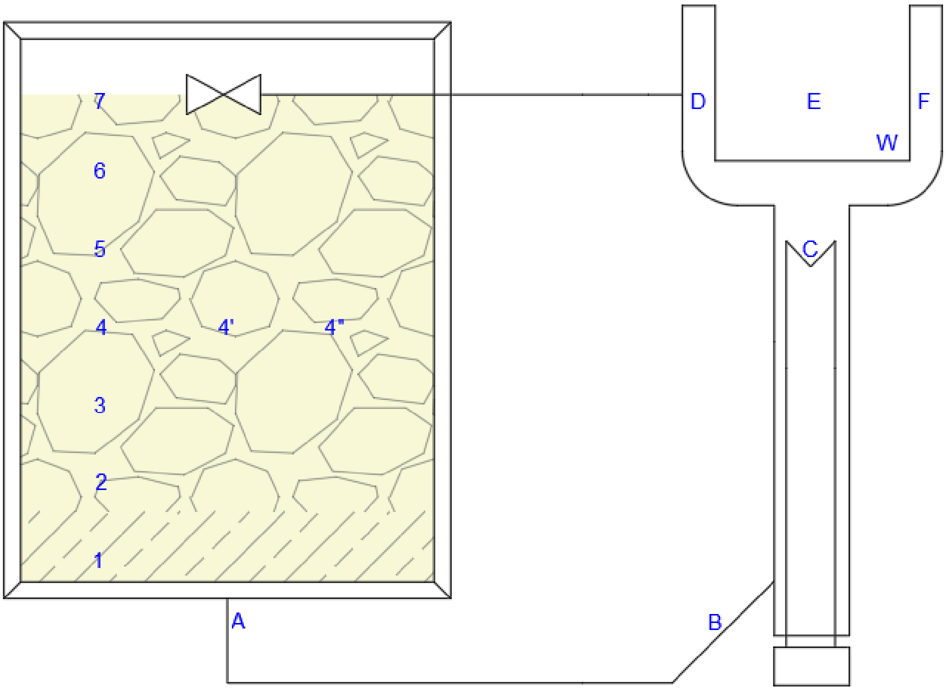


Figure 4.3: Simplified system sketch with TC placement used for preliminary testing

TC	Height	Color	TC	Height	Color
1	3 cm	■	7	51 cm	■
2	11 cm	■	A	- 3 cm	■
3	19 cm	■	B	- 3 cm	■
4	27 cm	■	C	40 cm	-
4’	27 cm	■	D	51 cm	■
4”	27 cm	■	E	51 cm	■
5	35 cm	■	F	51 cm	■
6	43 cm	■	W	-	■

Table 4.1: TC placement measured from the bottom of the SHTES and according color code used when illustrating temperature distribution in the system

4.3.3 Faulty temperature measurements

Through the course of experiments on the Dual Tank System, a few of the TCs in the system have registered faulty data. This is the case for TC 7 in experiments A1 and A2. For experiments A1 and A2 in respectively Appendix A1.1 and section 4.4, TC 7 shows highly fluctuating data for the measured temperature. This was due to an error where the TC was placed too high in the tank. Therefore, when oil started to flow into the top pipe and the oil level in the SHTES dropped, the TC did not make contact with the oil. For the other experiments, this was not an issue as the initial oil level was high enough to always cover the TC. TC B, which is placed at the bottom inlet in the cooker, also appears to log faulty data but throughout the entire experiment course. The TC registered lower temperatures than all other TCs in several experiments and had rapid fluctuations in measured data inconsistent with what is expected based on system behavior. The behavior is assumed to be from thermal contact with the pipe wall. Due to its placement repositioning the TC is very difficult. As an effect, data from TC B has been removed from all experiments but is kept in experiment A4 to illustrate the behavior.

Several of the TCs in the system show small rapid fluctuations in temperature. This can, for instance, be seen in figure 4.4 for TC C and D with lines of varying thickness. This is either experimental noise, or a boundary layer effect as the fluctuations are only viewed in TCs placed close to surfaces

4.4 Charging experiments

Several experiments were conducted to test the behavior of the Dual Tank System while being supplied with energy from the heating element (Charging). The experiments include, among several others, testing system behavior while cooking and the thermal stratification of the SHTES when supplied with energy. A list of the goals for the conducted charging experiments, together with their initial setups, is shown in table 4.2. In this section, the experimental course and results from experiments with significant findings will be presented, with the remaining experiments presented in Appendix A1.1.

Experiment	Goal
A1	Testing general system behaviour and measuring equipment
A2	Testing high power cooking and stratification of the SHTES
A4	Testing charging with high initial temperatures in the SHTES
A6	Testing valve regulation
A8	Controlling boiling rate while charging
A10	Testing low power cooking

Experiment	Water	Valve position	Power	Avg temp cooker	Avg temp SHTES
A1	T=25^oC	Fully downwards	High	T=21^oC	T=21^oC
A2	T=22^oC	Fully upwards	High	T=21^oC	T=24^oC
A4	-	Middle	High	T=55^oC	T=106^oC
A6	-	Fully upwards	High	T=42^oC	T=78^oC
A8	T=11 ^oC	Fully upwards	High	T=40^oC	T=73^oC
A10	T=10^oC	Fully upwards	Low	T=19^oC	T=23^oC

Table 4.2: Initial setup and goal for the charging experiments conducted on the Dual Tank System

Experiment A2, high power cooking

Experiment A2 was the second experiment conducted and aimed to test if cooking could be achieved with high power from an initial cold system, and the following stratification of the SHTES during charging. The initial setup of the experiment is shown in table 4.2. At the experiment start, a sharp increase in temperature for the TCs placed in the cooker can be seen on the left-hand side of figure 4.4, increasing the temperature difference between the pot and oil. This causes heat transfer to the pot, and after only 0.75hours, the water in the pot started to boil. The first dotted line in the figure indicates when the water is removed, which is then followed by a sharp temperature increase in the cooker due to the removal of the heat sink. The second line indicates when the valve is turned down to allow overflow into SHTES, where temperatures in the cooker can be seen stagnating. The valve was turned further down at 1.75h to reduce temperatures in the cooker, which can be clearly seen in figure 4.4. The system was then left to charge without changes before the experiment was terminated after 5.5h.

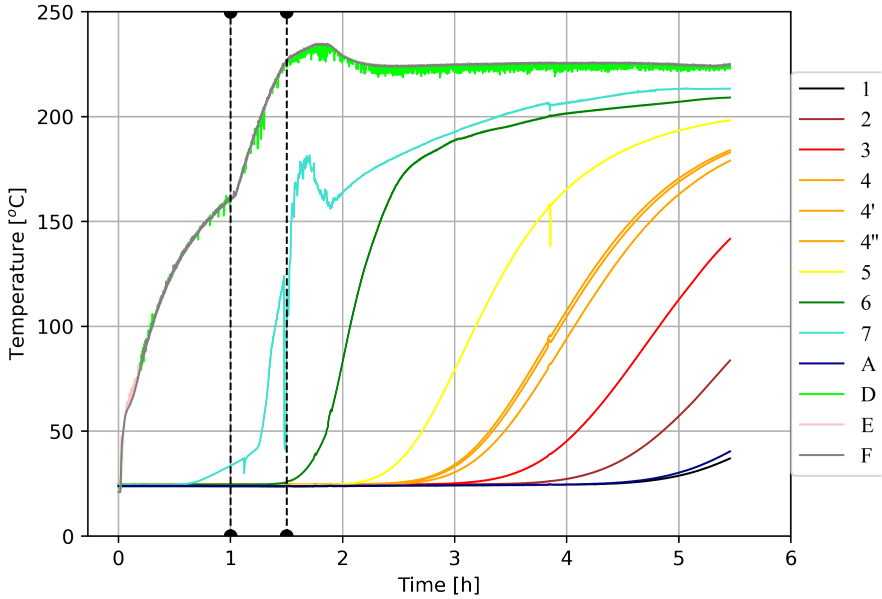


Figure 4.4: Temperature distribution during charging in experiment A2, demonstrating the formation of thermal stratification in the SHTES from an initially cold system

Data from the SHTES clearly show the thermal stratification of the tank during the experiment. TC 7, which is the highest placed measuring point in the SHTES, shows a temperature increase after approximately 0.75h. This was while the valve was turned fully upwards, which should hinder the overflow of hot oil from the cooker and thereby most heat transfer. This was due to an internal leakage in the valve, which was observed through visual inspection of the system. The rapid changes in temperature were due to the TC being placed too high in the oil, as explained in section 4.3.3. While TC 7 drastically rises in temperature, TC 6, placed in the next height interval, slowly begins to register a temperature increase after 1.5h. This is followed by a sharp rise in temperature before again stagnating, showing a moving thermocline in the storage. TCs placed in descending height experience similar behavior over the following hours, but with less and less sharp temperature increase. The temperature profiles in the SHTES are illustrated in figure 4.5, showing the temperature distribution over time. At the end of the experiment, the SHTES can clearly be seen thermally stratified with TC 7 reading T=213 ^oC, while TC 1 reading T=37 ^oC. During the experiment, data from TC 4, 4' and 4" show only minor differences in the radial temperature distribution in the SHTES. These follow the exact same pattern throughout the experiment, and the small temperature difference between the TCs was most likely due to small height differences when installing them.

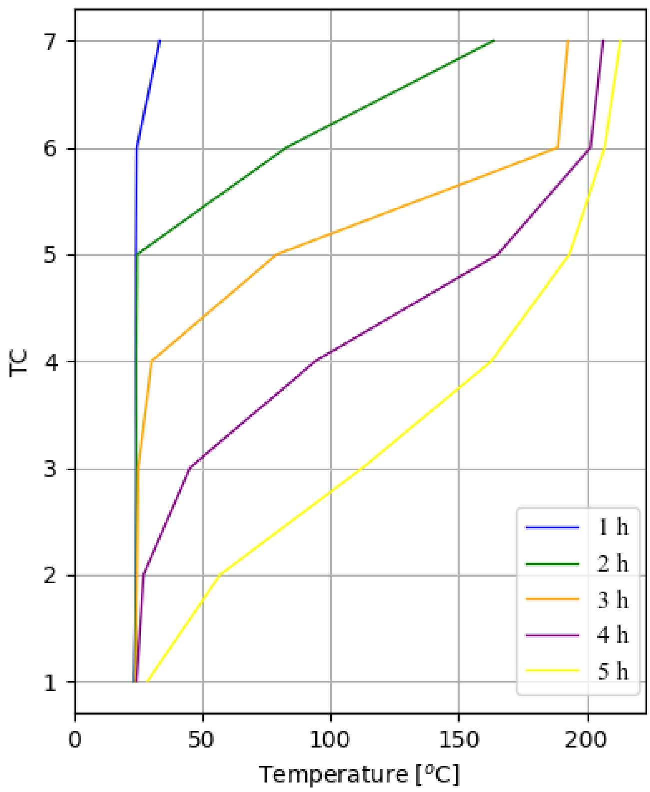


Figure 4.5: Temperature distribution in the SHTES over time in experiment A2, illustrating a moving thermocline. TC 7 is the highest, while TC 1 the lowest in the SHTES

Experiment A10, low power cooking

Experiment A10 aimed to test the Dual Tank Systems capabilities in regards of low power cooking. The initial setup of the experiment was, therefore, as shown in table 4.2. The experiment course is shown in figure 4.6, and as can be seen, the temperature in the pot, shown by TC W, increased linearly before boiling was achieved after 139 minutes. Concurrently with the temperature increase in the cooker and pot, temperatures in the SHTES remained constant, showing overflow did not take place and limited heat transfer between them. Therefore the time for boiling achieved is expected to be the lowest possible time with the current setup.

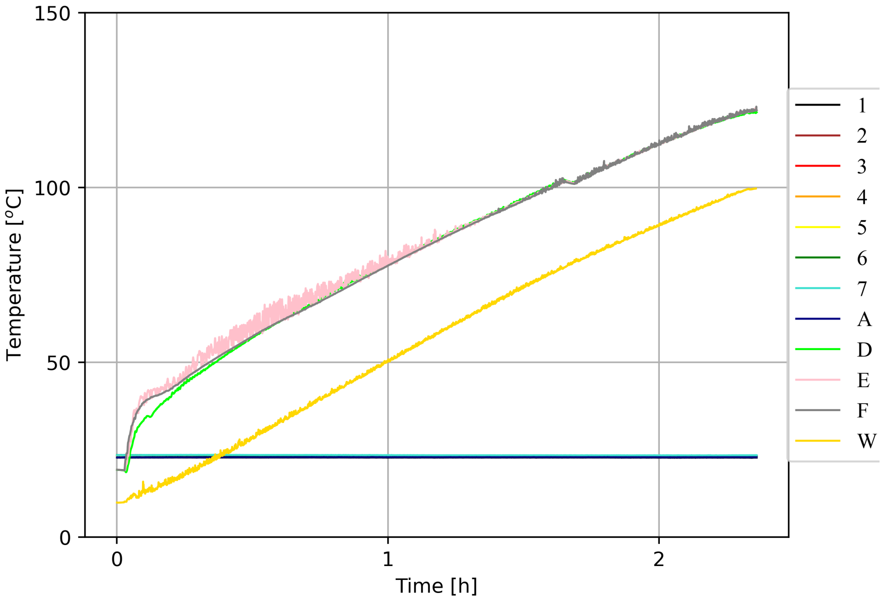


Figure 4.6: Temperature distribution during low power cooking in experiment A10 from an initially cold system

Experiment A6, temperature control using valve

Experiment A6 served two important purposes for testing the system: positioning of the valve and a bubble formation phenomena..

As the Dual Tank System is to be used for cooking, sufficient temperature control in the cooker is important. An experiment was therefore conducted where the system was heated, and the valve was adjusted to different heights during the experiment to see the following effect on the system. This was conducted without using water as a thermal load. The initial setup of the system was as shown in table 4.2, and the results from the experiment are shown in figure 4.7. At the beginning of the experiment, the initial valve position allowed overflow into the SHTES, and as can be seen, temperatures for TC's D, E, and F placed in the cooker quickly began to rise before stagnating at approximately T=150^oC. This is an effect of the natural circulation in the system transporting heat away from the cooker and charging the storage, as can be seen from the increase in readings from TCs in the SHTES. At the first dotted line in figure 4.7, the valve was turned upwards until overflow into the storage was barely achieved. The effect can clearly be seen in the cooker by a sharp temperature increase before again stagnating as the oil level in the cooker rose, and overflow increased. The effect was repeated again at the second dotted line with the exact same effect. The system was then left to charge, and after 3 hours, the temperature in the cooker again began to rise. This happens very close to the rise in temperature for TC 1, which is the oil layer where oil is transported to the cooker through natural circulation. It appears that the clear control through the valve position shown in the first 3 hours, is lost when a steady supply of cold oil is no longer available. Other means of regulating the temperature and thereby heat transfer to the pot may become necessary. This is further tested in experiment A8.

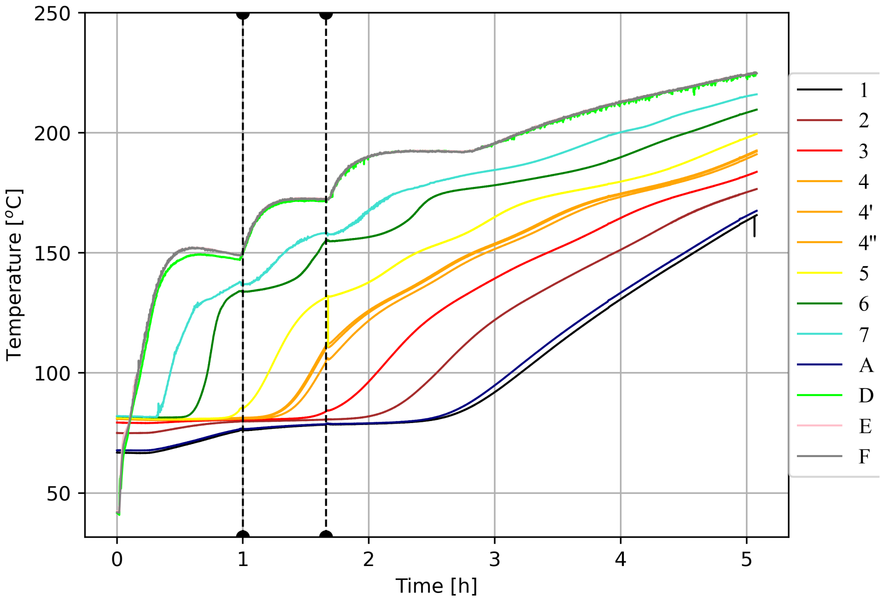


Figure 4.7: Temperature distribution during experiment A6 with high power, demonstrating loss of temperature control with increasing SHTES temperatures

The second purpose of the test was to control the bubble formation phenomena discovered in experiment A4 and described in Appendix A1.1. The phenomena occurred when charging the SHTES, and the temperature in the bottom pipe approached T=125^{o}C. At this point, large bubbles were observed both in the storage and cooker, together with accompanying noises that continued even after power to the system was removed. When charging the storage, close attention was given to the system when temperatures again reached T=125^{o}C. Surprisingly, no bubbles were detected and neither for the remainder of the experiment. The formation of bubbles is therefore attributed to water residue or other contaminants left in the system after the construction and not from system design. It, therefore, seems important to thoroughly clean the system before use for future versions.

Experiment A8, cooking control using valve

In this experiment, further testing of the valve was completed during charging, with the goal of testing if the degree of boiling in the pot could be changed by regulating the valve. This is a continuation of experiment A6 but is now tested for cooking purposes. In the experiment, three different boiling series were conducted with the storage charged to different degrees for the series. All boiling series was completed with high power to the heating element, meaning if successful, regulation should also be possible for lower power levels. The initial setup of the system was as shown in table 4.2. When boiling occurred after experiment start, the degree of boiling was observed, and the valve was then turned fully down. After the system had stabilized, new observations of boiling were then made. The valve was turned fully upwards, water removed, and the system left to charge until higher temperatures were reached, and the test was repeated again. This was repeated for a total of three boiling series. The temperature distribution during the experiment can be seen in figure 4.8.

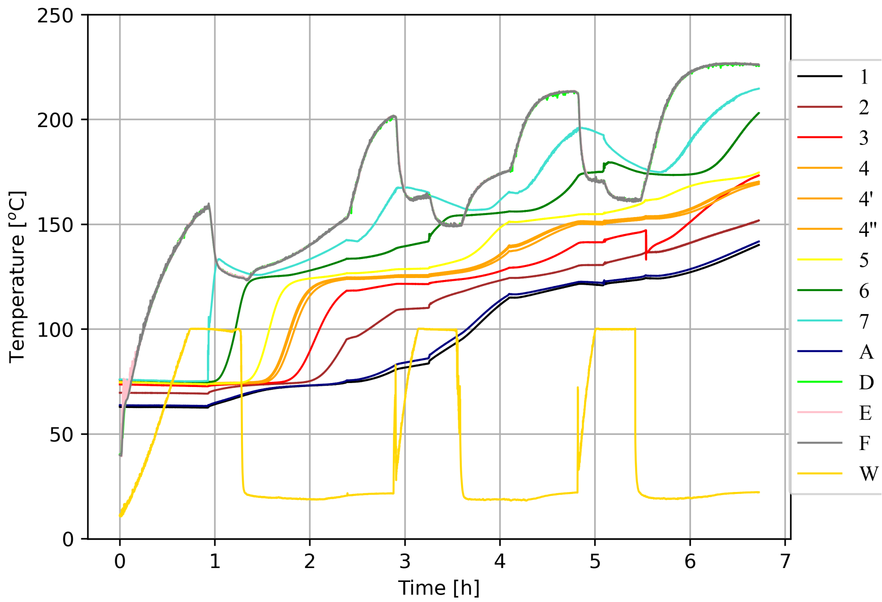


Figure 4.8: Temperature distribution during experiment A8, testing cooking control with high power

During boiling test 1 listed in table 4.3, rapid boiling in the pot was observed when overflow of oil was hindered, shown in figure 4.9a. This was due to the supplied energy to the heating element solely heating the surrounding oil of the pot, increasing the temperature and thus the heat transfer to the pot. When the valve was then turned fully downwards, allowing overflow, the surrounding temperature of oil dropped, as can be seen after approximately 55 minutes in figure 4.8, and heat transfer to the pot reduced. Eight minutes after the valve was initially turned fully down, the boiling intensity changed to only minor simmering, as shown in figure 4.9b, which was the goal of the test. When completing boiling test 2, the same behavior repeated itself, but the switching time between the boiling states was now increased to 15 minutes. When repeating the test for boiling test 3, simmering could no longer be achieved. When analyzing the data from the TCs in the system, the reason becomes clear. The temperature of the oil surrounding the cooker seen in TC D, E, and F are increasing for each boiling series, in turn increasing heat transfer to the pot. This is because, when regulating overflow from the cooker, the overflow temperature can only be regulated to a certain degree. This is due to the temperature of the supplied oil to the heating element through the bottom pipe increases in temperature during charging of the SHTES shown by TC A. Therefore, when supplying energy to the heating element, the already hot oil increases in temperature and becomes the lower limit for temperature in the cooker.

Boiling series	Switching time [min]	Temperature TC A [^oC]
1	8	63
2	15	85
3	-	122

Table 4.3: Time used for boiling intensity to change after adjustment of the valve, together with the according temperature in the bottom pipe

(a) Fully upwards (b) Fully downwards

Figure 4.9: Boiling intensity with different valve position for boiling series 1

4.5 Storage experiments

To test the storage behavior of the Dual Tank System, two experiments were conducted where the system was left to store energy over a longer time period. For both of these experiments, the system was initially charged, and then unplugged from the power source for the entire duration of the experiment. In this section, the results from these experiments will be presented and discussed. The goal of the conducted experiments, together with their initial setups, is shown in table 4.4

Experiment	Goal			
A3	Testing temperature development during overnight storage with overflow			
A9	Testing temperature development during overnight storage without overflow			
Experiment	Valve position	Storage period	Avg temp cooker	Avg temp SHTES
A3	Fully downwards	t=16h	T=215^oC	T=151^oC
A9	Fully upwards	t=16h	T=222^oC	T=174^oC

Table 4.4: Initial setup and goal for the storage experiments conducted on the Dual Tank System

The first storage experiment conducted was experiment A3 which aimed to test the temperature development in the system when the valve was turned fully downwards, allowing overflow and potential natural circulation between the tanks. The temperature development for the experiment is shown in figure 4.10, with "AVG" showing the average temperature in the SHTES. As can be seen, the SHTES slowly decreased in temperature and slowly became less and less stratified as time passed, with the top parts decreasing in temperature faster than the lower in the SHTES. At the beginning, temperatures in the bottom of the SHTES actually increased in value. During the experiment, the average temperature in the SHTES dropped from T=151^oC to T=106 ^oC over the 16 hours storage period. While the SHTES had a moderate temperature drop during the experiment course, the cooker had a significantly higher loss. The cooker dropped from T=215^oC

to just T=56^oC. Thermal imaging completed at the beginning of the experiment in figure 4.11, illustrate the surface temperature of the system. The region with the highest surface temperature is the cooker, which could be an explanation for the larger temperature drop.

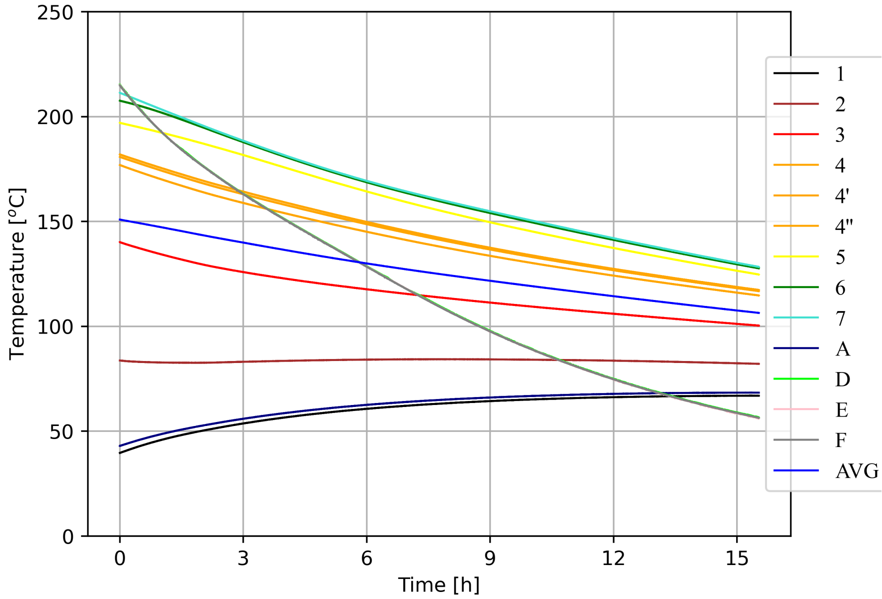


Figure 4.10: Temperature distribution during storage experiment A3, with valve position allowing overflow

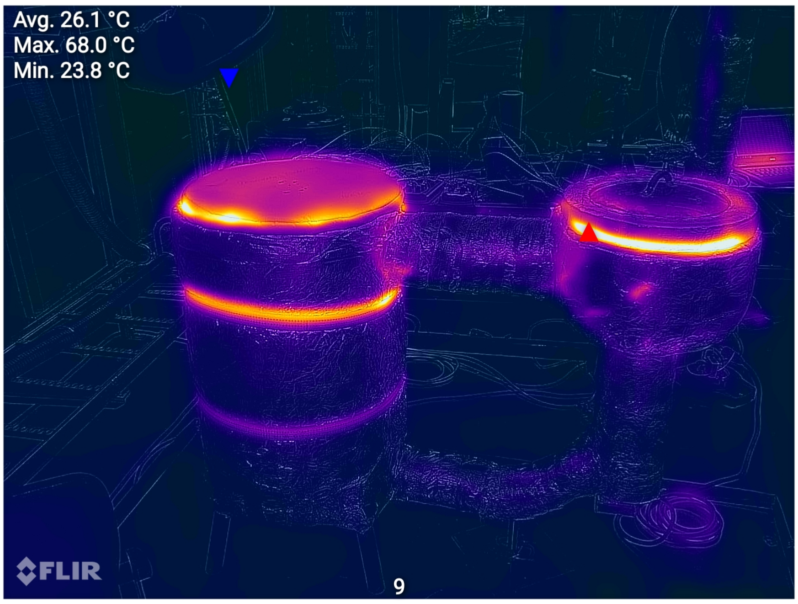
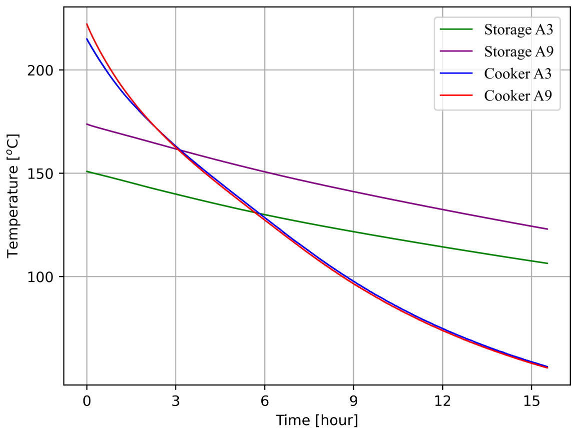


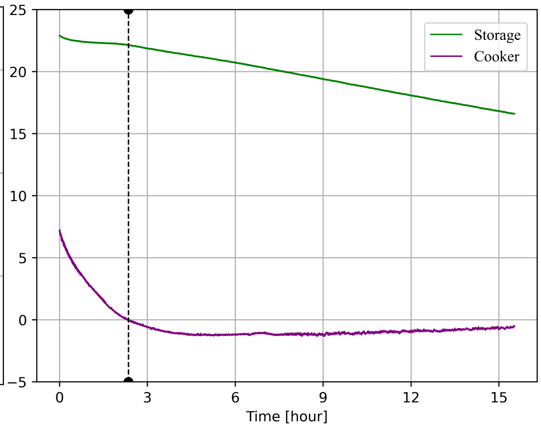
Figure 4.11: Thermal imaging showing local temperature hot spots for experiment A3. The red arrow indicates the hottest point, while blue the coldest

The second storage experiment was experiment A9, and a full description of the experimental course and temperature distribution during the experiment is shown in Appendix A1.2. A summary of the temperature development of this experiment together with experiment A3 is given in figure

4.12. As illustrated by the two graphs, the temperature of the cooker for experiment A9 dropped at a significantly higher rate than A3, as the initial temperature was higher but dropped below A3 after 2.5 hours, marked by the dotted line. For the SHTES, the average temperatures slowly approached each other over time, with experiment A9 having a larger temperature drop.



(a) Average temperature



(b) Average temperature difference (A9-A3)

Figure 4.12: Comparison of temperature distribution during storage experiments A3, and A9

The overall heat transfer coefficient, U-value, has been determined experimentally for the Dual Tank System within the temperature range of the storage process. The U-value is calculated based on the change in the average temperature of oil in the system, estimating the heat loss. The overall heat transfer coefficient was first determined for each increment of measurement, and then an average value was calculated for the entire temperature range. Calculations were completed based on equation (3), with the surface area of the system including insulation amounting to a total of $2.81m^2$. The overall heat transfer coefficient of the Dual Tank System is determined to be **0.61**W/m^2K, between an average temperature of T=177^oC and T=102^oC. The energy content of the system at the start and end of both experiments has been calculated as well using the method described in section 4.2.1 and is listed in table 4.5.

	Experiment A3	Experiment A9
Initial total energy content	7.1 kWh	8.2 kWh
Final total energy content	4.0 kWh	4.8 kWh
Initial usable energy content	3.7 kWh	4.3 kWh
Final usable energy content	0.7 kWh	1.2 kWh

Table 4.5: Initial and final energy content of storage experiment A3 and A9

4.6 Discharging experiments

A large number of experiments were conducted to test the discharging behavior of the Dual Tank System, with mixed results in achieving the objectives listed in section 4.1. In this section, the experimental course and results from experiments with significant findings will be presented, with the remaining experiments presented in Appendix A1.3. The goals of the experiments, together with their initial setups, are shown in table 4.6.

Experiment	Goal
A5	Testing discharging from a near fully-charged SHTES
A7	Testing discharging from a near fully-charged SHTES cooking efficiency
A11	Testing discharging from a semi-charged SHTES
A12	Testing discharging from a semi-charged SHTES
A13	Testing discharging from a semi-charged SHTES
A14	Testing discharging from a semi-charged SHTES
A15	Testing discharging from a semi-charged SHTES

Experiment	Water	Valve	Avg temp SHTES	Avg temp cooker	Total energy
A5	T=25^oC	Middle	173.9 ^oC	184.4 ^oC	8.0 kWh
A7	T=20^oC	Middle	194.6 ^oC	223.7 ^oC	9.3 kWh
A11	T=20^oC	Middle	96.0 ^oC	208.6 ^oC	4.5 kWh
A12	T=20^oC	Middle	118.7 ^oC	207.8 ^oC	5.4 kWh
A13	T=20^oC	Middle	104.6 ^oC	209.2 ^oC	4.8 kWh
A14	T=20^oC	Middle	131.9 ^oC	194.2 ^oC	6.0 kWh
A15	T=14^oC	Middle	142.6 ^oC	179.8 ^oC	6.4 kWh

Table 4.6: Initial setup and goal for the discharging experiments conducted on the Dual Tank System

Experiment A7, discharging from a near fully-charged SHTES

Experiment A7 was the second discharging test completed on the simplified Dual Tank System and aimed to further test the discharging behavior and cooking efficiency of the system. The initial setup of the experiment is shown in table 4.6. During the entire experiment, the valve was left in its initial position but was turned fully down after 1h45min. During the experiment a total of 8 batches of water was heated to a boil only using stored energy in the system. The final boiling test, number 8, was only completed for 2.5L due to increased boiling time and was left in the pot until boiling could no longer be sustained.

When cold water is added to the pot at the beginning of experiment A7, the thermal stratification of the SHTES begins to diminish. Figure 4.13 shows the temperature distribution during the experiment, and 4.14 shows the first hour to better display changes in the system. Four minutes after experiment start, water was added to the pot, which can be seen by the temperature increase in TC W. TCs placed in the cooker show a sudden drop in temperature as an effect of the new heat sink. This is followed by a fast rise in temperature, indicating natural circulation is occurring, transporting hot oil from the SHTES, discharging it. At the same time as circulation initializes, TC placed at the bottom of the SHTES shows an increase in temperature. Cooled oil from the cooker is flowing into the bottom of the SHTES but is at a higher temperature than the pre-existing oil layers. This contributes to breaking parts of the stratification in the tank, which can be seen by TC 1, 2, 3, 4, and 5, all quickly turning into the same temperature over the next 20 minutes. This is shown in figure 4.15 illustrating the temperature distribution over time. Only when TC A measures lower temperatures than the bottom of the SHTES the diminishing of stratification stops.

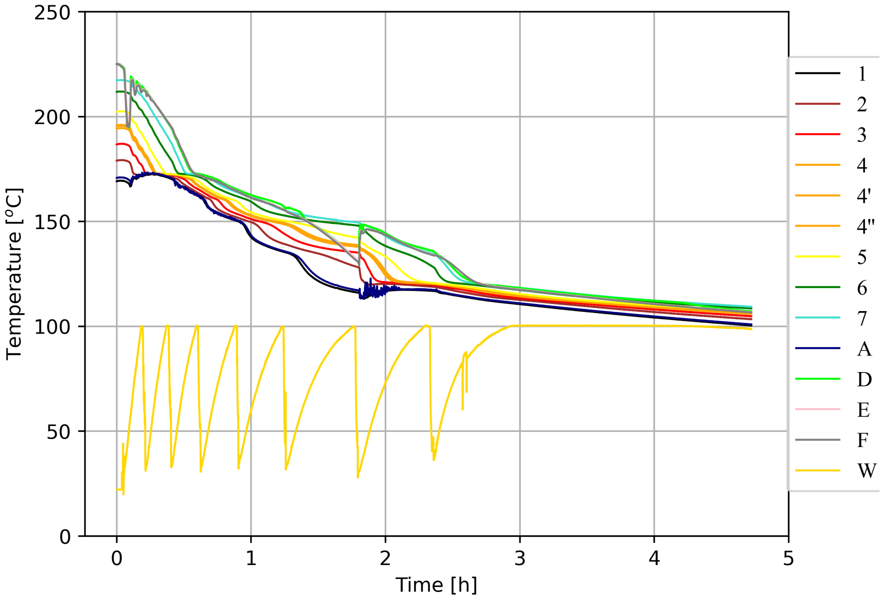


Figure 4.13: Temperature distribution during discharging from a near fully-charged SHTES in experiment A7

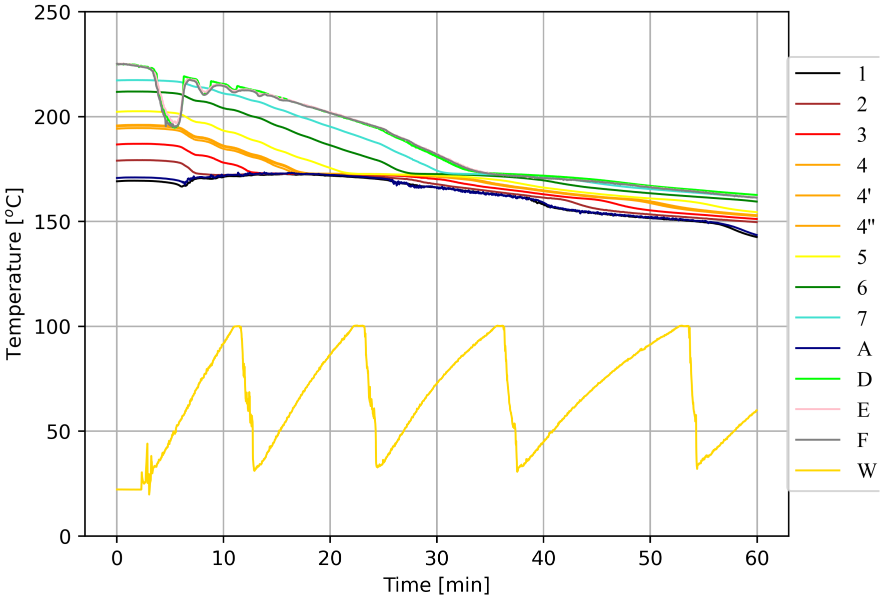


Figure 4.14: Temperature distribution during the first hour of experiment A7

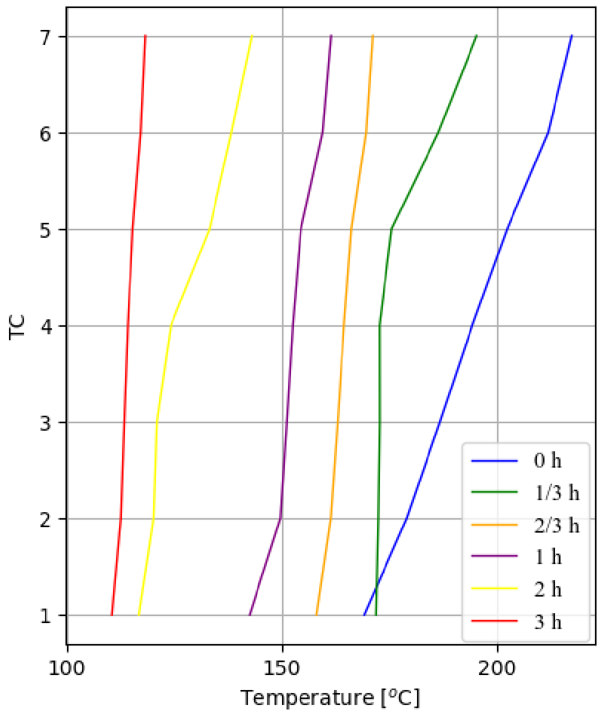


Figure 4.15: Temperature distribution over time in experiment A7, illustrating destruction of thermal stratification

The boiling tests showed that boiling times are directly linked to the temperature of oil in the cooker. Figure 4.16 shows the correlation between the time used for achieving boiling after the initial filling of the pot and the correlating temperature in the cooker. Analysis of the first six boiling series for the system show that the temperature in the cooker decreased linearly while the time to achieve boiling increases exponentially. This is due to the decrease in heat transfer to the pot based on the decreasing temperature difference between the pot and oil in the cooker. This can also be seen in figure 4.13, where boiling could no longer be maintained when temperatures in the cooker reached T=108^oC. Series 7 and 8 are neglected in this analysis due to a change in valve position, which increased the flow rate of oil in the system, and series 8 also due to a reduced amount of water in the pot.

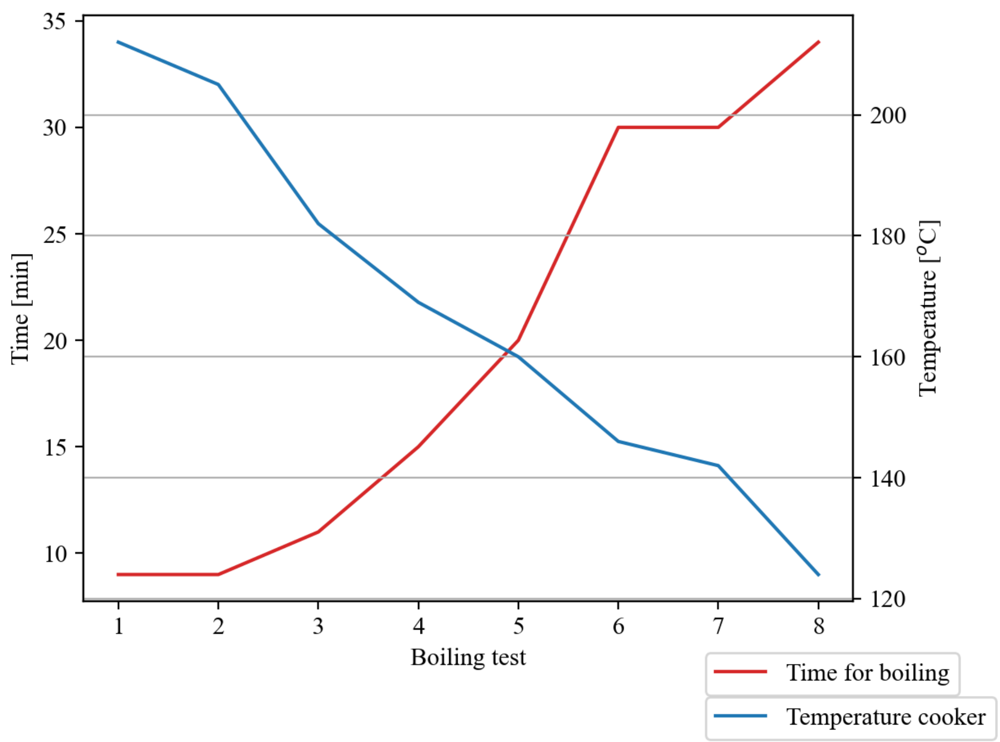


Figure 4.16: Comparison of the time used for achieving boiling and the average temperature in the the top of the cooker during experiment A7

When discharging the Dual Tank System, it was possible to extract a substantial amount of the stored energy for cooking. Table 4.7 shows an overview of the stored energy at the beginning and end of experiment A7. The table shows both values for the total amount of energy in the system, which is the amount above ambient temperature (T=20^oC) and, therefore, the amount that needs to be added to the system, but also the amount of usable energy. This is the amount of energy that can be extracted for cooking based on a lower temperature limit of oil that enables sufficient heat transfer to the pot. A lower temperature limit for boiling was discovered in the previous paragraph, but due to some food types can be cooked at lower temperatures than boiling, the lower limit for achieving cooking is estimated to be T=100^oC. Through the conducted boiling tests, the total amount of energy extracted was 3.5kWh. This is to be regarded as the minimum amount of energy extracted as the calculation does not account for the mass transfer of water through boiling, meaning the 104 minutes of sustained boiling after the last fill is not accounted for. This could not be estimated due to residual amounts of water in the pot when filling for the last boiling test. Still, this amounts to 64.8% of the initial amount of usable energy.

Initial total energy	Final total energy	Initial usable energy
9.3 kWh	4.3 kWh	5.4 kWh
Final usable energy	Extracted energy	η_{Cook}
0.4 kWh	Min 3.5 kWh	64.8 %

Table 4.7: Overview of energy content for discharging experiment A7

Experiments A11-15, discharging from a semi-charged SHTES

An objective for the Dual Tank System was to allow for cooking through sufficient natural circulation while discharging the SHTES. This is also important from a semi-charged SHTES to allow the use of stored energy when needed and not only when fully-charged. Several discharging experiments were therefore completed with the SHTES charged to different levels to test the behavior of the system. The tests were conducted in the same manner as experiment A7, but the valve position was changed several times during some of the experiments to maximize the amount of extracted energy. A selected few of the experiments is shown below, with the remaining in Appendix A1.3.

Experiment A11 was the first of the semi-charged discharging experiments and provided unsatisfactory results. The initial setup was as shown in table 4.6, and at experiment start, when water was added to the pot, the temperature in the cooker can be seen quickly dropping by TC D, E, F in figure 4.17 showing the temperature development during the experiment. The fluctuations in water temperature at the start are caused by a small amount of water was first added to the pot, quickly rising in temperature, before the remaining was added. The experiment deviates from the previous discharging tests due to the cooker temperature continuing to drop for the entire first batch of water. Only when the water boiled and was exchanged with new V=5L of cold water, the cooker first dropped before slightly increasing in temperature. This was followed by the cooker decreasing in temperature for the remaining of the experiment, and boiling could no longer be achieved. Concurrently data from TC 6 and 7 show available energy in the form of oil greater than T=150 ^oC, far above the lower limit of cooking of T=100 ^oC. It therefore becomes clear that natural circulation to boil water was not achieved for the semi-charged SHTES. Data from TC 3 was removed from this experiment due to a defect sensor and was fixed before the next experiment.

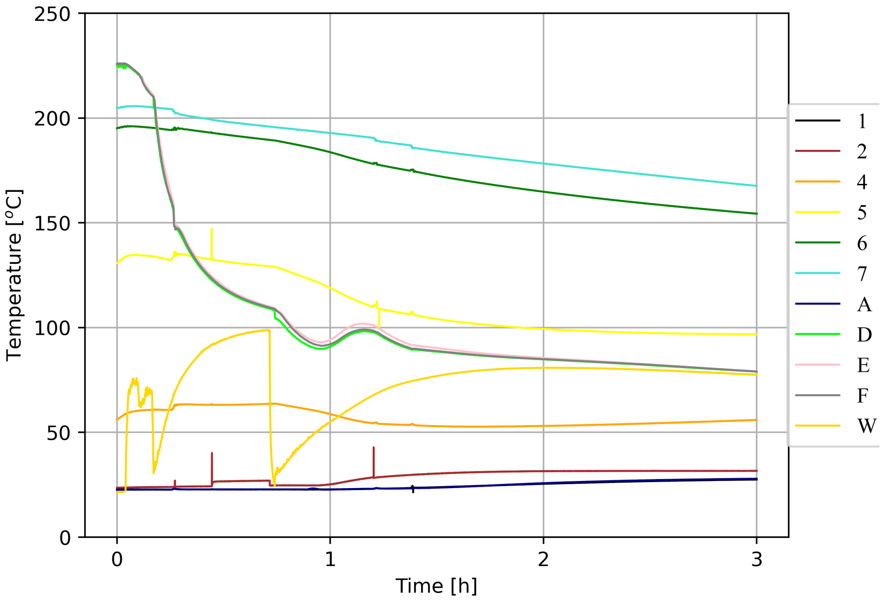


Figure 4.17: Temperature distribution during discharging from a semi-charged SHTES in experiment A11

Experiment A15 was the last of the semi-charged discharging experiments and provided more promising results. The initial setup was as shown in table 4.6, with the initial temperature of the system higher than in experiment A11, and therefore also the initial amount of energy. At experiment start, the temperature in the cooker again significantly dropped when water was added, but now the temperature quickly increased, insinuating natural circulation had occurred. This only lasted for a few minutes before the temperature again started to decrease. During the remaining parts of the experiment, the cooker temperature fluctuated with slow drops and sharp increases when either cold water was added to the cooker top or the valve position altered. The first dotted line marks when the valve was turned upwards, drawing oil from only the very top of the SHTES, and the second line marks where the valve was turned further down to allow more flow. When the discharging experiment was completed, the temperatures in the upper layers of the SHTES were far lower than for experiment A7 with TC 6 and 7, respectively reading T=103^oC and T=106^oC.

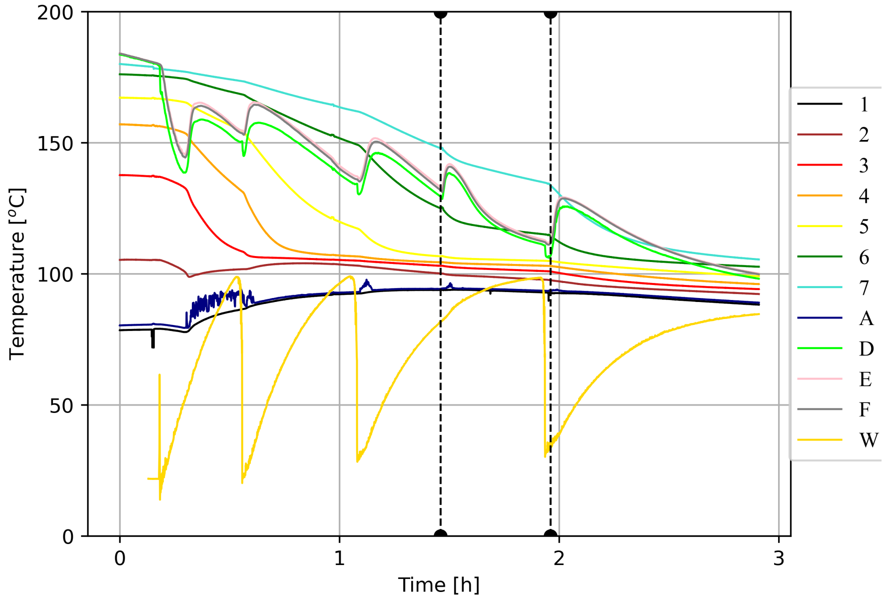


Figure 4.18: Temperature distribution during discharging from a semi-charged SHTES in experiment A15

Through the discharging experiments above and in Appendix A1.3, it was discovered that natural circulation could not be established long term for several cases. This resulted in a significant amount of energy remaining in the SHTES in the form of high-temperature oil, resulting in reduced cooking efficiency. This is demonstrated in table 4.8, which shows a parameter summary for all discharging experiments except A5 and A12, which deviated from the common testing procedure. Column marked "Init" shows the initial parameters at the start of the experiment, with "final" the end. From the table, it appears that the cooking efficiency of the discharging process increases with the average temperature of the system and/or the temperature in the bottom pipe.

Exp	Init SHTES	Init TC A	Init total	Init usable	Final usable	Extracted	η_{Cook}
A11	96.0 ^oC	23.0^oC	4.4 kWh	2.2 kWh	1.0 kWh	0.7 kWh	31.4 %
A13	104.6 ^oC	32.6 ^oC	4.8 kWh	2.2 kWh	1.0 kWh	0.8 kWh	35.8 %
A14	131.9 ^oC	52.1 ^oC	6.0 kWh	2.5 kWh	0.5 kWh	1.4 kWh	55.6 %
A15	142.6 ^oC	81.0 ^oC	6.4 kWh	2.7 kWh	0.1 kWh	1.8 kWh	67.9 %
A7	194.0 ^oC	170.7 ^oC	9.3 kWh	5.4 kWh	0.4 kWh	3.5 kWh	64.8 %

Table 4.8: Parameter overview of conducted discharging experiments

The conducted discharging experiments, reveal that the discharging process is highly sensitive to the valve position. If the valve position is placed too low, it appears the oil flowing to the cooker is drawn lower in the SHTES, resulting in lower temperature oil flowing to the cooker. This reduces the temperature difference between the pot and oil and reduces flow. This can be seen when the valve is turned upwards in experiment A15, and the temperatures in the cooker quickly rising. On the other hand, if the valve is turned too high, the amount of flow is reduced due to a significantly reduced area for the oil to flow. The effect can be seen in the same experiment where the temperature in the cooker increased when the valve was turned downwards. Although in this case, the effect is coupled with the filling of cold water in the pot, causing larger temperature differences inducing circulation.

4.7 Experiment discussion

4.7.1 Sources of uncertainty

When testing the Dual Tank System, sources of uncertainty are present that can affect the validity of the results. A constant uncertainty present is the precision of the installed TCs in the system. The accuracy provided by the TC-08 pico logger is the sum of ±0.2% of the reading and ±0.5 °C [44]. As the maximum reading in the experiments was T=251°C, the maximum inaccuracy of temperature measurements was 1.002°C. The deviation is considered to have little impact on the validity of results due to the nature of testing.

During the conducted experiments, some of the TCs showed strange behaviours. This was for TC 7 in experiments A1 and A2, where the TC was not covered by oil due to being unexpanded. This does not affect the results for the combined testing, as the results from experiments, A1 and A2 are confirmed through other experiments. TC D and TC 3 also measured strange data in respectively experiments A5 and A11 but are again considered to have little effect for the same reason as listed above. The final discovered TC showing strange behavior was TC B, which is suspected from making thermal contact with the pipe it is placed within. Data from the TC was therefore removed, and indications of flow were therefore harder to detect.

When estimating the energy content of the Dual Tank System in the form of high-temperature oil, the number of installed TCs limits the accuracy of calculations. As the system is thermally stratified often with a moving thermocline, a large amount of measuring points is required to accurately measure the temperature distribution of the system. Due to only a finite amount of installed TCs for testing purposes, estimations of average temperature and energy content have therefore been calculated based on dividing the system into zones where TCs are placed and assuming uniform temperature in the zones. This is not considered to be realistic but is the closest estimation possible, and uncertainty therefore remains. The largest amount of uncertainty is a result of inadequate sensors in the cooker, with only TC D, E, and F in the top of the cooker providing temperature measurements. Calculations were therefore solely based on values from these, assuming uniform temperature in the entire cooker. As the heating element supplies energy evenly for the first z=0.4m in the bottom of the cooker, this is not expected to be far off, but some thermal stratification will still be present, resulting in a lower average temperature than estimated. Comparing results from experiments to each other is still seen as viable due to having the same basis of estimation.

When calculating the amount of extracted energy from the system in the form of heated water, residual amounts of water in the pot cause uncertainty. Due to the shape of the pot, when emptying the pot to prepare for the next batch, a small residual amount of water is always left in the cooker top. This is accounted for by measuring the water temperature before filling the pot to reduce uncertainties, but estimating the amount of boil-off is close to impossible. This is therefore unaccounted for when estimating the extracted energy, and the estimation is to be regarded as a minimum.

The final source of uncertainty discovered when testing is the lack of flow measuring equipment. Through the experiments, flow patterns and if natural circulation is occurring has been estimated based on temperature readings. This provides the possibility to measure if natural circulation of significance is occurring, but estimating the mass flow and minor circulation is not possible. Flow measuring equipment was not installed due to its high costs as a result of the high working temperature in the system.

4.7.2 Charging

The conducted charging experiments form a good understanding of the system behavior, and clarify several of the listed objectives in section 4.1.

The first objective was to test if the SHTES could be charged through natural circulation by supplying power to the heating element. Through all the conducted experiments, with the exception of experiment A10, where overflow was hindered for the entire experiment, this was the case. When oil in the cooker had expanded sufficiently as a result of the supplied energy, it entered the top pipe and flowed into the SHTES. This increased the pressure in the SHTES due to the added liquid volume, which started to push oil into the cooker through the bottom pipe, and natural circulation initialized.

The second objective was to test if the SHTES thermally stratifies and remains stratified through charging. Through the several charging experiments, the subsequent thermal stratification of the SHTES was observed. When oil flows into the SHTES with a higher temperature than the already present oil, it floats on the surface due to the lower density. This forces colder oil into the cooker through the bottom pipe, charging the SHTES as described above, in the process, thermally stratifying the SHTES. This can be seen in experiment A2, where the temperature distribution over time is shown in figure 4.5. The figure shows the SHTES gradually being heated, with a thermocline moving through the storage when passing the TCs. This is confirmed through various other experiments as well. In the same experiments, the radial temperature distribution was also studied to locate potential streamlines of hot oil from the upper parts of the SHTES flowing at a faster rate into the bottom outlet of the SHTES, destroying the thermal stratification. TC's 4,4' and 4" was installed to monitor this, but through the experiments, no clear variation was found. However, small differences were observed but are most likely a result of being installed at slightly varying heights. It is therefore deducted that there are no radial differences in temperature distribution along the main volume of the SHTES, but boundary layer effects near the walls could still be present.

The effect of the valve has been studied through the conducted charging experiments and shows promising results. By being able to control the height of when oil is allowed to flow from the cooker to the SHTES allows control over the temperatures. This is seen in experiment A6, where it is clearly shown that the turning the valve changes the overflow temperature from the cooker to the SHTES. This is both useful in terms of providing controlled cooking temperatures, but also being able to increase the overflow temperature to increase thermal stratification of the SHTES when the system is not used for cooking. In experiment A8, the function of the valve was further studied in regards of temperature control for cooking. Results from the experiment showed that the valve, although providing sufficient temperature control when supplied with cold oil from the SHTES, struggled when temperatures increased. Boiling tests showed that when temperatures in the bottom pipe approached T=122^oC, simmering in the pot could no longer be achieved, only rapid boiling. This indicates that other forms for controlling the heat transfer to the pot should be implemented, such as the pot in pot solution.

The effect of cooking from different power levels using the heating element has been studied to test the necessary capacity of renewable energy sources to power the system and further study system behavior. Experiments A2 and A10 were therefore conducted where both aimed to test the amount of time needed to achieve boiling of V=5L of cold water from an initially cold SHTES and cooker, which is the worst conditions for the system in terms of cooking time. A summary of the setup and results from the experiments is listed in table 4.9. As can be seen, both experiments used a substantial amount of time, but managed to bring water to a boil, with the low power configuration using a total of 139 minutes! The significant amount of time for the low power setup is due to the limited capacity of 580W of power supplied to the system, compared to the substantial amount of energy required for bringing the water to a boil of 0.53kWh, and also initial cold oil in the cooker acting as a heat sink. Still, during normal use of the system, the initial temperature of oil in the system would be significantly higher as a result of previously generated energy when the system is not in use, reducing the time for boiling as well as cooking. The system is therefore deemed to reach its objective, but correctly sizing the power source and heating element capacity is important based on the amount of cooking required.

Experiment	Time	Power	Initial water temp	Initial cooker temp
A2	45 min	High (1800W)	T=25^oC	T=21^oC
A10	139 min	Low (580W)	T=11^oC	T=19^oC

Table 4.9: Time to achieve boiling from an initial cold system for experiment A2 and A10

4.7.3 Storage

The temperature development in the SHTES was as expected for both of the storage experiments. Over time the system in both of the experiments experienced a reduction in stored energy shown in table 4.5 and became less thermally stratified, with the warmer parts of the storage experiencing a greater temperature reduction than the colder. This can partially be explained by a larger heat loss to the environment due to the larger temperature difference, as explained by heat transfer in section 2.1, and due to internal conduction in the SHTES with the upper layers heating the bottom. This can be seen in figure 4.10 where the lower layers increases in temperature for the entire experiment due to internal conduction overpowering heat loss to the environment. The larger heat loss of experiment A9 than A3 is also due to an initial higher average temperature.

The temperature development in the cooker was more surprising for the experiments. In experiment A3, demonstrated by figure 4.10, it becomes apparent that the cooker experiences a significantly higher reduction in temperature over time than the SHTES, which is also the case for A9. This is expected to be partly due to the larger surface area of the cooker compared to the amount of oil it contains in regards to the SHTES and what appears to be worse insulation. Due to the complex shape of the curved end cap and the removable pot, insulating the cooker is rather difficult, and gaps in the insulation can be present. This is illustrated in figure 4.11, clearly showing areas of higher surface temperature in the cooker. This is an issue as heat exchange between the pot and oil in the cooker both enables cooking and provides the driving forces for initializing natural circulation transporting heat to the cooker. This results in cooking may not be achieved even when the SHTES contains sufficient energy to sustain cooking.

In terms of the effect for the valve position, results indicate that obstructing overflow between the tanks can mitigate heat loss in the system. As can be seen in figure 4.12b the average temperature was initially higher in the cooker of experiment A9, but after approximately 2.5 hours, the temperature in the cooker dropped below that for experiment A3. This indicates that circulation may be present during experiment A3, replenishing hot oil into the cooker, maintaining higher temperatures than for experiment A9. This is further indicated by the temperature differences in the storage's, where there is a steeper temperature drop for the entire experiment, except between t $\in [0.5, 2.5]$h. This is seen as an effect of the storage in experiment A3 discharging, as the temperature drop for the SHTES in experiment A9 should be larger due to the higher initial temperature. For the remaining parts of the experiments, the temperature in the cooker follows each other closely, indicating no circulation is present. As the temperature difference is only minor between the experiments, the effect of valve position seems insignificant, but obstructing overflow when the system is not in use or receiving power could mitigate heat loss.

4.7.4 Discharging

The completed discharging experiments have provided valuable information about the system in terms of its performance compared to the research objectives. The first objective was to test if sufficient natural circulation could be achieved to sustain cooking while discharging the SHTES. The conducted tests had variable results, with sufficient natural circulation only achieved in a few of the experiments. When the system was close to fully-charged in experiments A5 and A7, natural circulation can be seen maintained for the entire experiment duration, with the cooker having sufficient temperatures to maintain boiling for long periods of time. In these experiments, large quantities of usable energy were also extracted. For the semi-charged experiments, this was not the case, with many of the experiments only able to maintain sufficient natural circulation for a short amount of time. This resulted in a low cooking efficiency for the system. Still, this does not mean the generated energy is lost but that it cannot be extracted with the current temperature distribution. Depending on the efficiency of insulation, a large quantity can still be used at a later time when supplied with additional energy.

The inadequacy of natural circulation for the semi-charged discharging experiments is a complex problem. For the experiments, the temperature in the cooker can be seen fluctuating, usually increasing after cold water had been replaced in the pot but quickly dropping again, demonstrating that sufficient natural circulation for cooking occurs, but only temporarily. The same fluctuation can be seen at the beginning of experiments A5 and A7, but only for a short duration of time before stabilizing. This is quite strange behavior as sufficient driving forces to power circulation are available in both cases due to the heat sink in the cooker and the separation of the tanks. The main theories for lack of sufficient circulation from a semi-charged SHTES are described below.

- The mass flow of natural circulation is determined by the driving forces compared to pressure loss in the system as described by natural circulation in section 2.3. As the viscosity of Duratherm-630 increases significantly at lower temperatures, cold oil in the bottom pipe can limit the amount of flow as the pressure loss increases in the pipe. The phenomena is described by pipe flow in section 2.4.1. Relatively cold oil was present for all of the semi-charged discharging experiments.
- When natural circulation initializes, hot oil flows from the top of the SHTES into the cooker. This will force colder oil from the cooker into the SHTES through the bottom pipe to even out the pressure. This could potentially cause an oscillating process where oil flows into the cooker, pushing an equal volume of oil into the SHTES but at a lower density, now increasing pressure in SHTES, causing it to flow back into the cooker. The process should only be momentarily, but could contribute to fluctuations of temperature in the cooker.
- The final theory is that the Dual Tank System potentially short circuits where natural circulation occurs but circulates cold oil from the lower layers of the SHTES. No significant radial differences are detected through the experiments, but flow along the SHTES wall could still be of significance.

The second objective was to test if the SHTES would remain thermally stratified through the discharging process. Through the conducted experiments, it was found that this was partially not the case. In the experiments where natural circulation occurred and was maintained for longer periods, the lower layers in the SHTES quickly rose in temperature. This was caused by natural circulation where oil flowed into the bottom of the SHTES, which had a higher temperature than the bottom layers of the tank. This mixed with the pre-existing oil and caused a uniform temperature in the lower layers of the SHTES, and therefore destroyed parts of the stratification. This can clearly be seen in experiments A5 and A7, where the lower layers raised in temperature at the beginning of the experiments. For experiment A7, this is illustrated in figure 4.15, showing the temperature distribution in the SHTES becoming more uniform with time. This is a concern as the amount of usable energy in the system diminishes as described by exergy in section 2.2.2, and changes to the system could be necessary. In experiment A7, a lower limit for achieving cooking of T=100^oC was also estimated, further indicating the need for thermal stratification to maintain usable energy. Reducing the amount of circulation when discharging could be a solution as this would cause the temperature of oil to drop further in the cooker before entering the SHTES, reducing the amount of mixing.

The third and final objective of the completed testing was to control if the Dual Tank System and cooking could be regulated through the valve when discharging. The main goal when discharging is to control the mass transfer between the two tanks, and in turn the heat transfer as the available temperature in the SHTES is a given. In regards to limiting the heat transfer to the cooker from the SHTES and in turn the pot, the valve works well. By turning the valve higher, the mass flow of oil to the cooker can be reduced, resulting in less heat transfer. This also provides some control over cooking as the heat transfer to the pot will be reduced with reduced temperature in the cooker. In regards to increasing the heat transfer it became apparent through the experiments that the valve has limited impact. If sufficient driving forces are not available to initialize or maintain natural circulation, the valve and its position are of minor impact.

4.7.5 Valve

During the course of experiments, a weakness of the valve concept was discovered. As mentioned in section 3.2, the installed valve was not meant to be used in the final version of the system due to its placement in the SHTES, prohibiting regulation directly from the cooker. The installed valve is still based on the same concept as the pipe in pipe valve originally designed, and potential issues are therefore transferable. During testing, it was found that the valve turned increasingly hard with increasing temperature of oil. This resulted in large amounts of force needed to turn the valve, which could only be applied using a large pipe wrench. This is expected to be a result of the pipe in pipe solution where the inner pipe thermally expands more than the outer due to being in direct contact with oil. The designed valve described in section 3.1 will therefore not function as the force required to turn it will be too large. Internal leakage in the valve, although minor was also observed.

4.7.6 Summary

Based on the conducted experiments for the Dual Tank System, the conclusion is the system partially works. In regards of charging the system functions well, with natural circulation occurring transporting heat from the cooker to the SHTES, and the valve provides sufficient temperature control until the system is of high temperature. Cooking is possible from an initially cold system with both a low and high power configuration, but selecting the correct capacity for heating element and energy source based on the amount of food that should be cooked, is important for a well functioning system.

The storage of high-temperature oil over time functions well for the system, with only minor concerns. When the SHTES is supplied with high-temperature oil, the SHTES thermally stratifies, and it remains stratified for long storage periods with the current insulation thickness. The insulation of the cooker seems insufficient as the temperature decrease is far higher than for the SHTES. No radial temperature differences were observed in the SHTES without the use of a top diffusor which is therefore deemed unnecessary.

During discharging of the Dual Tank System a major concern was discovered. Due to the separation of the two tanks, natural circulation is needed to transport energy between them to enable cooking. When the system has high initial temperatures and is close to fully-charged, natural circulation transports the stored energy well, enabling cooking and discharging with relatively high cooking efficiency. But with a semi-charged SHTES, in several cases sufficient natural circulation could only be established over short time periods, leaving a large amount of energy in the SHTES.

Based on the above, further improvements and testing is therefore required for the system to be deemed sufficient as a heat storage for cooking.

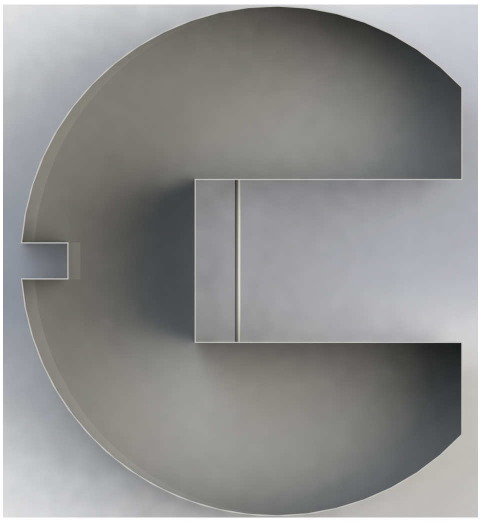
5 Design modification

In this section, a modified version of the Dual Tank System with several modifications, based on the findings and discovered weaknesses discussed in section 4.7, will be presented.

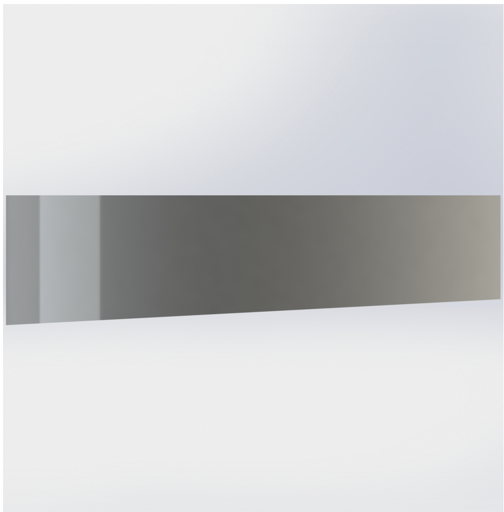
5.1 Displacement valve

A new valve was designed to provide the equivalent control of the turning valve, but without the issues described in section 4.7.5. A new concept was therefore used. Instead of moving a mechanical barrier to prevent or allow overflow between the tanks, the mechanical barrier will remain fixed, but the height of the liquid column will be changed instead. This is enabled by using a displacement volume floating on the oil surface, that can be pulled downwards displacing oil; so the height of the liquid column in both tanks can be increased due to being connected through the bottom pipe. This allows control of the overflow temperature when charging the system, as when the oil height rises, less thermal expansion is needed to reach the top pipe. When discharging, the displacement valve may also allow control over the mass flow rate from the SHTES by decreasing or increasing the oil level, if sufficient driving forces for circulation are available. A preliminary experiment to test the behavior was completed before the displacement valve was finalized (See Appendix A2), with results confirming the above.

The displacement valve consists of four components. The main component is the displacement volume. The bottom surface of the volume has a tilted angle towards the top pipe to direct flow towards the pipe, and mitigate potential dead zones where oil could stagnate. It is designed with a large opening in the center of the SHTES where oil can flow undisturbed, hopefully resulting in no radial temperature differences in the system. The surface area is half of the cross-sectional area of the system, resulting in an equal height increase of oil as the volume is pulled down. The displacement valve is regulated by a wire placed inside a guide tube connected to a winch or similar device. The wire is connected to a horizontal bar placed at the volume center of the displacement volume. By turning the winch, the volume can be lowered or raised to float on top of the oil. The displacement volume is illustrated in figure 5.1, and the entire solution in figure 5.2.



(a) Top view



(b) Side view

Figure 5.1: Rendering of the displacement volume which can be lowered or raised in the system

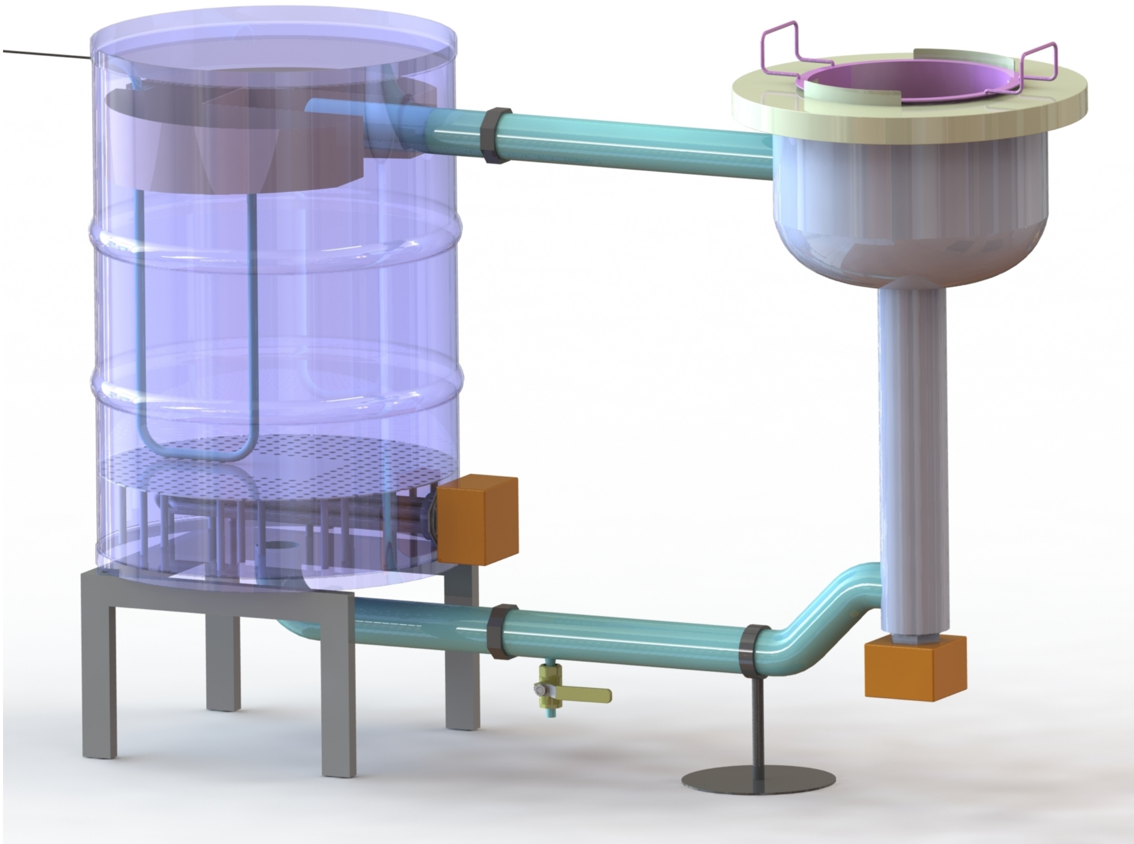


Figure 5.2: Overview of the system with a see-through SHTES illustrating the displacement valve

The displacement valve has clear benefits, but also some drawbacks compared to previous solutions. A clear benefit is that the system can be regulated from the outside, allowing safe use as it removes interaction between the user and high-temperature oil. The guide tube exit can also be placed in whichever direction is wanted, and the wire can therefore be guided to the cooker, allowing the user control from where food is cooked. The valve should also be easier to produce than previous versions due to not requiring precision machining. A potential drawback of the system is the destruction of thermal stratification due to the guide tube's vertical placement, acting as a heat conductor between layers in the SHTES. The movement of the displacement volume can also cause some mixing due to disturbing the oil when moved. These effects remain to be tested.

5.2 Insulation

Through testing in section 4.7.3, it was found that the insulation of the cooker was inadequate to maintain high temperatures over longer periods without charging. To combat this, a new cooker top was designed to allow room to improve the insulation in the upper parts of the cooker. The new top has a similar design to the previous version, but the sides are extended to allow insulation between the cooker wall and top. The space will be insulated with a layer of 50mm Fyrewrap. From thermal imaging during storage tests, this was found to be an area with the worst insulation and, therefore, the largest heat loss. The external area of the cooker top can also be insulated. The cooker top will both allow cooking directly in the pot or a pot in pot solution. A render of the new top is shown in figure 5.3 and can also be seen in figure 5.2 on the right-hand side.

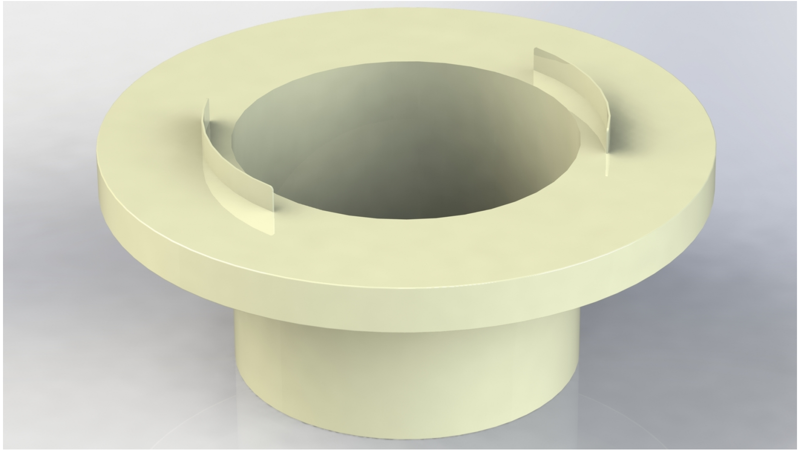


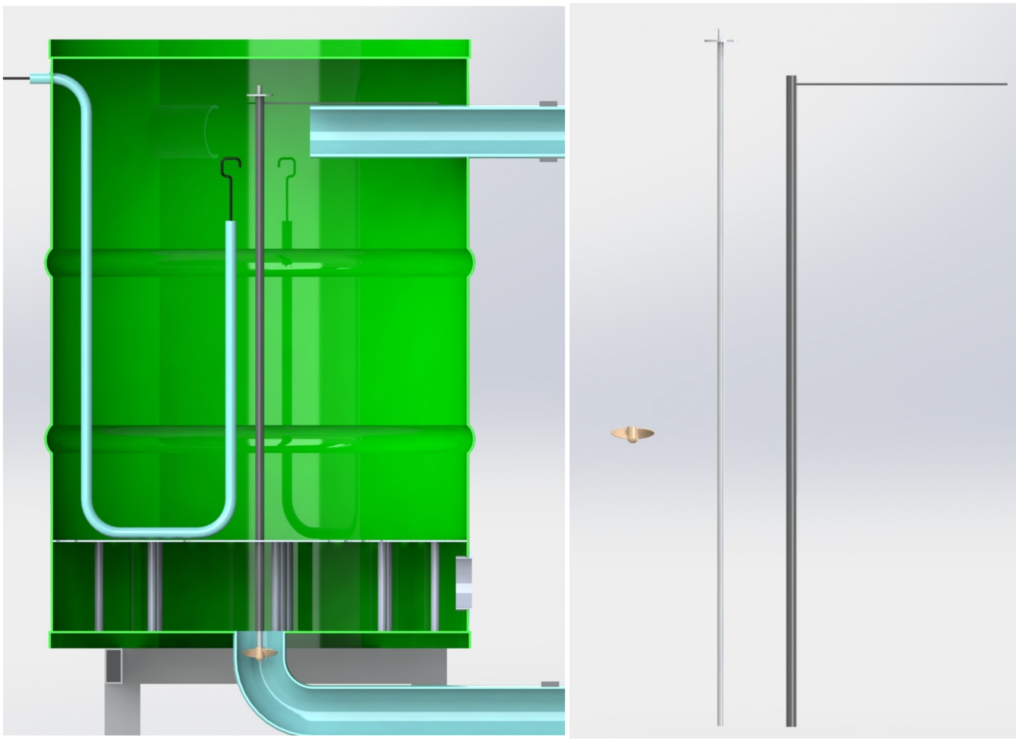
Figure 5.3: New cooker cooker top with extended sides

5.3 Pump

A simple pump was designed, that when powered, would induce circulation to discharge the SHTES when cooking without power. Originally, this was an undesired complication in the Dual Tank System due to increasing costs, but as preliminary testing discovered, natural circulation was not sufficient to maintain cooking when discharging the SHTES for several cases, leaving substantial amounts of usable energy in the SHTES. The pump will be hand-powered to reduce costs and complexity, and several different designs to achieve this are possible. The pump can for example be gravity-driven, driven by a high gear ratio pulley system, or similar. For simplicity, this aspect will not be designed in this thesis, but for testing purposes the pump will be powered by an electrical drill.

The pump consists of three major components, the propeller, the guide tube, and the axle. The components are illustrated in figure 5.4, with (a) showing the pump placement in the SHTES, and (b) an exploded view of the three components. The propeller, which is a dual blade propeller, is 45mm in diameter and is placed directly into the bottom pipe entry. It can force oil either into or out of the SHTES as needed based on the direction it is turned in. The propeller is placed 50mm into the bottom pipe and connected to a 6mm diameter axle with 640 mm in length, which allows it to be rotated from the top of the tank. At the top, a standard drill bit is connected to the axle, allowing it to be rotated using an electric drill, and can later be replaced with a hand-powered solution. The axle is placed into a guide tube placed at the center of the SHTES and connected to the bottom diffuser and the top pipe to keep it stable.

The solution could contribute to some mixing and destruction of thermal stratification as for the displacement valve, but the benefit of added energy extraction is considered to outweigh the losses.



(a) Half view of SHTES with hidden displacement volume

(b) Exploded view, with the propeller on the left and guide tube on the right

Figure 5.4: Rendering showing the new pump design and placement

Technical drawings of the modifications to the system are shown in Appendix A3.2.

5.4 Built system

The changes made to the prototype Dual Tank System are illustrated in the following figures. Figure 5.5 shows the emptied SHTES with the guide tube and the pump. For demonstration purposes, the displacement volume was removed and is connected to the wire seen on the left-hand side. Figure 5.6 shows the same SHTES but now filled with oil and the displacement volume. The rocks seen are used to stabilize the shape such that it is level with the oil surface. The final figure, figure 5.7 shows the new cooker top without external insulation. The external insulation consists of a single layer of ISOFRAX®1260 FILT of 18mm thickness covering the top surface with U-value of 4.44 W/m^2K [42]. The spacers were not added to the cooker top as time limitations would not allow proper testing.

Figure 5.5: Guide tube and top of pump in empty modified SHTES

Figure 5.6: Displacement valve and top of pump in modified SHTES

Figure 5.7: New cooker top without spacers and external insulation

6 Final testing

This section provides a description of the experimental setup, results, and discussion of the final testing of the Dual Tank System. The experiments are grouped into tests regarding the modifications, along with discharging of a mixed SHTES, and cooking.

6.1 Objective

To further validate the system and the effectiveness of the implemented modifications, a final set of experiments were conducted. These include testing of the displacement valve, new insulation, the pump, and discharging tests including the cooking of beans. Through experiments, the following were to be tested for the modified Dual Tank System:

- Can the displacement valve provide equivalent or better control of the system than the turning valve
- Will mixing the SHTES increase the cooking efficiency when discharging a semi-charged SHTES
- Can the pump provide sufficient circulation to further deplete the SHTES of usable energy
- Is the heat loss of the cooker reduced by new cooker top and insulation, so that usable temperatures are maintained over longer time periods
- Can food be cooked sufficiently by the Dual Tank System while discharging

6.1.1 System configuration

During the final testing of the Dual Tank System, the system had two main configurations. Configuration 1 included the implementation of the displacement valve described in section 5.1, while configuration 2 included the displacement valve with the new cooker top and pump. As for preliminary testing, rocks were not implemented for both configurations of the system. This was done to allow the comparison between preliminary testing and final testing to validate the effect of the modifications. The system was therefore filled with V=0.092m^3 of Duratherm-630, a slightly smaller amount the previously, to allow space for the displacement valve until a height level of z=0.495m was reached in the tanks. All experiments were completed with a single pot solution, with the exception of experiment B7, which was tested with the pot in pot solution.

6.2 Definition of Terms

The experiments are explained using the same terms as described in section 4.2, but with the addition of terms for the new displacement valve, which are explained in the list below:

- **Floating** The volume is left to float on the surface in the SHTES, leaving the height of oil unaffected
- **Lowered** The volume is pulled downwards, displacing oil, increasing the height of the liquid column in both tanks

- **Raised** The volume is released upwards, displacing less oil, in turn lowering the height of the liquid column

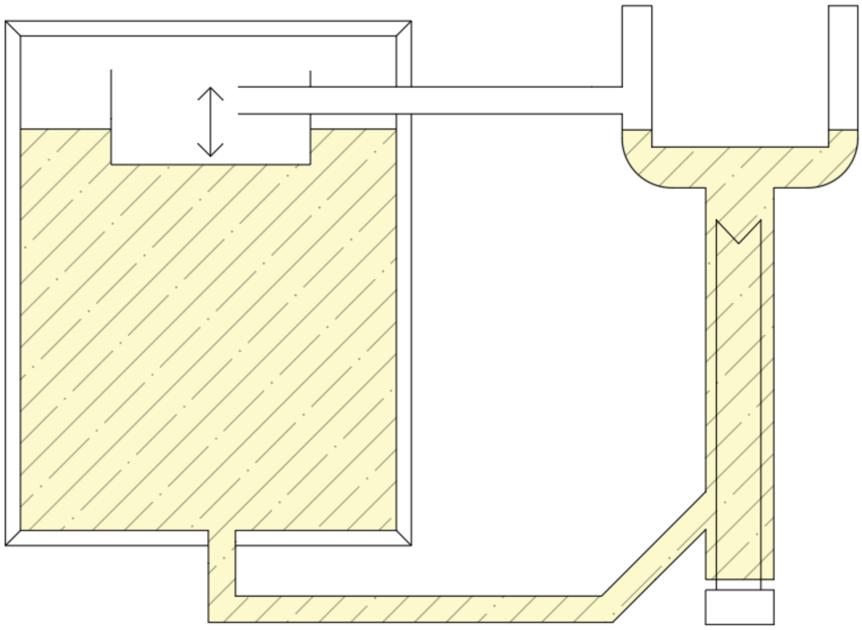


Figure 6.1: Simplified system overview, demonstrating valve adjustment

6.3 Method

6.3.1 General procedure

The final experiments follow a similar general procedure for testing as for the preliminary testing described in section 4.3.1 with only minor differences. These were the following:

- To regulate the valve, in turn, the overflow temperature and flow rate, the valve could now be regulated externally from the SHTES using a winch. This resulted in fewer disturbances in the system, but the SHTES was still opened to conduct visual inspections on several occasions.
- The cooking capabilities of the system were still tested using a standardized amount of V=5L of water, but a cooking test with beans was also conducted.
- A transformer was no longer used to alter the current to the heating element. All experiments were conducted using high power of 1800W from the heating element.
- When conducting discharging experiments, the system was again initially charged with high power and then disconnected from the power source, but the regulation of the valve differs. Instead of turning the valve to allow contact between the tanks, the valve was now lowered until the oil levels were high enough to flow between them.

6.3.2 Experimental setup

The same array of TCs used in the preliminary testing of the Dual Tank System was used for the final testing. The exception is the installment of another TC, which is placed within the top pipe to provide a more precise measurement of overflow temperature and circulation. This is named TC G and is also a TC of type K. Figure 6.2 shows a simplified view of the system with the installed TCs and the corresponding height in table 6.1. Between preliminary and final testing TC B was also slightly repositioned to avoid thermal contact with the pipe wall and provide accurate temperature measurements.

During testing of configuration 2, TC A had to be removed to allow room for the new pump. This is considered to have little effect on the results, as other TCs can provide sufficient data to supplement the loss.

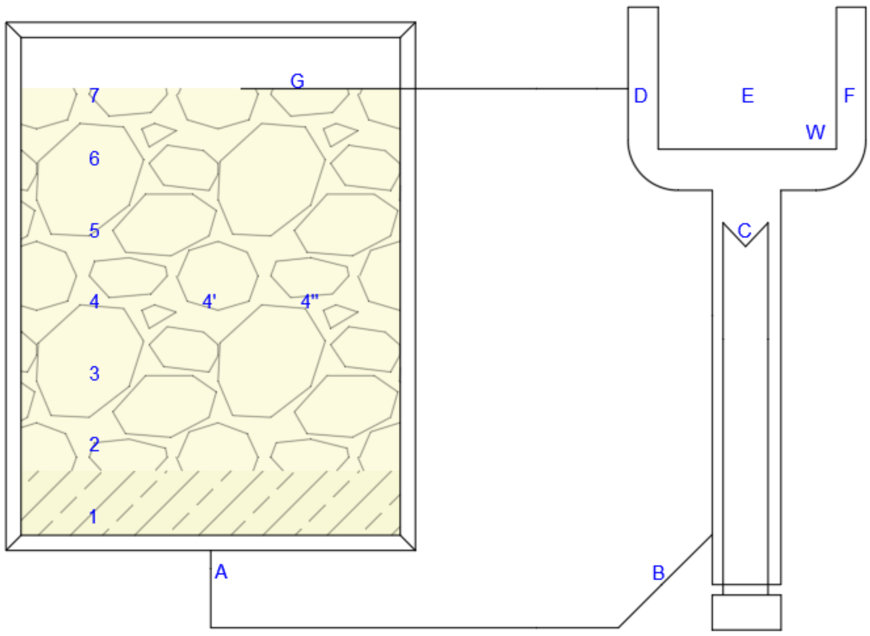


Figure 6.2: Simplified system sketch with TC placement for final testing

TC	Height	Color	TC	Height	Color
1	3 cm	■	A	- 3 cm	■
2	11 cm	■	B	- 3 cm	■
3	19 cm	■	C	40 cm	-
4	27 cm	■	D	51 cm	■
4’	27 cm	■	E	51 cm	■
4”	27 cm	■	F	51 cm	■
5	35 cm	■	G	54 cm	■
6	43 cm	■	W	-	■
7	51 cm	■			

Table 6.1: TC placement measured from the bottom of the SHTES and according color code used when illustrating temperature distribution for final testing

6.3.3 Faulty temperature measurements

When conducting experiments, one of the TCs registered strange values for the entire experiment course. This is the case for TC D, which registered highly fluctuating values with a magnitude of T= $\pm$ 10^oC between the sample rate of data which was 1 second. This is significantly higher than what is expected and is deducted as experimental noise due to a faulty sensor. An approximation formula has therefore been used to present the data to even out the differences between measurements. The data presented for TC D is, therefore, the average of 5 measurements before and after the data point. The average temperature from the TC is also believed to be slightly lower than the actual temperature based on results from initial testing.

6.4 Displacement valve experiments

To test the displacement valve, two experiments were conducted. These consist of a charging and discharging experiment, where the goal was to control the overflow temperature, and in turn, the temperature in the cooker by regulating the valve. The initial setups and goals for both of the experiments are listed in table 6.2.

Experiment	Goal					
B1	Test the effect of the discharging valve during charging					
B2	Test the effect of the discharging valve during discharging					
Experiment	Water	Valve position	Power	Avg temp cooker	Avg temp SHTES	Config
B1	-	Floating	High	T=23^oC	T=23^oC	1
B2	T=23^oC	Floating	-	T=197^oC	T=134^oC	1

Table 6.2: Initial setup and goal for conducted discharging valve experiments

Experiment B1, valve control while charging

Experiment B1 was the first test conducted on the modified Dual Tank System and showed promising results in terms of controlling temperatures in the system. The initial setup was as listed in table 6.2, and at experiment start, the temperature in the cooker can quickly be seen rising by the temperature distribution illustrated in figure 6.3 due to the added energy from the heating element. The variation of temperature in TC D, E, and F at the beginning of the experiment is due to minor differences in the height of the TCs and the oil level rising, reaching one by one. The first line from the left-hand side in the figure marks when the displacement valve was lowered to induce overflow and lower the temperature in the cooker. As can be seen, overflow followed by the increase in temperature of TC 7, and the new TC G placed in the top pipe. The temperature in the cooker still continued to rise due to the system being filled with too little oil, therefore requiring high temperatures to expand sufficiently to flow (At this point the system was only filled with V=0.089m^3 of Duratherm-630). At the second line, the displacement valve was raised to a floating position, and the system was filled with an additional V=3L of Duratherm-630, bringing the total amount in the system to the listed amount in section 6.1.1. This caused the temperature drop in the system, as seen by TC G, 6, and 7, but caused the temperature in the cooker to stagnate at the desired T=220 ^oC. The system was then left to charge until the third line, where the displacement volume was lowered to its lowest point, causing the overflow temperature and temperature in the cooker to drop for the next time period. Only after 1h55min when the valve was raised again, did the temperature in the cooker increase, showing similar behavior to the conducted preliminary experiment B0 described in Appendix A2. This clearly illustrated the displacement valve's ability to control temperatures while charging.

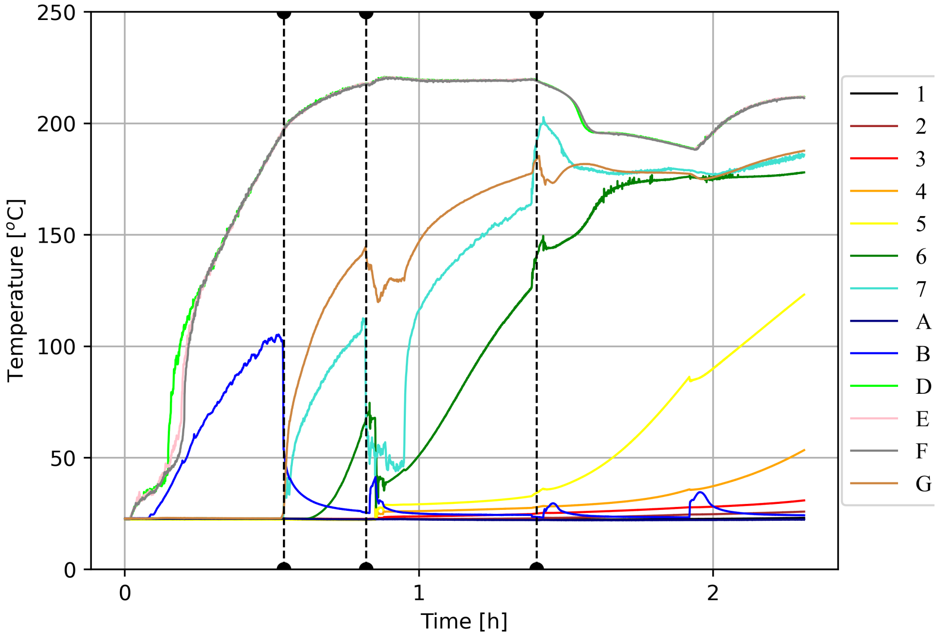


Figure 6.3: Temperature distribution during high power charging controlled by the displacement valve in experiment B1

Experiment B2, valve control while discharging

In this experiment, a discharging test was completed to test the displacement valve's effect on the system while discharging. The initial setup was as listed in table 6.2, and at experiment start illustrated in figure 6.4, the temperature in the cooker quickly dropped due to the presence of cold water in the cooker top. For the following time period, the temperature continued to drop with little to no sign of initializing sufficient natural circulation to transport heat to the cooker. At the first line from the left-hand side, the displacement valve was therefore lowered by approximately z=1cm to attempt to initialize circulation. This increased the height of the liquid column in the SHTES and forced hot oil into the cooker, increasing the average temperature in the cooker from T=116^oC to T=142^oC. Sadly, the effect was only brief as the temperature dropped again afterwards. The same effect repeated itself over the following time period, with the next three lines marking when the valve was further lowered with and the third line marking when the valve was pulled fully down. The fifth and final line marks when the valve was raised to only allow a thin liquid film in the top pipe to mitigate heat transfer from the SHTES to the cooker. The temperature in the cooker continued to drop after this until the valve was again lowered to utilize the remaining energy in the SHTES at 2h7min, marked by the temperature increase in the cooker. The experiment was terminated when the water no longer increased in temperature with high-temperature oil still left in the SHTES. During the experiment, two batches of V=5L of water were boiled, with an additional batch being heated to T=92^oC.

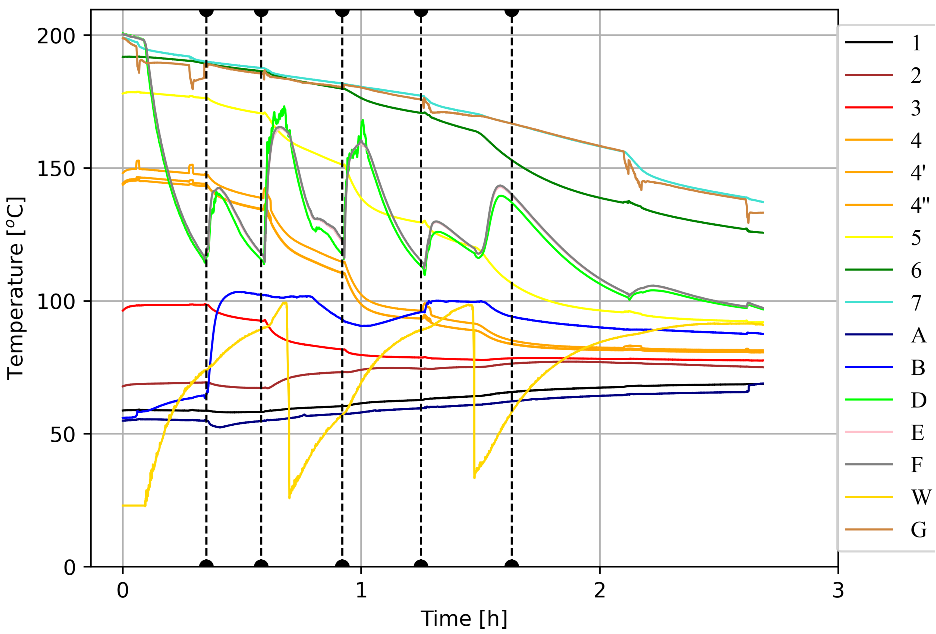


Figure 6.4: Temperature distribution during discharging controlled by the displacement valve in experiment B2

To analyze the performance of the displacement valve, the system can be compared to previous experiments conducted under similar conditions. The energy content and amount of extracted energy have therefore been calculated for experiment B2 and are listed in table 6.3 together with results from experiment A13. The energy contents have been calculated as described in section 4.2.1 for an ambient temperature of T=23^oC. As can be seen, the initial amount of usable energy is the same, but experiment A14 is slightly more efficient.

Exp	Initial SHTES	Initial total	Initial usable	Final usable	Extracted	η_{Cook}
A14	131.9 ^oC	6.0 kWh	2.5 kWh	0.5 kWh	1.4 kWh	55.6%
B2	133.7 ^oC	5.6 kWh	2.5 kWh	0.4 kWh	1.4 kWh	53.6 %

Table 6.3: Amount of stored and extracted energy in experiment B2 and A14

6.5 Discharging from a mixed semi-charged SHTES experiment

Through preliminary testing, it was found that the Dual Tank System struggled to discharge efficiently from a semi-charged SHTES, and a new experiment was therefore conducted with a slightly different setup than previously. Now the discharging test would be conducted from a semi-charged but mixed system, meaning less thermal stratification of the SHTES. This was completed to test the theories presented in section 4.6 in regards to low-temperature oil in the bottom pipe and SHTES and short-circuiting contributing to mitigate sufficient circulation. To achieve the desired mixing in the SHTES, the system was first fully-charged, and an initial discharging test was completed before the system was charged again in preparation for the experiment. The process is described in Appendix A2 under "Initial Experiment B3".

Exp	Goal					
B3	Testing discharging from a mixed semi-charged SHTES					
Exp	Water	Valve position	Power	Avg temp cooker	Avg temp SHTES	Config
B3	T=21^oC	Floating	-	T=181^oC	T=156^oC	1

Table 6.4: Discharging from a mixed SHTES initial setup and goal

Experiment B3 was conducted by boiling several batches of water in the pot, resulting in the temperature development illustrated in figure 6.5. The setup at experiment start was as listed in table 6.4, with the minimum and maximum temperature in the SHTES at T=137^oC and T=180^oC in respectively TC 1 and TC 7. The vertical lines mark when the displacement valve was lowered z=1.5cm to increase the temperature in the cooker due to increasing boiling times. During the experiment, two batches of water were fully boiled and swapped before the third was heated until a temperature of T=94^oC. The water was expected to reach boiling but had to be swapped to allow the filling of a fourth batch of cold water to extract the usable energy, as the operator could no longer supervise the system. Concurrently when filling the fourth water batch, the displacement valve was lowered until its lowest position to allow the full use of the stored energy. The heating of water could no longer be sustained when the water reached T=96^oC, and the experiment was terminated.

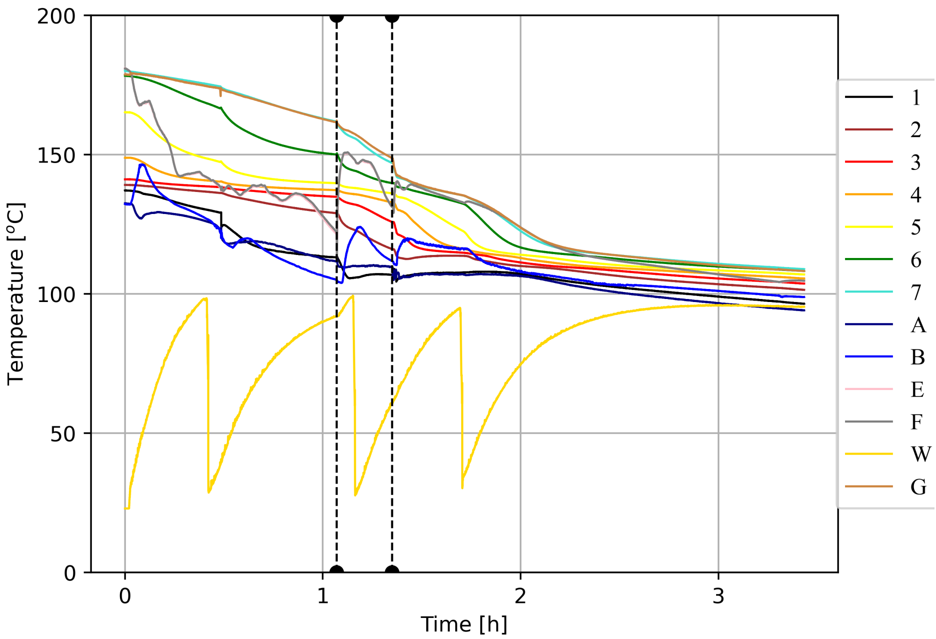


Figure 6.5: Temperature distribution during discharging from an initially mixed SHTES in experiment B3

Experiment B3 resulted in mixed results regarding discharging from a semi-charged SHTES. This is due to when discharging the system, a mixed SHTES did not result in increased cooking efficiency compared to previous experiments. The energy content and efficiency of experiment B3 are presented together with experiment A15 which had a similar setup in table 6.5. The energy contents have been calculated as described in section 4.2.1 for an ambient temperature of T=23^oC. As can be seen, even though experiment A15 had a lower average initial temperature than B3, the cooking efficiency was higher as shown by column η_{Cook}. Discharging from a mixed SHTES does therefore not seem to increase the efficiency, but it still managed to extract a substantial amount of energy for cooking.

Exp	Initial SHTES	Initial total	Initial usable	Final usable	Extracted	η_{Cook}
A15	142.6 ^oC	6.4 kWh	2.7 kWh	0.1 kWh	1.8 kWh	67.9 %
B3	155.7 ^oC	6.5 kWh	2.9 kWh	0.3 kWh	1.8 kWh	62.6 %

Table 6.5: Amount of stored and extracted energy in experiment B3 and A15

6.6 Pump experiments

Two experiments were conducted to verify and study the pump designed in section 5.3. These consist of two discharging experiments from a semi-charged SHTES where the pump is used to assist the circulation of hot oil between the tanks. The conducted experiments with their goal and initial setup are shown in table 6.6. These experiments mark the transition from configuration 1 to configuration 2 of the system.

Experiment	Goal					
B4	Testing the effect of the pump during discharging					
B5	Testing the effect of the pump during discharging					
Experiment	Water	Valve position	Power	Avg temp cooker	Avg temp SHTES	Config
B4	T=24^oC	Lowered	-	T=215^oC	T=103^oC	2
B5	T=23^oC	Lowered	-	T=219^oC	T=118^oC	2

Table 6.6: Initial setup and goal for conducted pump experiments

Experiment B4, discharging with slow rotating pump

Experiment B4 was the first of the two experiments; in terms of increasing circulation by using the pump the results were dissatisfactory. The initial setup was as listed in table 6.6, and at the beginning of the experiment, temperatures in the cooker quickly dropped as the water absorbed the available energy, as illustrated in figure 6.6. After the water was swapped, there were still no signs of natural circulation, and at the first vertical line, the pump was therefore powered by the electric drill to initialize circulation. The propeller was turned at approximately 300 rpm for 1 minute but with minimal effect. Only when the displacement valve was lowered at roughly the same time did the temperature in the cooker increase. The pump was again powered at the second vertical line for another minute, but this time at 500rpm with only a minor temperature increase of T=7 ^oC. At the third line, the pump was again powered for 1 minute at 500rpm, but this time rotated in the reverse direction, resulting in a minor temperature decrease. The experiment was terminated shortly after, with substantial amounts of high-temperature oil at T=170^oC left in the SHTES.

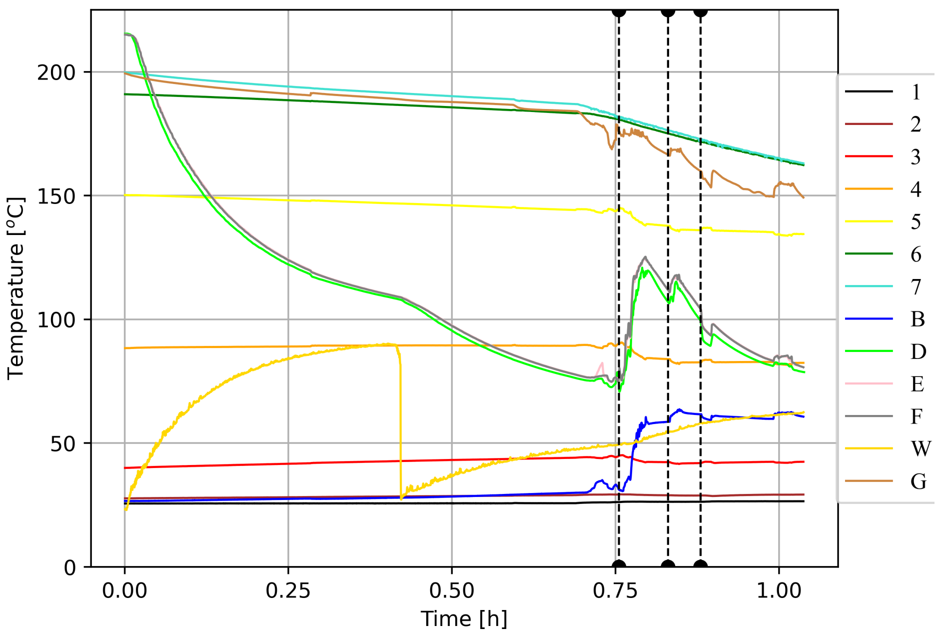


Figure 6.6: Temperature distribution during discharging of a semi-charged SHTES utilizing the pump at low rotation speed in experiment B4

Experiment B5, discharging with fast rotating pump

A second experiment using the pump was conducted with far better results in terms of increasing circulation. The initial setup was as listed in table 6.6, and the temperature distribution during the experiment is illustrated in figure 6.7. The figure has been simplified, only showing data from a selected few TCs as it otherwise was rather chaotic. At experiment start, the temperature in the cooker quickly dropped and continued to do so with temperatures reaching T=118^oC. After approximately 22 minutes, the pump was powered for 1 minute to attempt to increase the temperature, but unlike in experiment B4, the propeller was now spun at approximately 1300rpm. A significant temperature increase followed with the cooker reaching T=154^oC, and flow between the two tanks could be visually observed when conducting the experiment. In the rest of the system, changes could also be observed from the temperature readings. When powering the drill, the temperature in TC B substantially increased, indicating that hot oil was forced through the bottom pipe, and TC 7 shows the temperature dropping as a result of discharging the SHTES, which was thermally stratified. Circulation did not continue after the use of the pump, and the temperature started to decrease in the cooker again. The pump was therefore powered several times for the remainder of the experiment each time the temperature in the cooker was deemed insufficient for boiling water. The pump was again powered at 1300rpm for 1-minute duration's, illustrated in figure 6.7 by each significant temperature increase in the cooker. The experiment was terminated when the highest temperature in the SHTES approached T=100^oC. The vertical line in the figure marks when the displacement valve was further lowered to increase the oil level in the SHTES.

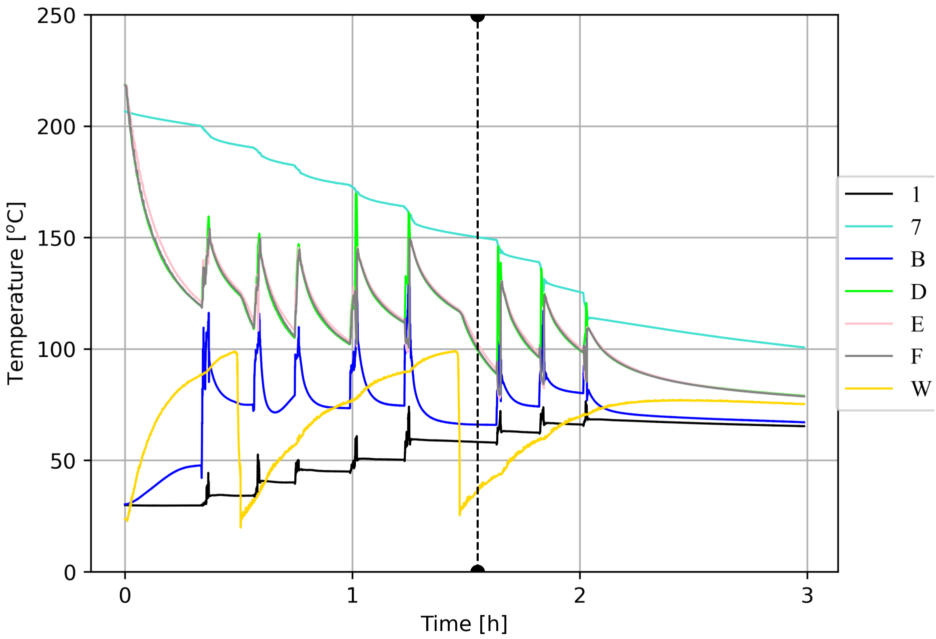


Figure 6.7: Temperature distribution during discharging of a semi-charged SHTES utilizing the pump at high rotation speed in experiment B5

The energy amount and cooking efficiency of the experiment have been calculated and listed in table 6.7 together with a similar experiment during preliminary testing. The values have been calculated as described in section 4.2.1 for an ambient temperature of T=23^oC. As demonstrated in the table, the pump managed to extract virtually all of the usable energy in the system and increased the cooking efficiency compared to a previous similar experiment. What also became apparent is that the pump solution degrades a significant amount of usable energy. Only half of the usable energy was extracted, but none was left in the system after use. The reason behind this, is the loss of thermal stratification, which is illustrated in figure 6.8, showing the temperature distribution over time in the SHTES.

Exp	Initial SHTES	Initial total	Initial usable	Final usable	Extracted	η_{Cook}
A13	104.6 ^oC	4.8 kWh	2.2 kWh	1.0 kWh	0.8 kWh	35.8 %
B5	117.5 ^oC	5.0 kWh	2.6 kWh	0.0 kWh	1.3 kWh	49.3 %

Table 6.7: Amount of stored and extracted energy in experiment B5 and A13

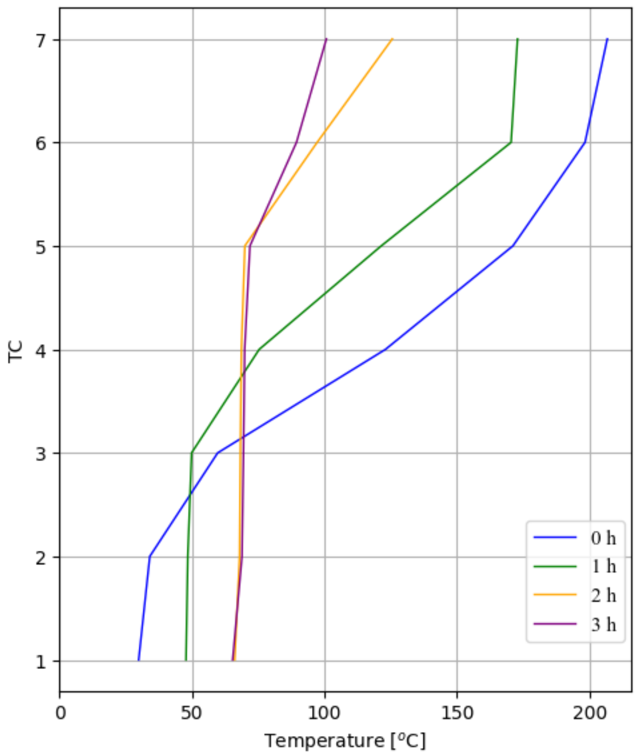


Figure 6.8: Temperature distribution in SHTES over time during experiment B5, illustrating loss of thermal stratification

6.7 Insulation experiment

In section 5.2 a new cooker top was designed to allow for better insulation of the cooker to maintain higher temperatures over time. A storage experiment was therefore conducted to test the effect of the new design. The system was first charged before being left to store energy overnight while being monitored. The system was disconnected from power for the entire storage period, and the initial setup of the experiment is listed in table 6.8.

Experiment	Goal				
B6	Testing temperature development during overnight storage				
Experiment	Valve position	Storage period	Avg temp cooker	Avg temp SHTES	Config
B6	Floating	t=16h	T=206^oC	T=144^oC	2

Table 6.8: Initial setup and goal for the conducted storage experiment

Results from Experiment B6 proved inconclusive due to a testing error. As illustrated in the temperature distribution during the experiment in figure 6.9, after approximately 6 hours marked by the vertical line, readings from TC D, E, and F started to differ. These had, up until this point, showed highly similar values as also seen in experiment A3 during preliminary testing, but suddenly TC D dropped in temperature. The reason behind the sudden drop is deducted as the TC no longer making contact with oil due to the thermal contraction of the Duratherm-630 as the temperature in the system decreased. As TC D, E and F are placed at a very similar height, the remaining TCs will also have lost contact with the oil shortly after. The temperature of oil in the cooker can therefore not be estimated after approximately 6 hours rendering the results inconclusive.

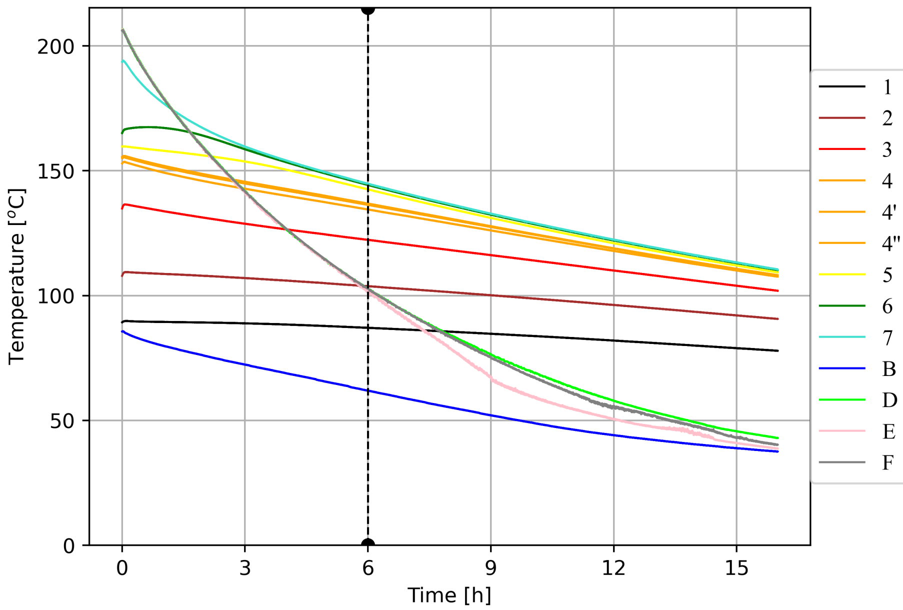


Figure 6.9: Temperature distribution during storage experiment B6

During the beginning of the storage period, thermal imaging was completed to locate local temperature hot spots in the system, with the imaging illustrated in figure 6.10. From the figure, it becomes apparent that the top of the SHTES now has the highest temperature. For preliminary testing, on the contrary, the hottest surface temperature was at the top of the cooker.

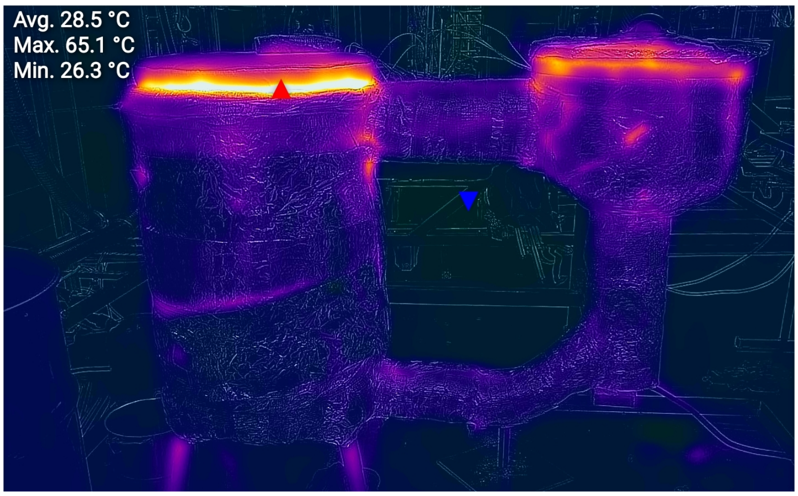


Figure 6.10: Thermal imaging showing local temperature hot spots for experiment B6. The red arrow indicates the hottest point, while blue the coldest

6.8 Cooking experiment with beans

To complete testing of the Dual Tank System, a cooking experiment of food was conducted. The experiment consisted of cooking 2kg of dry kidney beans solely from stored energy in the system.

Experiment	Goal					
B7	Test if the system can provide adequate cooking of beans					
Experiment	Food	Valve position	Power	Avg temp cooker	Avg temp SHTES	Config
B7	T=23^oC	Floating	-	T=230^oC	T=171^oC	2

Table 6.9: Cooking experiment with beans initial setup and goal

To conduct the experiment, the beans were first left to soak overnight in V=5L of water in the inner pot of the pot in pot solution. The system was then charged until the SHTES was thermally stratified and reached the average temperature listed in table 6.9. The power to the heating element was then disconnected, and the inner pot was placed in the cooker top with a small amount of Duratherm-630 between them to increase heat transfer, and the cooking of beans began. The temperature in the cooker quickly dropped, as illustrated in figure 6.12 showing the temperature distribution of the system after the beans were added. After approximately 20 minutes, the temperature began increasing again marking the start of significant natural circulation transporting energy from the SHTES to the cooker. After approximately 30 minutes, simmering was observed in the pot, and continued to do so for the remaining part of the experiment. The vertical lines mark when the displacement valve was lowered z=1.5cm to increase the oil level, and a temperature increase in the cooker followed. 85 minutes after experiment start, an additional V=1L of water was added to the pot to account for evaporation of water as the beans were cooked without a lid. After a total of 2h22min, the beans were fully cooked and removed from the cooker. The beans during and after the experiment are shown in figure 6.11. No burns or damage was observed in the beans as a result of the cooking process.

(a) Simmering with pot in pot solution

(b) Cooked and removed from cooker

Figure 6.11: Beans during and after cooking

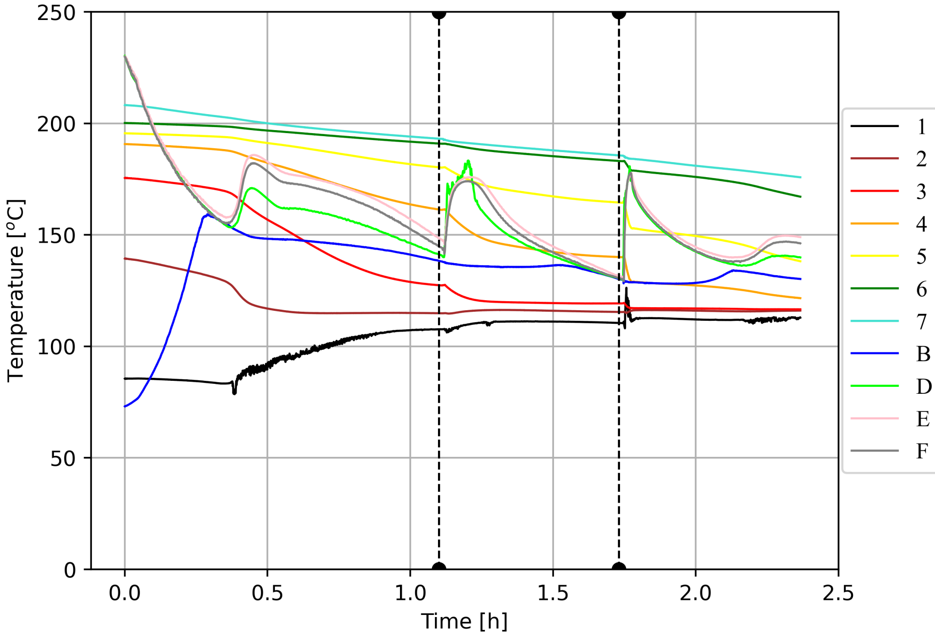


Figure 6.12: Temperature distribution during discharging of a near fully-charged SHTES utilized for cooking kidney beans in experiment B7

During the experiment, the Dual Tank System managed to cook a high-energy-requiring meal from stored energy powered solely by natural circulation. The 2kg of dry beans prepared is sufficient to cover the daily intake of beans for approximately fourteen people based on data for families in rural areas of Uganda [41]. By comparing this to the loss of energy in the system, an estimate for the amount of cooking can be provided. The energy content before and after the cooking experiment is listed in table 6.10 and has been calculated based on the method described in section 4.2.1 for an ambient temperature of T=23^oC. As can be seen, the total amount of energy in the system drops by 2.1kWh, while the amount of usable energy drops by 2.3 kWh. This is a significant consumption of energy, but a total of 1.8kWh of usable energy is still left in the system after the beans were prepared that can be utilized for cooking. Assuming that the entire amount of usable energy can be utilized for cooking, an additional amount of beans for approximately eleven people can be cooked from stored energy left in the system.

Initial SHTES	Final SHTES	Initial total	Final total	Initial usable	Final usable
170.7^oC	135.5 ^oC	7.5 kWh	5.4 kWh	4.1 kWh	1.8 kWh

Table 6.10: Energy content and average temperature at beginning and end of experiment B7

Substantial deviations between the TCs placed in the top of the cooker were observed during the experiment. After 25 minutes, TC D registers T=15^oC lower than TC E, and after 70 minutes, TC D suddenly registers T=8^oC higher than the other TCs with highly fluctuating data. Concurrently no significant difference in boiling rate was observed locally in the pot.

6.9 Experiment discussion

6.9.1 Sources of uncertainty

The sources of uncertainty for the final experiments are largely matching the uncertainty of preliminary testing as described in section 4.7.1. The only differences are in regards to the maximum inaccuracy of temperature measurements and faulty measurement data, which are described below.

The pico-logger used to measure temperature data for the final testing of the Dual Tank System has an accuracy of the sum of ±0.2% of reading and ±0.5 °C [45]. The maximum reading during testing was T=230.5^oC, and the maximum inaccuracy of temperature measurements was therefore 0.961°C. A deviation considered to have little impact on the validity of results due to the nature of testing.

As for the initial testing, one of the TCs in the system showed strange behavior. This is the case for TC D, which showed very rapid fluctuations in temperature, and measured lower temperatures than expected. The data presented from this particular TC has therefore been averaged using an approximation formula to visualize the behavior of the system better. Calculations of the energy content and temperature in the cooker are still based on the average value of TC D, E, and F, causing minor uncertainty.

6.9.2 Displacement valve

Through the conducted experiments in section 6.4 together with the remaining experiments during final testing of the system, a good comparison of the turning and discharging valve can be achieved. In regards to charging, the overflow and cooker temperature can easily be regulated by the displacement valve as for the turning valve. By lowering or raising the valve, the amount of expansion in the oil needed to reach the top pipe is altered, and subsequently, the temperature changes. Still, when charging, similar issues as the turning valve will be encountered in regards to temperature control when the SHTES approaches fully-charged. When hot oil starts to flow into the bottom of the cooker, the already hot oil increases in temperature and expands even further, lowering the density. Lowering the displacement valve will contribute to lowering the temperature somewhat, but temperatures above the flash point will be reached with insufficient regulation available.

In regards to discharging, the displacement valve provides similar control as the turning valve, with slight differences. As for the turning valve, when the liquid level in the SHTES decreases with decreasing temperature, the valve can simply be lowered to enable oil to enter the top pipe, as demonstrated in experiments B2, B3, and others. Also, when discharging the system, the cooking efficiency is highly similar when using the displacement valve compared to the turning valve. This can be deduced by comparing the cooking efficiency for experiments A14 and B2, where the initial setup was very similar, and the respective efficiency was 55.6 % and 53.6 %. The solutions still differ somewhat. The displacement valve allows a temporary increase in mass flow to the cooker from the SHTES when lowering the displacement valve, which was not observed with the turning valve. Still, as previously, if sufficient driving forces are not available to maintain natural circulation, the valve and its position have little impact. The displacement valve, on the other hand, fails to reduce the amount of mass flow between the tanks if the oil level is too high. Also when the system was close to fully-charged, the displacement valve could not be raised high enough to bring the liquid level below the top pipe, and could therefore not reduce the mass transfer if intended (This will not be an issue if filled with less oil, or if the SHTES is partially filled with rocks, as the height increase with expansion would be significantly less in the SHTES).

A concern for the displacement valve was the radial temperature difference and potential mixing that could occur due to dead zones and disturbances when moving the valve. Through testing, this does not appear to be of significance. This is demonstrated in experiment B2, where TC 4, 4', and 4" did not measure temperature differences of significance in the system. The slight difference between them is most likely due to minor differences in height which were observed when being installed in the system. In regards to mixing, the movement of the displacement valve causes some disturbances but appears to be insignificant. Based on the above, the displacement valve is therefore considered to provide the equivalent control of the turning valve, but with the advantage to be regulated from outside the system.

By visual observations during the experiment, it was found that the displacement volume could sink, if not adequately controlled. If the valve was pulled too far downwards, oil could easily flow into the volume, making it sink. The valve should therefore either be taller and more enclosed, or have a mechanism to stop the valve from being lowered too far.

6.9.3 Discharging from a mixed semi-charged SHTES

Experiment B3 addresses several aspects of the discharging process from a semi-charged SHTES, in regards to theories presented in section 4.7.4. A concern for the discharging process was potential short-circuiting in the SHTES with colder oil flowing along the walls into the top pipe, causing natural circulation to not transport sufficient energy to power cooking. TC G confirms that this is not the case, with temperatures in the top pipe consistent with that of the top in the SHTES. This is also the case for experiment B3, which is thermally stratified. Another theory was that the mass flow of oil as a result of natural circulation is mitigated due to cold oil present in the bottom pipe. Due to the mixing in experiment B3, and therefore relatively high bottom temperature of T=135^oC, this should not affect the system. The theory can therefore be tested by comparing the mass flow to a similar but thermally stratified experiment. Still, due to a lack of flow measuring equipment, quantifying the amount of mass flow is highly challenging and a valid comparison can therefore not be established. Nevertheless, based on the temperature in the cooker and SHTES, significant natural circulation appears to take place during the mixed experiment.

Concerning the objective, to test if mixing the SHTES would contribute to increasing the cooking efficiency when discharging, the results do not appear promising. Experiment A15, which is the most analogous experiment in terms of initial usable energy content, has a higher although quite similar cooking efficiency. The potential gain of increased circulation with mixing appears to be offset by the loss of exergy in the system as a result of decreased thermal stratification.

6.9.4 Pump

Through experiments B4 and B5, it becomes clear that the pump can provide sufficient circulation to deplete the SHTES of usable energy, but it needs to be sufficiently rotated. This was demonstrated in experiment B4 when the pump rotated with a maximum of 500rpm and could not achieve sufficient circulation, but in experiment B5 this was easily achieved with 1300rpm.

Although the pump succeeded in providing circulation to deplete the SHTES of usable energy, it resulted in a decrease of thermal stratification. Presented data in table 6.7 show that the use of the pump significantly increased the amount of extracted energy and cooking efficiency compared to previous experiments, but also degraded larger quantities of usable energy. While experiment A13 only had a loss of 0.4kWh of usable energy in the discharging experiment (Still, unable to extract a significant amount of energy), experiment B3 lost 1.3kWh of usable energy. Based on the temperature distribution during the experiment, it appears that when powering the pump, circulation was too rapid and transported large quantities of energy through the cooker without being used, heating the bottom layers of the SHTES destroying thermal stratification.

Based on the above, the concept of using the pump is deemed to function well, but further development to minimize losses and optimize circulation is required. A slower and more consistent mass flow of oil should contribute to mitigate the loss of usable energy.

6.9.5 Insulation

Due to the lack of contact between TCs and oil, the effect of the new cooker top and insulation could not be estimated based on experimental work. Therefore testing failed to enlighten the objective presented in section 6.1 of "Is the heat loss of the cooker reduced by new cooker top and insulation, so that usable temperatures are maintained over longer time periods". Further testing, where the TCs in the cooker are repositioned to maintain thermal contact with oil for the entire duration of the experiment, should be conducted. Still, based on thermal imaging illustrated in figure 6.10 it appears that the local temperature hot spot discovered in the cooker during preliminary testing has been reduced, and the weakest insulation now appears the in the top of the SHTES.

Inadequate insulation of the cooker, as described during preliminary testing in section 4.7.3, no longer appears to be a main concern. The main reason is that the transport of energy between the tanks no longer depends solely on natural circulation alone. If temperatures in the cooker are too low for cooking, the pump can simply be used to increase the temperature if usable energy is available in the SHTES.

6.9.6 Cooking beans

Experiment B7, where beans were cooked from stored energy, demonstrated that Dual Tank System can cook wet food sufficiently while discharging, as listed in the objectives. In the experiment, the system discharged through natural circulation with only minor adjustments, and a substantial amount of food was prepared with usable energy still left in the system for more. As beans are a food type that requires large quantities of energy to prepare, if exchanged with other foods as rice, that requires less energy, larger quantities of food could be cooked with the same setup. During the experiment, some differences in the measured temperature around the pot were discovered, although fluctuating, which could indicate uneven cooking of food as a result of local differences in heat transfer to the pot. Concurrently no significant differences in boiling or signs of burning food were observed in the pot. The temperature fluctuations could therefore be a result of local effects around the TCs, but their overall impact is not significant enough to affect the cooking of food. Although not tested here, the use of the pump can increase the cooking rate if needed by transporting more hot oil to the cooker; alternatively, the cooking rate can be reduced by lifting the inner pot onto spacers to decrease the thermal contact with the cooker top. Based on the above, the Dual Tank System is therefore considered to capable of cooking food sufficiently while discharging.

7 System discussion

In this section, the performance and design of the Dual Tank system as a clean cooking solution is discussed by comparing it to the objective and background of the thesis described in section 1.1 and 1.2.

By the use of the SHTES, the Dual Tank System is able to store supplied energy over time. This allows the system to provide steady cooking over time periods with limited or no access to electricity, provided that sufficient energy has previously been supplied and stored in the SHTES. Through the SHTES, the system therefore enables the use of intermittent energy sources such as solar, wind or others. Based on the SHTES size and thermal resistance provided by the insulation of the system, the amount of storable energy over time changes. The experimental work, as described in section 4.5, demonstrate that the developed prototype can store usable energy over a time period of 16 hours. The Dual Tank System can therefore provide cooking even during the nighttime if powered by an energy source such as solar power.

The separation of the SHTES and cooker in the Dual Tank System enables both low power cooking, and ease of upscaling. Low power cooking is enabled due to the relatively small amount of thermal mass that requires heating to, in turn, heat the content of the pot. This is due to a significantly smaller amount of oil stored in the cooker compared to the SHTES, and limited thermal contact between the two tanks when overflow is hindered, as demonstrated in experiment A10 in section 4.4. Although the system allows for cooking with relatively low power, the capacity of the heating element and power of the energy source needs to be considered in regard to cooking requirements and the SHTES storage capacity. The system enables ease of upscaling as the separation of the cooker, and SHTES, allows their relative size to altered with only minor system modifications required. Their separation through pipes also allows the cooker to be placed indoors, while the SHTES outside. This allows for implementing the system with a large SHTES without occupying a large amount of space indoors, and makes the system easy to upscale based on need.

To transport energy between the two tanks, the Dual Tank System utilizes natural circulation driven by thermal expansion of oil. In terms of charging, the system works well, with natural circulation initializing and transporting energy from the heating element in the cooker to the SHTES. This, in turn, limits overheating in the cooker as well as charging and thermally stratifying the SHTES when supplied with hot oil through the top pipe. In terms of discharging the system, sufficient natural circulation again occurs, enabling cooking from stored energy when fully charged, but the system struggles with lower charging levels. This results in a low cooking efficiency as usable energy is left in the SHTES, unable to be utilized. The issue was solved by designing and implementing a pump that mechanically initializes circulation. Further optimization is required to utilize the full potential of the added pump.

To provide sufficient temperature control in the Dual Tank System, two different valves have been designed and tested. The first version was the turning valve, which, although provided sufficient temperature control, was discarded due to being unsafe and tough to regulate. The second version was the displacement valve which uses a movable volume that can be adjusted from outside the system to regulate the temperature in the cooker. This provides controlled cooking temperatures, and can increase thermal stratification of the SHTES by increasing the overflow temperature when not used for cooking. Still, when charging, the displacement valve will lose control over temperatures when the SHTES approaches fully charged. Therefore a thermostat switch to cut power to the heating element, when exceeding the flash point of oil, should be implemented. Monitoring equipment for the temperatures in the cooker and SHTES should also be implemented to provide feedback to the user, as decisions for valve position have been based on TC data that will not be available in a final version.

The essential design requirement of any system utilizing high temperatures is safety. The Dual Tank System has been designed with a significant focus on safety, but no experiments related specific to safety have been carried out. By thoroughly insulating the system, the user is protected from burns due to eliminating contact with hot surfaces. The design of the cooker top and system prohibits water from entering the system, mitigating the risk of any potential rapid formation of steam, that together with hot oil could severely burn the user. The overflow pipe placed in the SHTES will protect from over-expansion of oil if the system is incorrectly filled with an excessive amount. Finally the thermostat proposed above will drastically limit the potential of fire by automatically cutting power to the system when the temperature of the oil becomes too high. The basic design of the Dual Tank System is therefore considered safe.

Through experimental testing, the system has been demonstrated to allow sufficient cooking of wet food. A significant quantity of kidney beans was cooked powered by natural circulation of stored energy with proficient temperature control in section 6.8. When temperatures in the cooker became too low, it was simply increased using the displacement valve. Some variations of temperature were observed around the pot, but no burns or differences in boiling were observed in the beans. The system is also considered to allow cooking when charging, based on the large number of boiling tests conducted, which can be approximated to preparing wet foods. Further testing should still be conducted in regards to cooking with the pot in pot solution, and testing other food types which are more sensitive to burning.

The final objective and a large design focus for the system was to be cheap and simple to manufacture to promote its use in areas currently affected by unclean cooking methods. Standard parts have been used to reduce costs and increase the simplicity of the system. Pipes between the cooker and SHTES, the end cap, the oil barrel used for SHTES, and the ball valve are all standard parts that can be bought at a relatively low cost. The displacement valve for controlling the flow of oil is made to be as simple and therefore as cheap as possible to manufacture. The pump complicates the production of the system, but this depends on the method for inducing rotation. A bigger concern in regards of costs is the electrical equipment such as the heating element, electricity supply and controller and various measuring instruments. A cost analysis is therefore required to consider the economic viability of the system.

Based on the above, the Dual Tank System is considered to be a viable clean cooking system, but further work is required to develop and evaluate its viability for implementation.

8 Conclusion

In this thesis, a natural-circulating heat storage for cooking has been reviewed, tested, and further developed, with the objective of providing clean cooking in a rural African environment. The work has resulted in a prototype that has the capabilities required for a clean cooker, named the Dual Tank System. The Dual Tank System consists of two tanks of different size that is connected to each other through two pipes. The system is filled with a liquid heat storage medium in the form of oil, which is heated by a heating element placed in the smallest tank named the cooker. As oil expands or contracts in the cooker with temperature changes, natural circulation is induced to transport energy to or from the large tank acting as a sensible heat thermal energy storage, SHTES. For the cooking process heat extraction from the system is occurring in the cooker through heat exchange between a pot and oil.

Testing demonstrated that when powering the heating element, oil between the two tanks circulates well, protecting the cooker from overheating and both charging and thermally stratifying the SHTES. When discharging the system, sufficient natural circulation occurs to sustain cooking when the system is close to fully charged, but struggles when only partially charged. A pump was therefore designed and tested that allowed the extraction of usable energy (stored energy above T=100^{o}C) from the SHTES. The maximum discharging efficiency achieved of usable energy during testing was approximately 68 %, which shows a substantial amount of stored energy can be re-extracted, but some uncertainties in regards of reliable effectiveness remains. With the implemented thermal insulation, the Dual Tank System managed to store considerable amounts of usable energy over a time period of 16 hours. This shows that the system can provide cooking even during night time if connected to energy sources such as solar power. A valve concept to provide reasonable temperature control between the Cooker and the SHTES was also tested, but the initial solution was difficult to regulate and deemed unsafe. A new displacement type valve was therefore developed and tested; it allowed for similar control but without the issues of the previous valve. A cooking test of 2kg kidney beans also showed that the system is proficient in cooking wet foods.

The Dual Tank System is designed with safety, simplicity, and affordability in mind. It is evaluated to succeed with the first two, based on, among others, the system being fully closed, and a simple working concept and parts used in the system. Further analysis is required for considering affordability, but the simplicity of the system decreases costs.

The conclusion is, therefore, that Dual Tank System is a sufficient heat storage for clean cooking. Still, further work is required to reach a final version that is listed in the section 8.1.

8.1 Further work

Through the thesis, several items were discovered that could benefit the Dual Tank System through further work. These items are listed below:

- The use of rocks, the secondary heating element, and spacers on the cooker top should be implemented and tested to validate the design and potentially improve the system in terms of functionality and cost.
- The system should be matured closer to its final design stage. This involves implementing the solution for powering the pump, installing a thermostat switch, and temperature measuring equipment to add more control and added safety to the system.

- Further cooking tests should be conducted with real food, with the system in both - a charging and discharging modus. This will determine food types the system can cook, and if flow controlling devices should be implemented to control the temperature distribution around the cooking pot to avoid any burning or uneven cooking. The system should also be tested in terms of frying due to its high working temperatures.
- The Dual Tank System should be tested in rural areas of Africa for its real-life use. This would allow for feedback from potential users for the further development of the system. The final design should be user driven.
- A cost analysis should be completed for the system. This would determine if the system is cost-efficient enough for the foreseen deployment areas and if specific components would need to be altered to decrease cost.

References

[1] International Energy Agency, World Energy Outlook 2021 [Internet], Paris: International Energy Agency, October 2021, [cited 2021-11-17], Available from: https://www.iea.org/reports/world-energy-outlook-2021.

[2] International Energy Agency, SDG7: Data and Projections [Internet], International Energy Agency , Paris, 2020, [cited 2021-12-14], Available from: https://www.iea.org/reports/sdg7-data-and-projections.

[3] Madhu Subedi, Robin B Matthews, Mark Pogson, Assefa Abegaz, Bedru Babulo Balana, Joseph Oyesiku-Blakemore, and Jo Smith. Can biogas digesters help to reduce deforestation in africa? *Biomass and Bioenergy*, 70:87–98, 2014.

[4] United Nations, The Sustainable Development Goals Report 2021 [Internet],New York, United Nations, 2021, [cited 2021-11-18], Available from: https://unstats.un.org/sdgs/report/2021/.

[5] ESMAP, Global Photovoltaic Power Potential by Country [Internet], Washington, DC, World Bank, June 2020, [cited 2021-11-18], Available from: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/466331592817725242/global-photovoltaic-power-potential-by-country.

[6] Norpart, NORHED ll 2021-2026 [Internet], Oslo, 2020-03-10, [cited 2021-11-18], Available from: https://www.norad.no/en/front/funding/norhed/.

[7] Peter Olsen. Alexander, Heat storage for cooking - Project work, Trondheim: NTNU, 2021.

[8] Gunn Helen Nylund and Andreas Bjørshol. Single tank oil based heat storage for cooking. Master's thesis, NTNU, 2021.

[9] Vilde Svanevik Stordal and Oda Kristine Sneen Fjeldsæter. Photovoltaic solar cooker with heat storage. Master's thesis, NTNU, 2020.

[10] Theodore L Bergman, Frank P Incropera, David P DeWitt, and Adrienne S Lavine. *Fundamentals of heat and mass transfer*. John Wiley & Sons, 7th edition, 2011.

[11] Ioan Sarbu and Calin Sebarchievici. A comprehensive review of thermal energy storage. *Sustainability*, 10(1):191, 2018.

[12] Ibrahim Dincer and Marc A.Rosen. *Thermal Energy Storage: Systems and Applications*. John Wiley & Sons, 2nd edition, 2011.

[13] Jacek D Wojcik and Jihong Wang. Technical feasibility study of thermal energy storage integration into the conventional power plant cycle. *Energies*, 10(2):205, 2017.

[14] HW Cooper and Gene Simmons. The effect of cracks on the thermal expansion of rocks. *Earth and Planetary Science Letters*, 36(3):404–412, 1977.

[15] Michael J Moran, Howard N Shapiro, Daisie D Boettner, and Margaret B Bailey. *Fundamentals of engineering thermodynamics*. John Wiley & Sons, 9th edition, 2018.

[16] Pierre Perrot. *A to Z of Thermodynamics*. Oxford University Press on Demand, 1998.

[17] Marc A Rosen. The exergy of stratified thermal energy storages. *Solar energy*, 71(3):173–185, 2001.

[18] M Misale, P Garibaldi, JC Passos, and G Ghisi De Bitencourt. Experiments in a single-phase natural circulation mini-loop. *Experimental Thermal and Fluid Science*, 31(8):1111–1120, 2007.

[19] R Greif. Natural circulation loops. *Journal of heat transfer*, 1988.

[20] Y Cengel and J Cimbala. *Fluid mechanics Fundamentals and Applications.* Tata McGraw-Hill Education, third edition, 2010.

[21] Mario Misale. Overview on single-phase natural circulation loops. In *Proc. of the intl. Conf. on advances in mechanical and automation engineering–MAE*, volume 2014, 2014.

[22] Kays W.M. and Crawford M.E. *Convective heat and mass transfer.* McGraw-Hill and Book Company, 2nd edition, 1980.

[23] A Harmim, M Merzouk, M Boukar, and M Amar. Solar cooking development in algerian sahara: Towards a socially suitable solar cooker. *Renewable and Sustainable Energy Reviews*, 37:207–214, 2014.

[24] Amal Herez, Mohamad Ramadan, and Mahmoud Khaled. Review on solar cooker systems: Economic and environmental study for different lebanese scenarios. *Renewable and Sustainable Energy Reviews*, 81:421–432, 2018.

[25] Klemens Schwarzer and Maria Eugenia Vieira Da Silva. Solar cooking system with or without heat storage for families and institutions. *Solar Energy*, 75(1):35–41, 2003.

[26] Maxime Mussard, Alexandre Gueno, and Ole Jørgen Nydal. Experimental study of solar cooking using heat storage in comparison with direct heating. *Solar Energy*, 98:375–383, 2013.

[27] Atul Sharma, CR Chen, VVS Murty, and Anant Shukla. Solar cooker with latent heat storage systems: a review. *Renewable and Sustainable Energy Reviews*, 13(6-7):1599–1605, 2009.

[28] Lameck Nkhonjera, Tunde Bello-Ochende, Geoffrey John, and Cecil K King'ondu. A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews*, 75:157–167, 2017.

[29] SD Sharma, D Buddhi, RL Sawhney, and Atul Sharma. Design, development and performance evaluation of a latent heat storage unit for evening cooking in a solar cooker. *Energy Conversion and Management*, 41(14):1497–1508, 2000.

[30] SD Sharma, Takeshi Iwata, Hiroaki Kitano, and Kazunobu Sagara. Thermal performance of a solar cooker based on an evacuated tube solar collector with a pcm storage unit. *Solar Energy*, 78(3):416–426, 2005.

[31] Antonio Lecuona, José-Ignacio Nogueira, Rubén Ventas, Mathieu Legrand, et al. Solar cooker of the portable parabolic type incorporating heat storage based on pcm. *Applied energy*, 111:1136–1146, 2013.

[32] Ndiaga Mbodji and Ali Hajji. Modeling, testing, and parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking. *Energy, Sustainability and Society*, 7(1):1–16, 2017.

[33] Maxime Mussard and Ole Jørgen Nydal. Charging of a heat storage coupled with a low-cost small-scale solar parabolic trough for cooking purposes. *Solar Energy*, 95:144–154, 2013.

[34] Rahul Khatri, Rahul Goyal, and Ravi Kumar Sharma. Advances in the developments of solar cooker for sustainable development: a comprehensive review. *Renewable and Sustainable Energy Reviews*, 145:111166, 2021.

[35] A Mawire and M McPherson. Experimental and simulated temperature distribution of an oil-pebble bed thermal energy storage system with a variable heat source. *Applied Thermal Engineering*, 29(5-6):1086–1095, 2009.

[36] R Lugolole, A Mawire, KA Lentswe, D Okello, and K Nyeinga. Thermal performance comparison of three sensible heat thermal energy storage systems during charging cycles. *Sustainable Energy Technologies and Assessments*, 30:37–51, 2018.

[37] Robert Lugolole, Ashmore Mawire, Denis Okello, Katlego A Lentswe, Karidewa Nyeinga, and Adedamola B Shobo. Experimental analyses of sensible heat thermal energy storage systems during discharging. *Sustainable Energy Technologies and Assessments*, 35:117–130, 2019.

[38] H Grirate, H Agalit, N Zari, A Elmchaouri, S Molina, and R Couturier. Experimental and numerical investigation of potential filler materials for thermal oil thermocline storage. *Solar energy*, 131:260–274, 2016.

[39] Eugene C Robertson and Bruce S Hemingway. *Estimating heat capacity and heat content of rocks*. US Geological Survey, 1995.

[40] Technical data duratherm 630, Duratherm fluids [Internet], [cited 2021-09-02], Available from: https://durathermfluids.com/pdf/productdata/heattransfer/duratherm-630.pdf.

[41] Pamella K Kajumba, Denis Okello, Karidewa Nyeinga, and Ole J Nydal. Assessment of the energy needs for cooking local food in uganda: A strategy for sizing thermal energy storage with cooker system. *Energy for Sustainable Development*, 67:67–80, 2022.

[42] UNIFRAX, Isofrax® 1260°C Felt [Internet], [cited 2022-03-10], Available from: https://www.unifrax.com/wp-content/uploads/2018/08/Isofrax-1260C-Felt-EN.pdf.

[43] FyreWrap, FyreWrap® LT Blanket [Internet], [cited 2022-03-10], Available from: https://www.bagges.no/wp-content/uploads/2016/02/FyreWrap-LT-Blanket-rev.11-311017-JJ.pdf.

[44] Pico Technology, Technical data TC-08 [Internet], [cited 2022-03-10], Available from: https://www.picotech.com/download/datasheets/usb-tc-08-thermocouple-data-logger-data-sheet.pdf.

[45] Pico Technology, Picolog 6 data logging software, Version - [Software], Cambridgeshire ,Pico Technology, [cited 2022-03-10], Available from: https://www.picotech.com/library/dataloggers/picolog-6-data-logger-software.

Appendix

A1 Preliminary testing

A1.1 Charging experiments

Experiment A1, system behaviour during charging

Experiment A1 was the first experiment and had the goal to test general system behaviour as listed in table 4.2. The results from the experiment are shown in figure A1.1. As can be seen from the TCs, the system started to increase in temperature on the cooker side, while temperatures remained constant in the SHTES. After approximately 15 minutes, overflow from the cooker to the SHTES was achieved, as can be seen by the sharp increase in temperature of TC 7. This happened at approximately 95 ^oC of the hottest oil in the cooker, shown by TC D, E, and F. The rapidly varying values from TC 7 were due to the TC being placed too high in the storage compared to the oil level as mentioned in section 4.3.3. Only after approximately 150 minutes was the oil level high enough to produce consistent readings. Overflow from the cooker to the SHTES resulted in a reduced temperature increase in the cooker, and after 30 minutes, increasing again when the valve was turned upwards, hindering overflow. After 50 minutes, boiling was achieved in the pot. The water was left to boil until 90 minutes, before it was removed from the pot, and the valve was turned upwards to limit overflow. The first sudden temperature rise and drop at the top of the graph was due to valve position causing temperatures to increase before the power was accidentally cut to the system at 105 minutes. When plugged back in, the temperature started to sharply increase before the power again was cut, but this time intentionally not to exceed the flash point of Duratherm-630. After some time, the valve was then turned downwards, and the power plugged back in, causing the oil temperature in the cooker to stabilize as can be seen by TC D, E, and F.

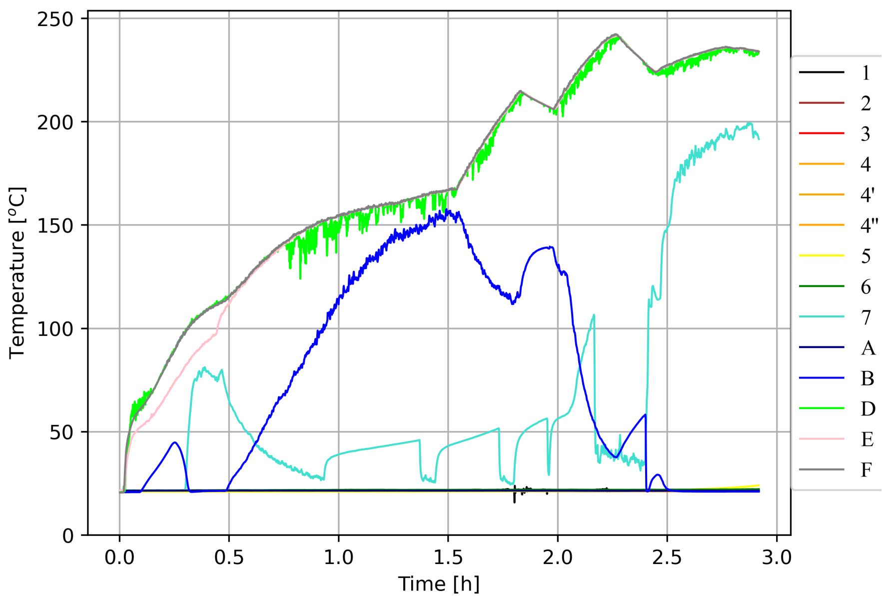


Figure A1.1: Temperature distribution during high power charging in experiment A1

Experiment A4, high initial temperature charging

Experiment A4 was the first charging test with higher initial temperatures, and the goal was to control if the oil temperature would stay within a reasonable range when overall temperatures increased in the system. The experiment was conducted with the configuration described in table 4.2, and lasted for a total of 210 minutes before it had to be terminated before conclusive results were reached. The temperature distribution in the system during the experiment can be seen in figure A1.2. The experiment was terminated due to the observation of noises in the system of both bubbles and similar noises too when deep-frying food. The noises quickly grew more violent before the power was unplugged after approximately 4 minutes from the first observation. The noises continued along with the formation of bubbles from what appeared to be the bottom pipe for several minutes after the first observation. It was therefore concluded that due to the quite rough behavior, the issue needed to be investigated further to locate the cause. New charging experiments were therefore conducted under closer monitoring of the system. This is described in section 4.4.

The data from TC B, as mentioned in section 4.3.3 is kept in figure A1.2 to illustrate the behavior of the TC. As can be seen, the TC consistently registers values below all other temperatures in the system. This is inconsistent with the flow direction where oil extracted from the SHTES flows past TC B, and should therefore have the same temperature if not higher due to being placed close to the heating element. It is therefore believed that the TC makes thermal contact with the pipe wall it is placed within, producing inconsistent readings.

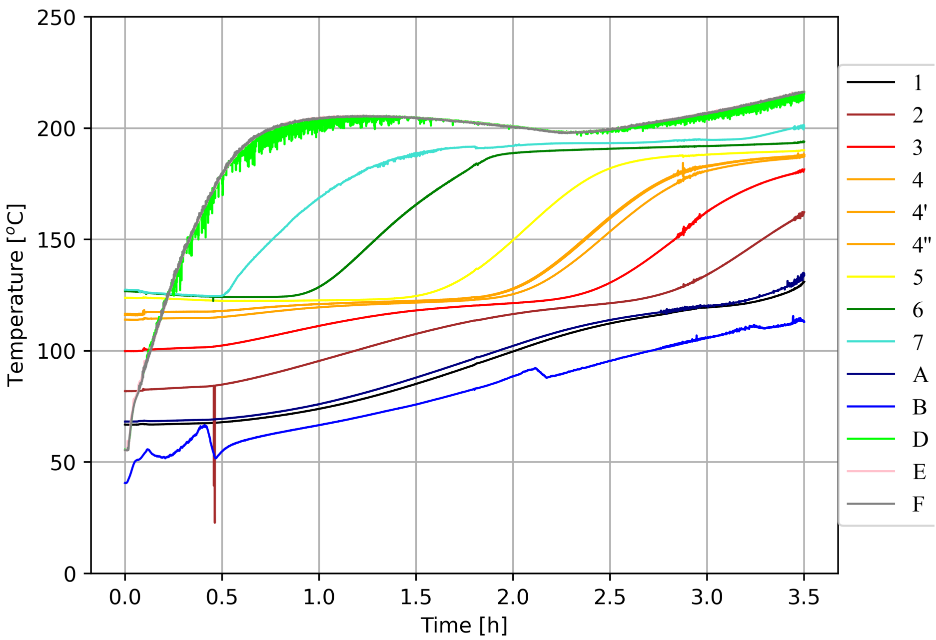


Figure A1.2: Temperature distribution during high power charging in experiment A4 with higher initial temperatures

A1.2 Storage experiment

Experiment A9, storage test with obstruction of flow

Experiment A9 was the second storage experiment completed, and aimed to test if the valve position during storage affected the heat loss. The experiment was completed with the same setup as described in experiment A3, but with the valve turned upwards, eliminating overflow between the two tanks. The temperature distribution during the test is shown in figure A1.3. During the experiment, the average temperature in the SHTES dropped from T=174^oC to T=123^oC, and for the top layer of the cooker, T=222^oC to T=56^oC.

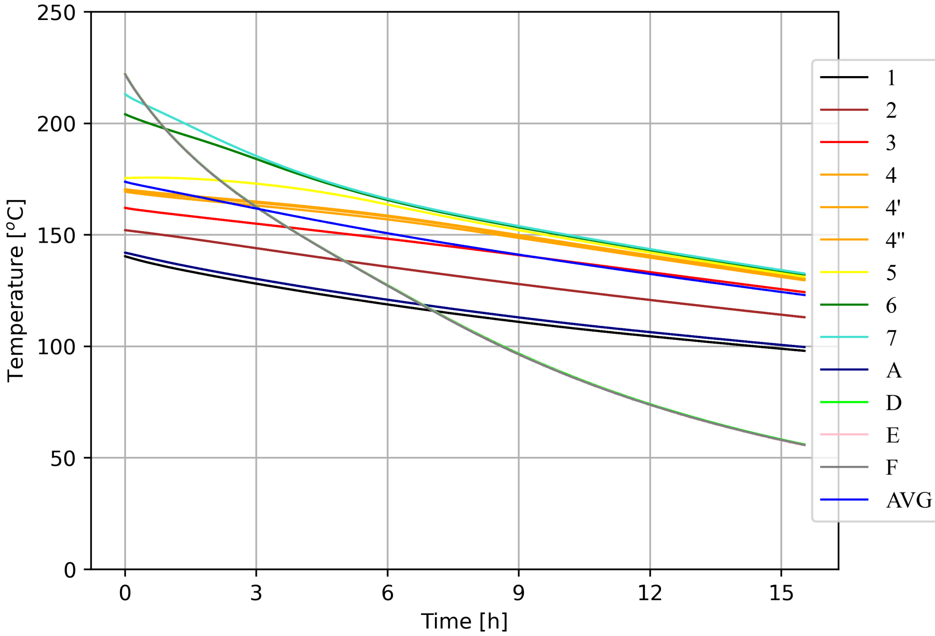


Figure A1.3: Temperature distribution during storage experiment A9 with the valve position eliminating circulation between the two tanks

A1.3 Discharging experiments

Experiment A5, discharging from a near fully charged SHTES

The first discharging test conducted on the Dual Tank System was conducted to form the foundation for further testing, and showed promising results in terms of achieving cooking while discharging the SHTES. Data from TC D is removed from the experiment as the TC made direct contact with the pot and therefore logged far lower temperatures than the actual surrounding oil. The experiment began with the configuration shown in table 4.6, and the temperature distribution during the experiment was as illustrated in figure A1.4. After only 10 minutes, the water in the pot started to boil, and was exchanged with another 5L of water at T=25^oC after additional 5 minutes marked by the line. The fresh batch of water started to boil after another 15 minutes, and was left in the pot for the rest of the experiment with a lid covering the pot. The system managed to sustain boiling in the pot until 160 minutes was reached. From temperature readings in the SHTES, the SHTES can clearly be seen discharging during the experiment only powered by natural circulation. The large fluctuations in temperature readings between 75 and 120 minutes were due to testing different valve positions.

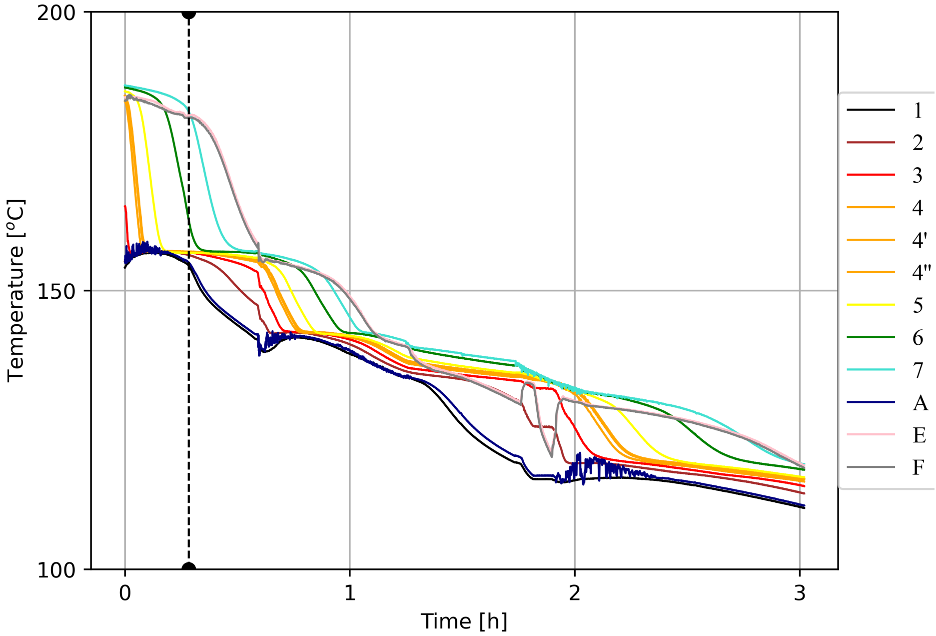


Figure A1.4: Temperature distribution during discharging of the system in the form of heating water in experiment A5

Experiment A12, discharging from a semi-charged SHTES

This experiment deviated from the standardized testing procedure for discharging experiments as ice was also used to test the system. The first boiling batch was for V=5L of water, and as can be seen by TCs in the cooker, natural circulation did not occur. The dotted line marks when the valve was turned fully down to examine the effect on the system, which appeared to make little to no difference, but remained in the position for the rest of the experiment. For the second boiling batch, the water was removed, and new V=5L was added to the pot, and the temperature in the cooker increased but quickly started to cool. After a total of 1h10min into the experiment, ice was added to the pot to try to initialize natural circulation with more significant temperature gradients between the pot and oil, but only with momentary success. The experiment was terminated after 2h30 min when the water stopped increasing in temperature. Oil of high temperature was still left in the SHTES.

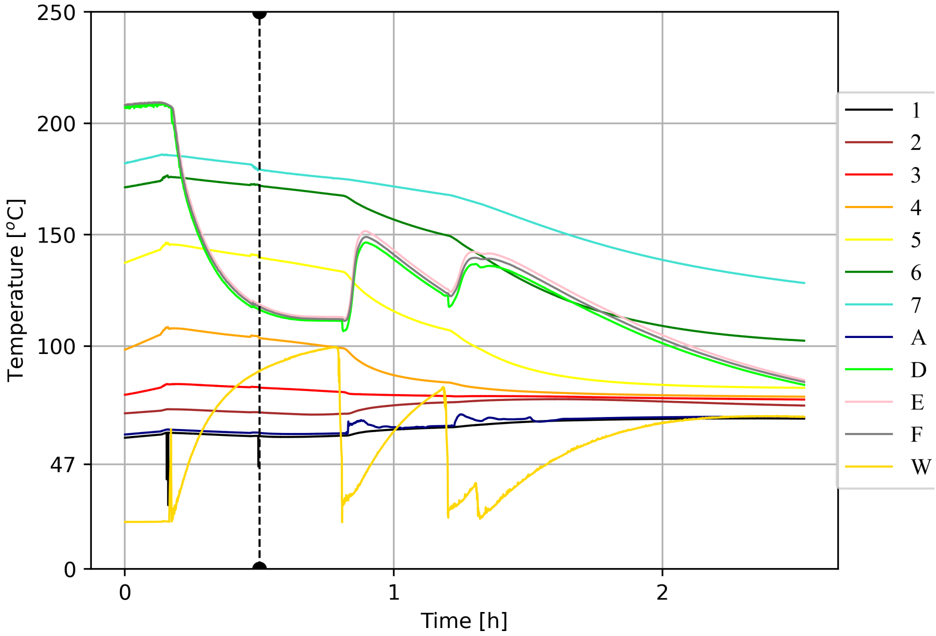


Figure A1.5: Temperature distribution during discharging from a semi-charged SHTES in experiment A12

Experiment A13, discharging from a semi-charged SHTES

Experiment A13 tested the discharging behavior of the system for a slightly higher average temperature in the SHTES than experiment A11, shown in table 4.6 together with the initial setup. As for previous experiments, natural circulation did not occur during the first boiling batch, with the temperatures in the cooker decreasing for the entire duration, becoming so low that boiling was not believed to be achieved. The water was therefore replaced with V=5L of cold water, and the temperature in the cooker increased by over T=30^oC before again declining. Towards the end of the experiment, marked by the dotted line, different solutions were tested to initialize circulation unsuccessfully. The experiment was terminated after 1h15min.

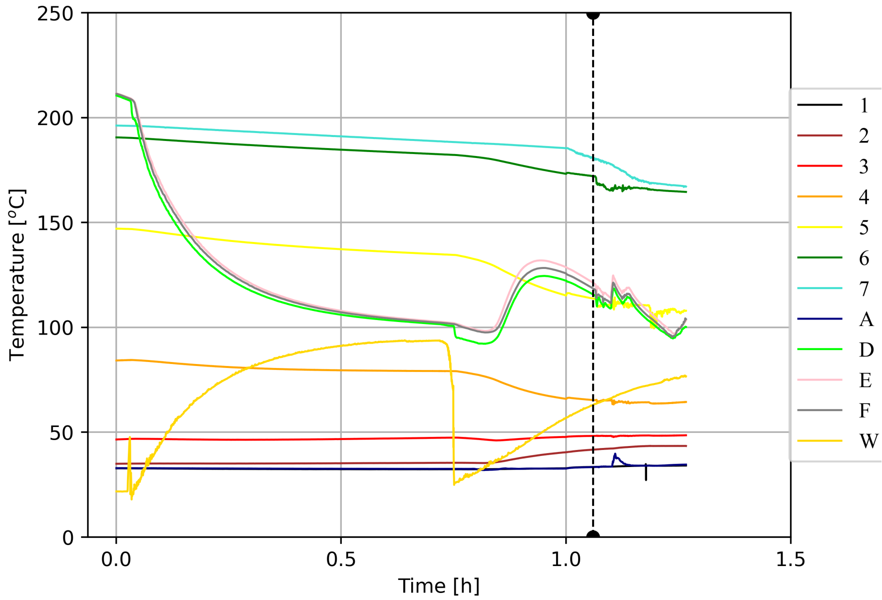


Figure A1.6: Temperature distribution during discharging from a semi-charged SHTES in experiment A13

Experiment A14, discharging from a semi-charged SHTES

The experiment was conducted with the initial setup listed in table 4.6, and the valve was left in its initial position for the entire experiment. As illustrated, the temperature in the cooker varied during the experiment insinuating the beginning of natural circulation multiple times, but never fully stabilizing. When boiling no longer could be achieved in the third water batch, the experiment was terminated with high-temperature oil was still left in the SHTES.

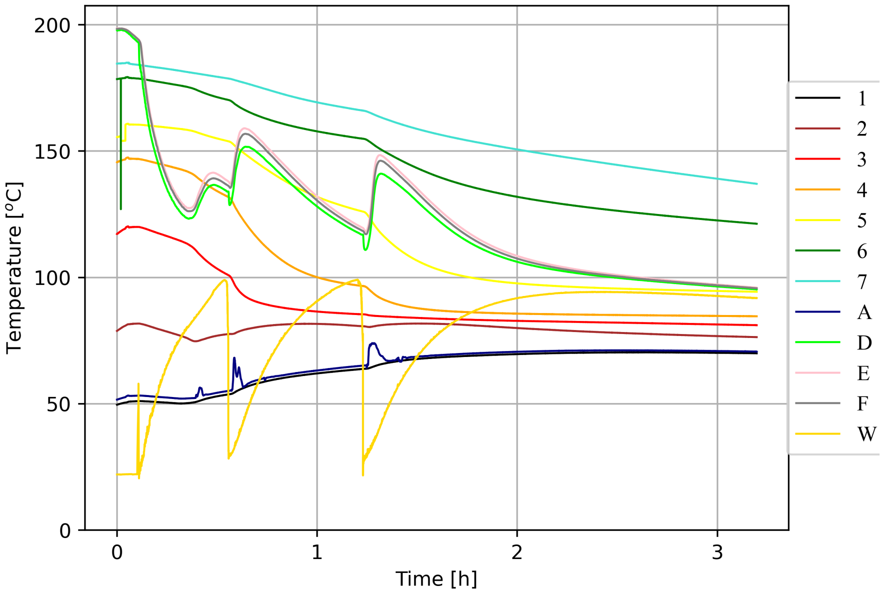


Figure A1.7: Temperature distribution during discharging from a semi-charged SHTES in experiment A14

A2 Final testing

Experiment B0, prototype displacement valve

The goal of the experiment was to test if temperature and flow control could be achieved by using a displacement valve. A charging and discharging experiment were therefore conducted with a pot directly placed into the SHTES and weighting it down manually to test the concept. The pot can be seen in figure A2.1. The experiment was conducted with high power and an oil volume of V=0.09m^3 to allow room for the pot in the SHTES. The temperature distribution during the experiment is shown in figure A2.2, and the experiment course was as described below.

Figure A2.1: Simplified displacement volume in SHTES

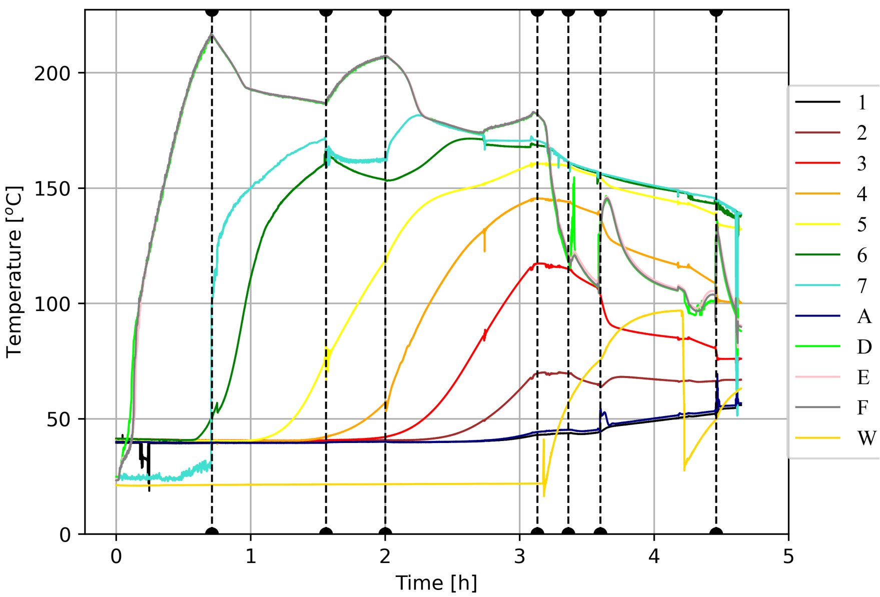


Figure A2.2: Temperature distribution during experiment B0 with a prototype displacement valve

- Power was then added to the system (1800W), and the temperature quickly rose and continued to do so before reaching 220^oC at the first line
- Pot was then weighted down at the first line, causing the oil level to rise, decreasing the overflow temperature, which can be clearly seen
- Weight is then removed at the second line, and the temperature in the funnel can be seen increasing
- Third line weight is added, and the temperature drops again
- At the fourth line, the power is removed, and 5L of cold water is added to the cooking pot, with a sharp temperature decrease in the cooker following
- At the fifth line, weight was added to the displacement volume to try to induce circulation, but only with a minor effect that could not be sustained
- At the sixth line, significantly more weight was added to the displacement volume, and the temperature in the cooker can be seen increasing abruptly, before again decreasing, indicating circulation is not maintained
- Water is swapped just before boiling as the time was taking long, and a small temperature increase in the funnel can be seen
- At the seventh line, the displacement volume was lowered further to try to induce circulation but could not be achieved.

From the experiment, it can be clearly seen that the temperature in the funnel can be controlled with the displacement valve during charging. By moving the displacement volume up or down controls the height of the oil, and can therefore also regulate the overflow temperature. During discharging with the valve, it is difficult to find conclusive results as the system was not able to achieve natural circulation due to too low temperatures in the storage.

Initial part of Experiment B3

Figure A2.3 illustrates the temperature development during the initial part of Experiment B3. The first line marks when the valve was lowered to reduce the temperature in the cooker, and the second marking when the power was unplugged, and a discharging test was completed where three batches of water were fully boiled, with an additional heated to T=78^oC. The second line marks where the water was removed from the system and power was reconnected to the system.

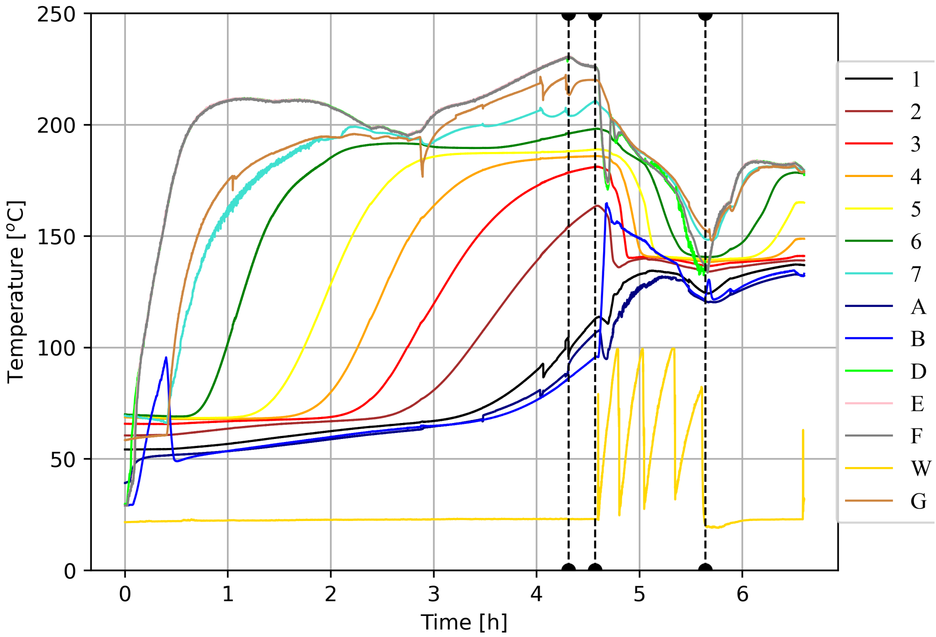
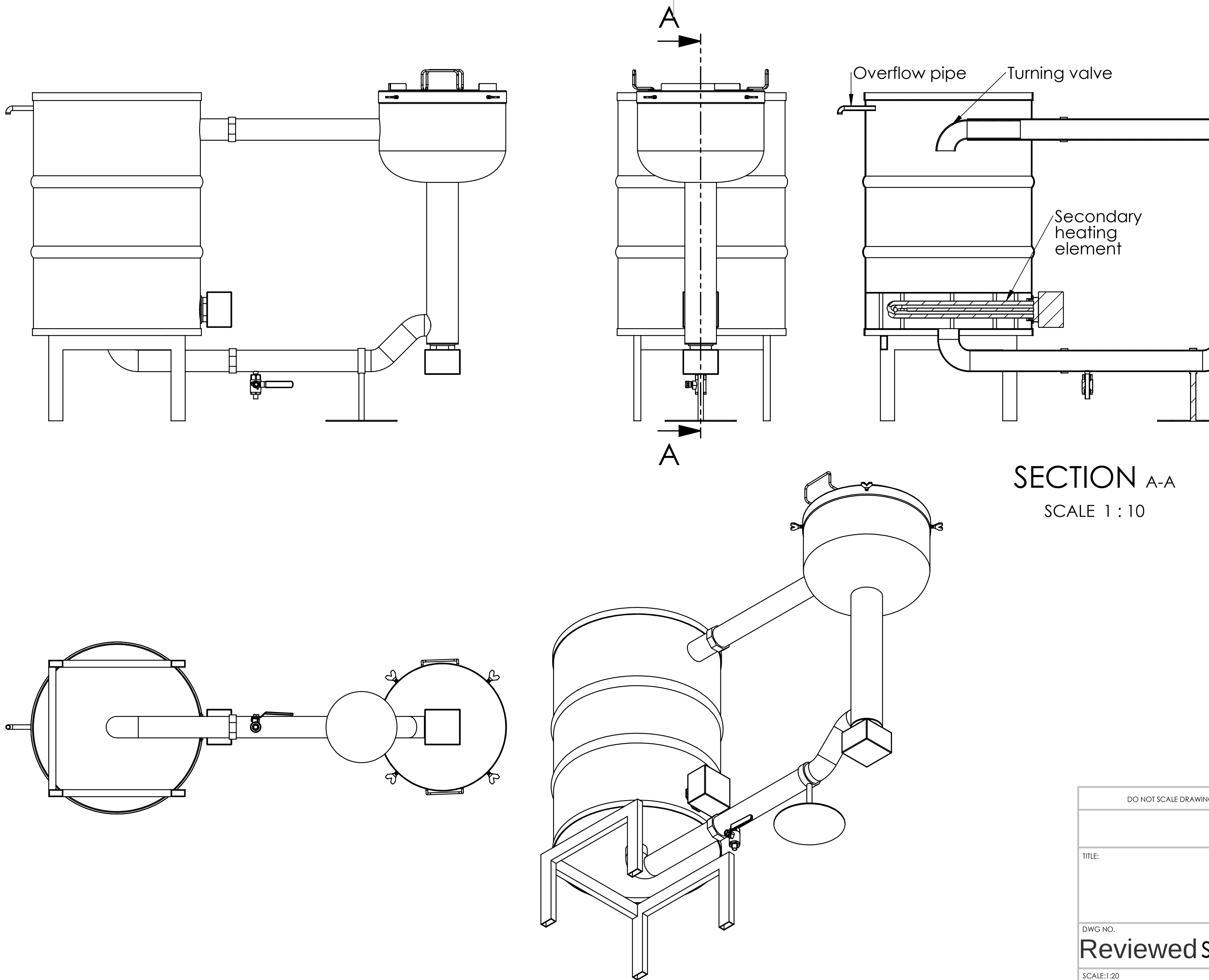


Figure A2.3: Temperature distribution of the Dual Tank System during the initial part of experiment B3

A3 Technical drawings Dual Tank System

A3.1 Reviewed system



DO NOT SCALE DRAWING

REVISION

TITLE:

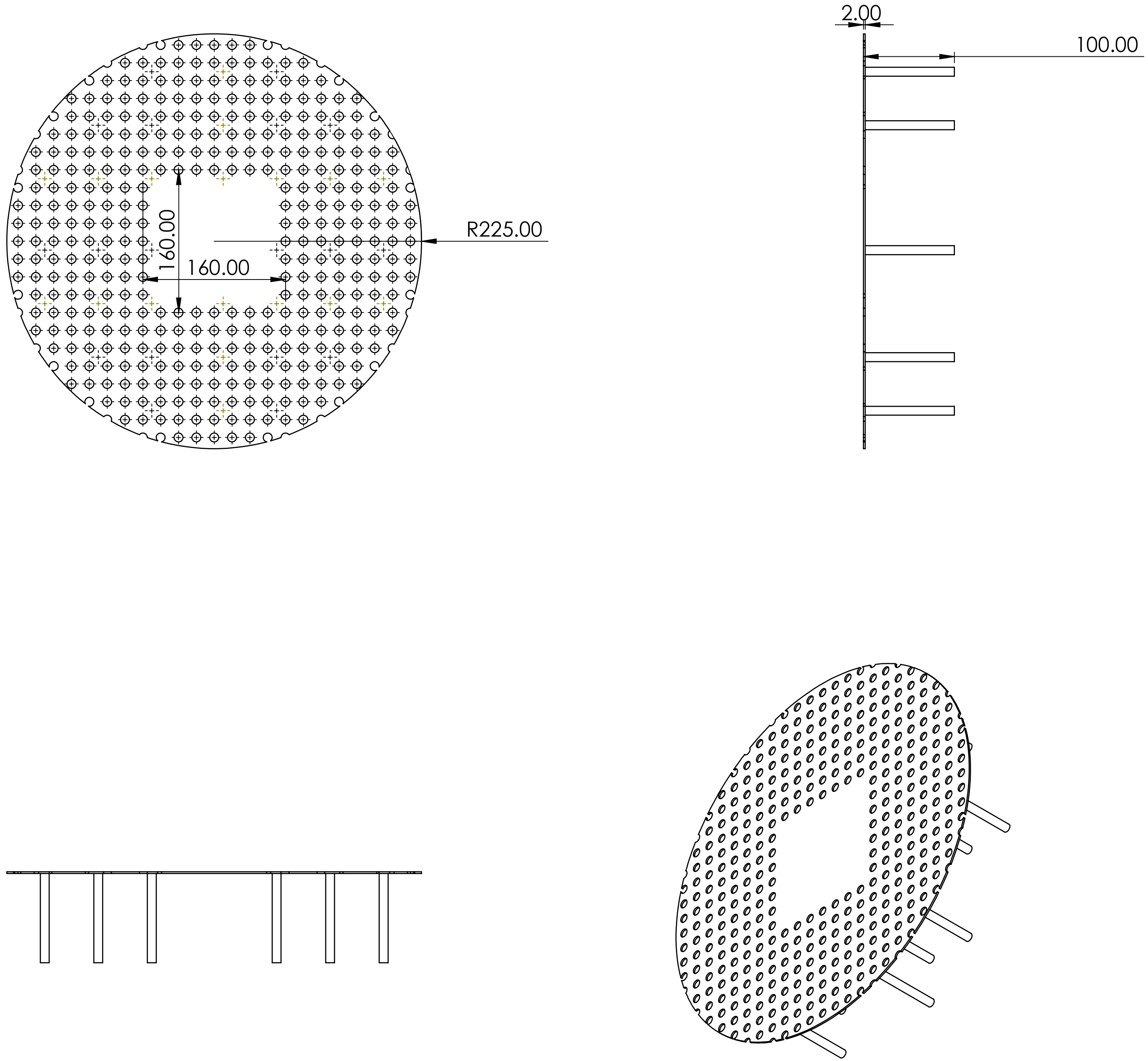
DWG NO.

Reviewed system

A3

SCALE:1:20

SHEET 1 OF 1



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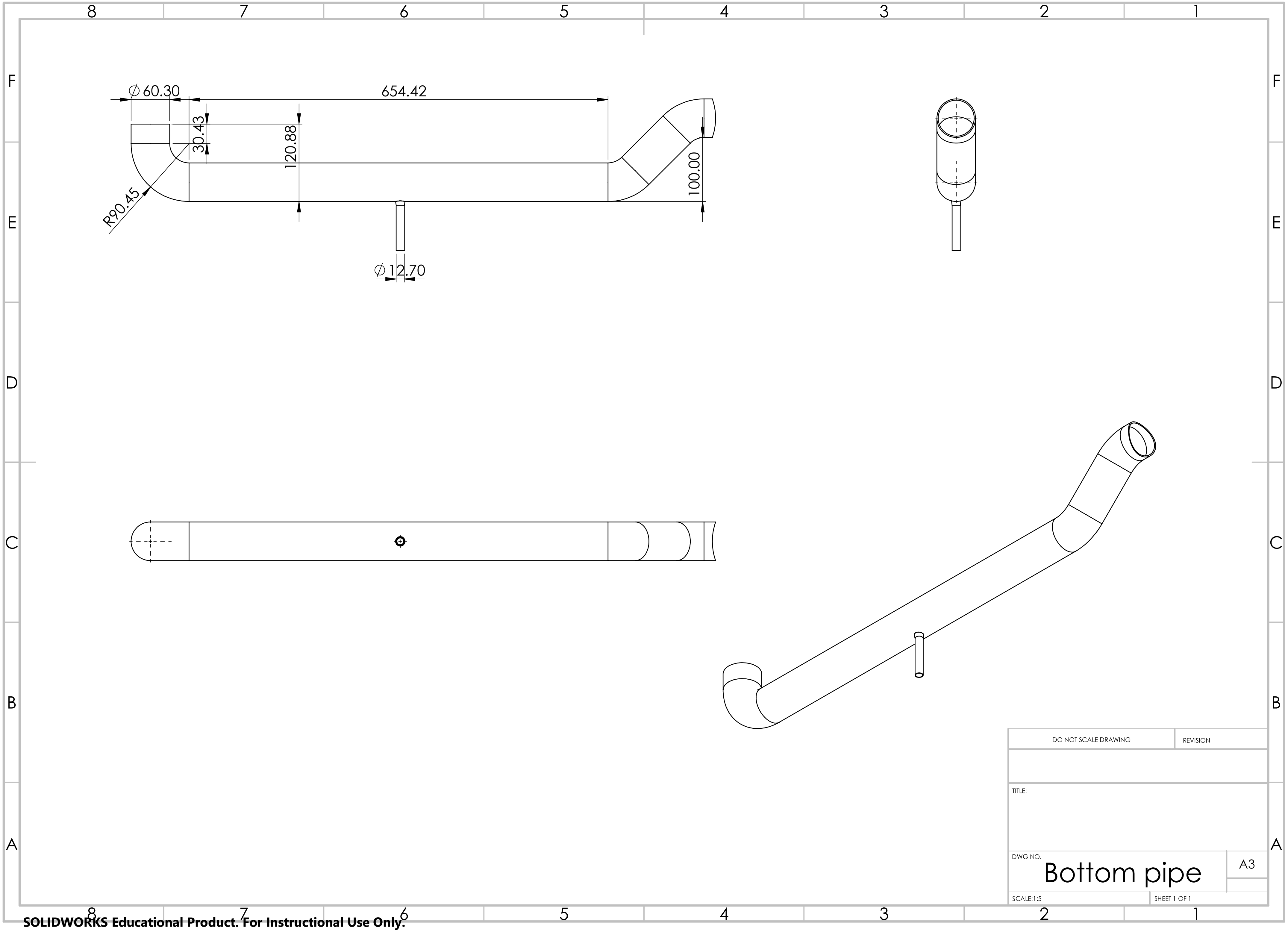
∅60.30
654.42
30.43
120.88
100.00
R90.45
∅12.70
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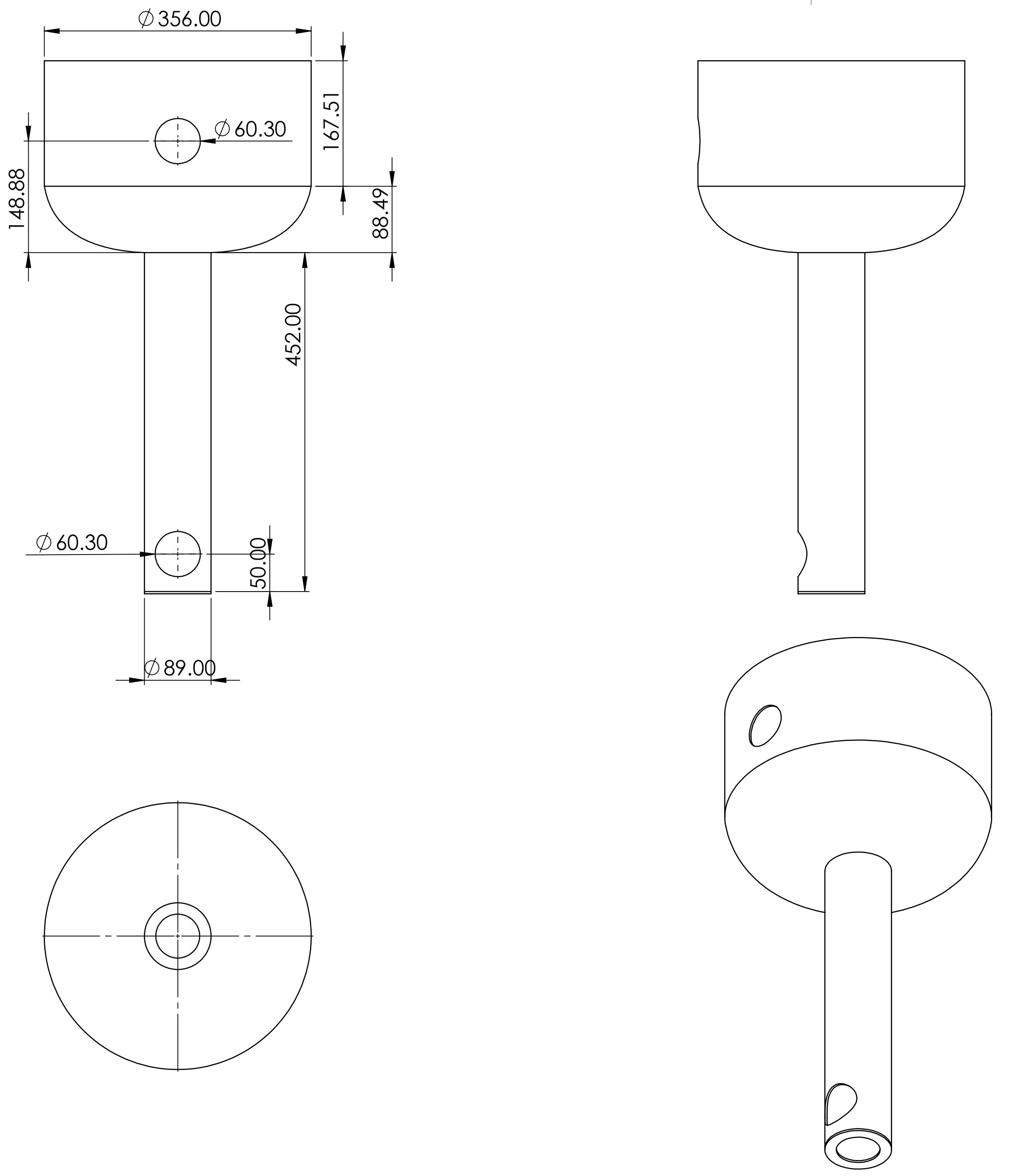
REVISION
TITLE:
DWG NO.
Bottom pipe
A3
SCALE:1:5
SHEET 1 OF 1



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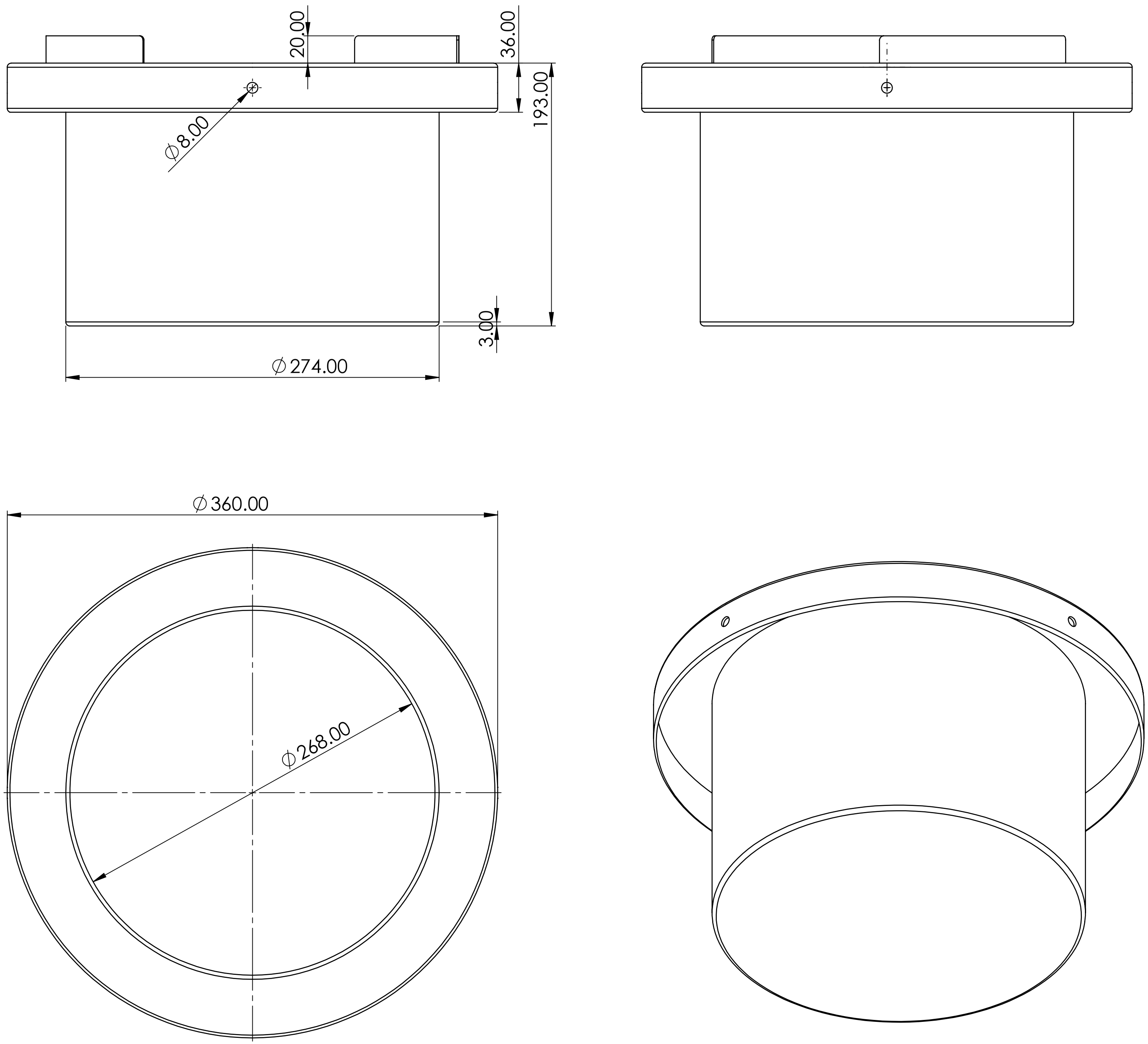

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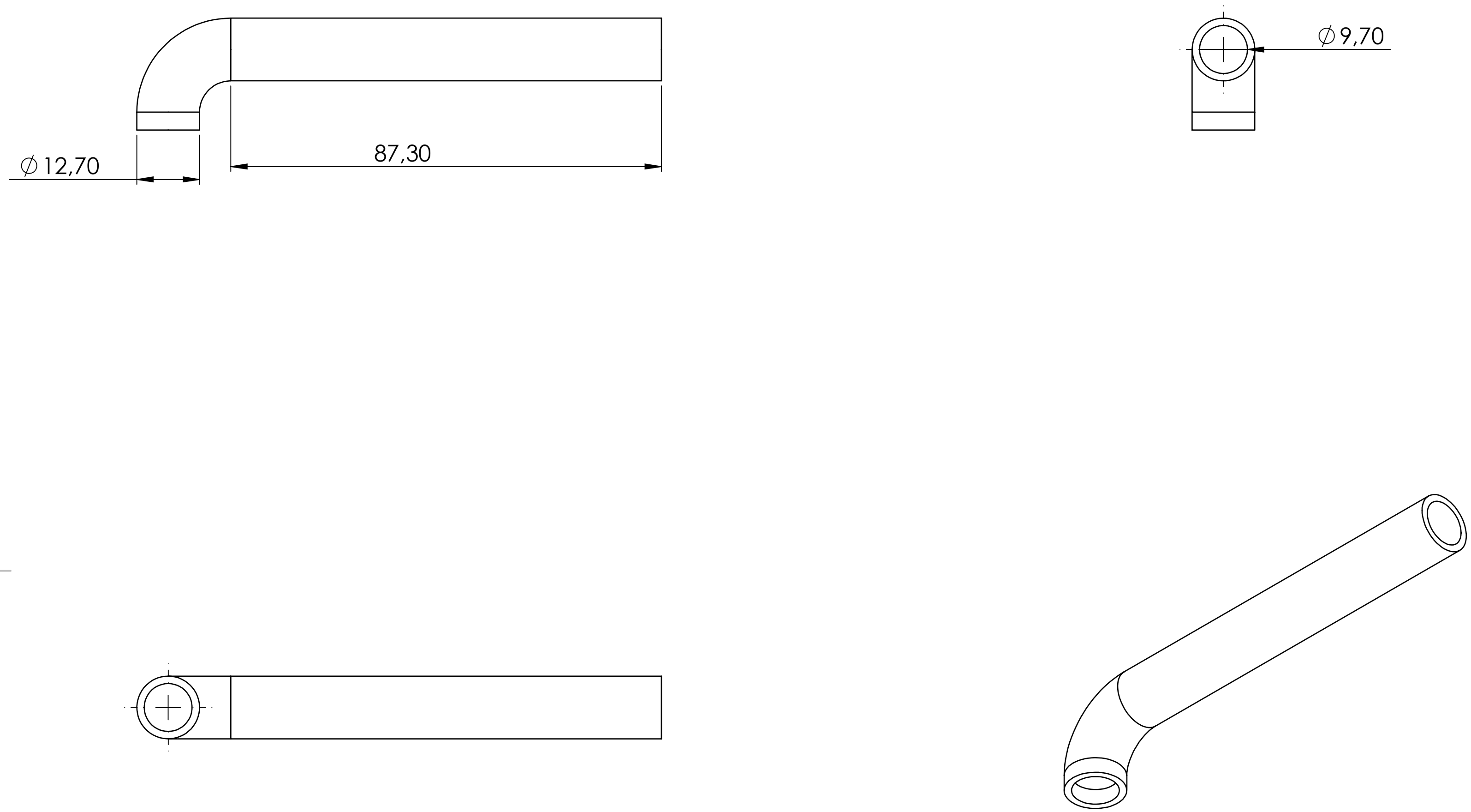

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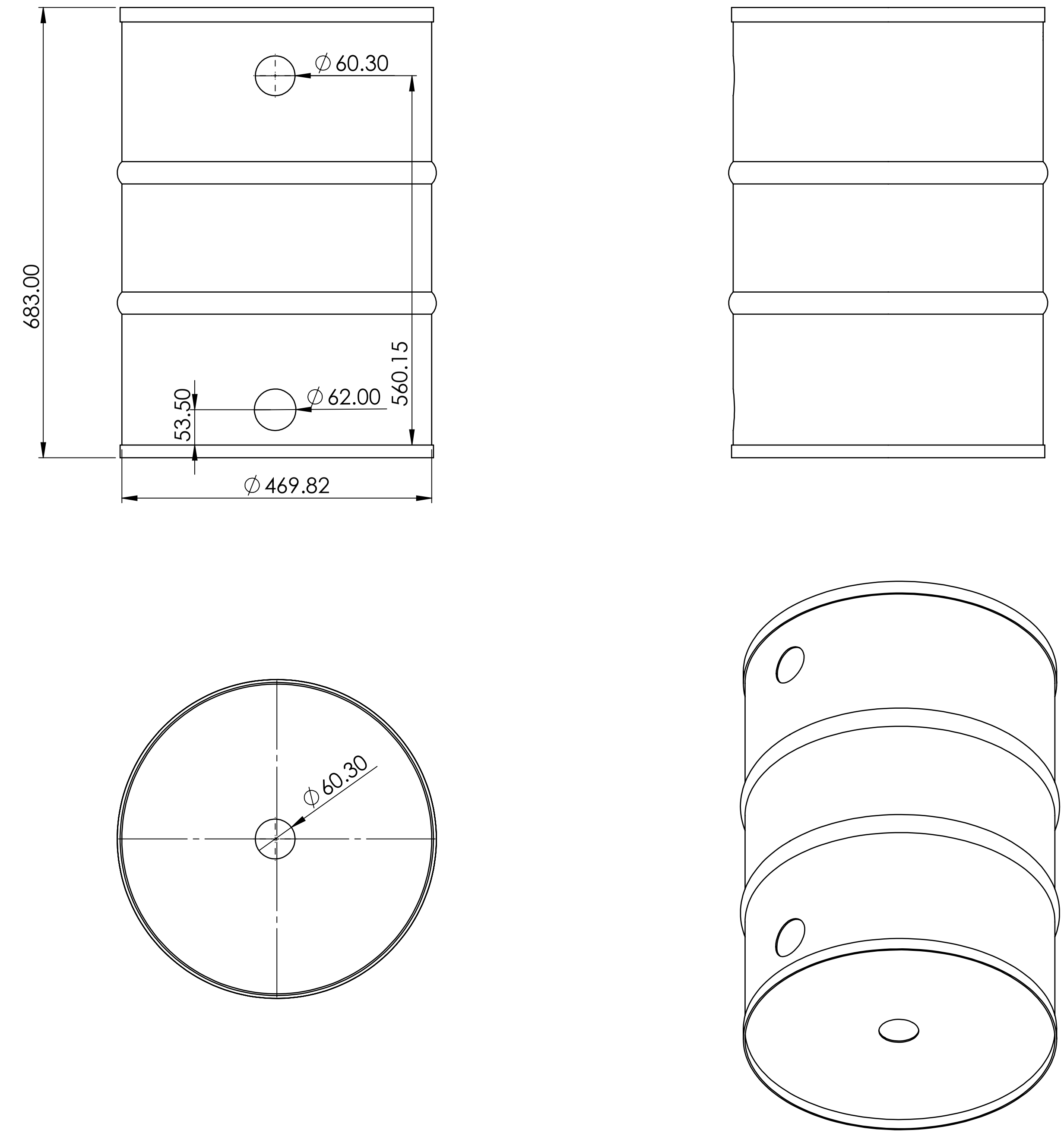

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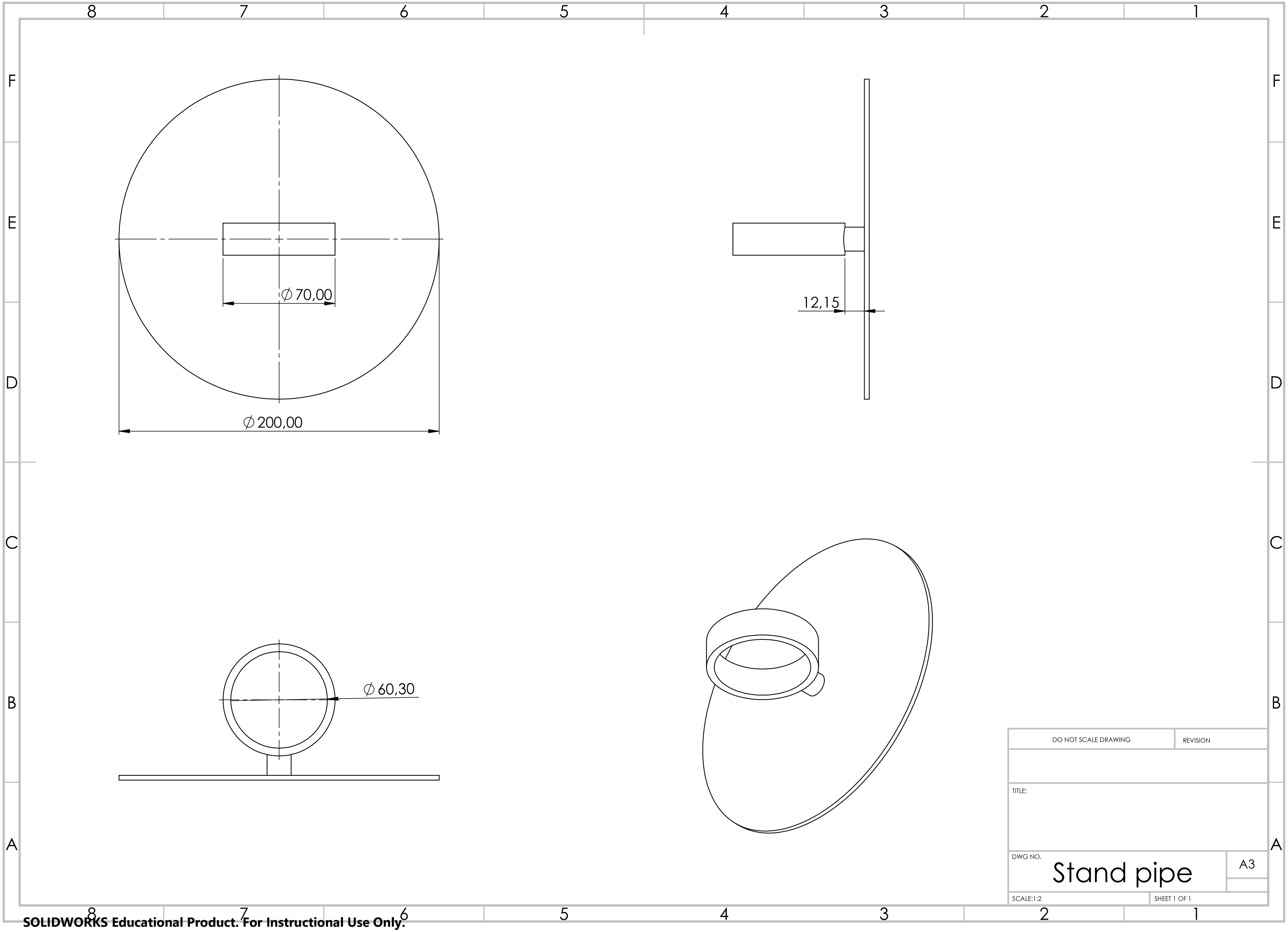

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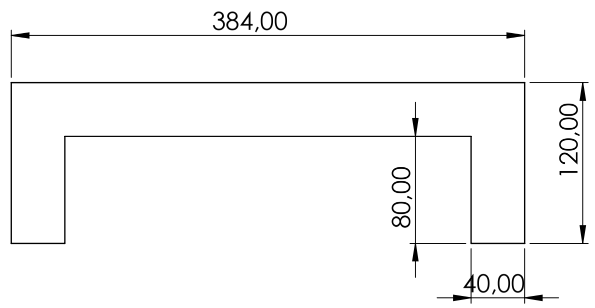
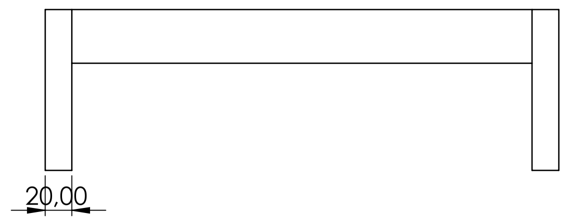
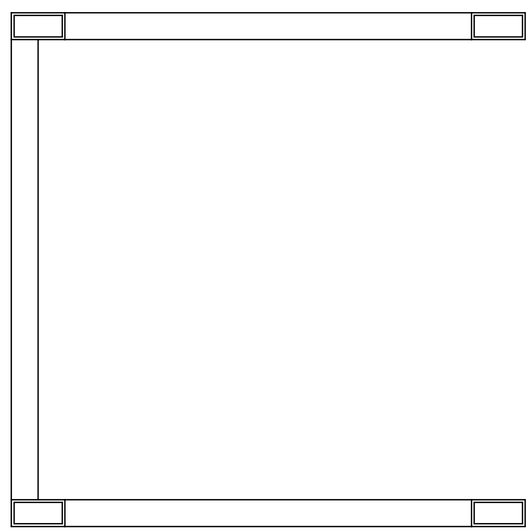
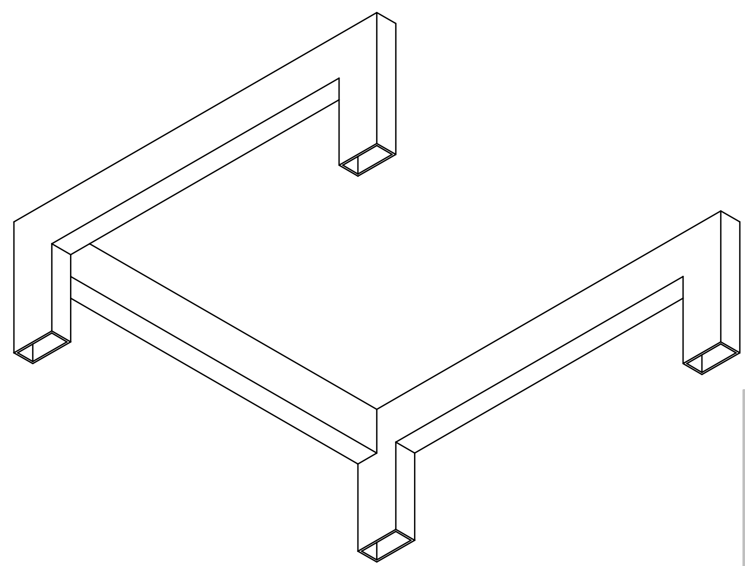
TITLE:	
DWG NO. Stand pipe	A3
SCALE:1:2	SHEET 1 OF 1









DO NOT SCALE DRAWING	REVISION
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DWG NO. Stand SHTES	A3
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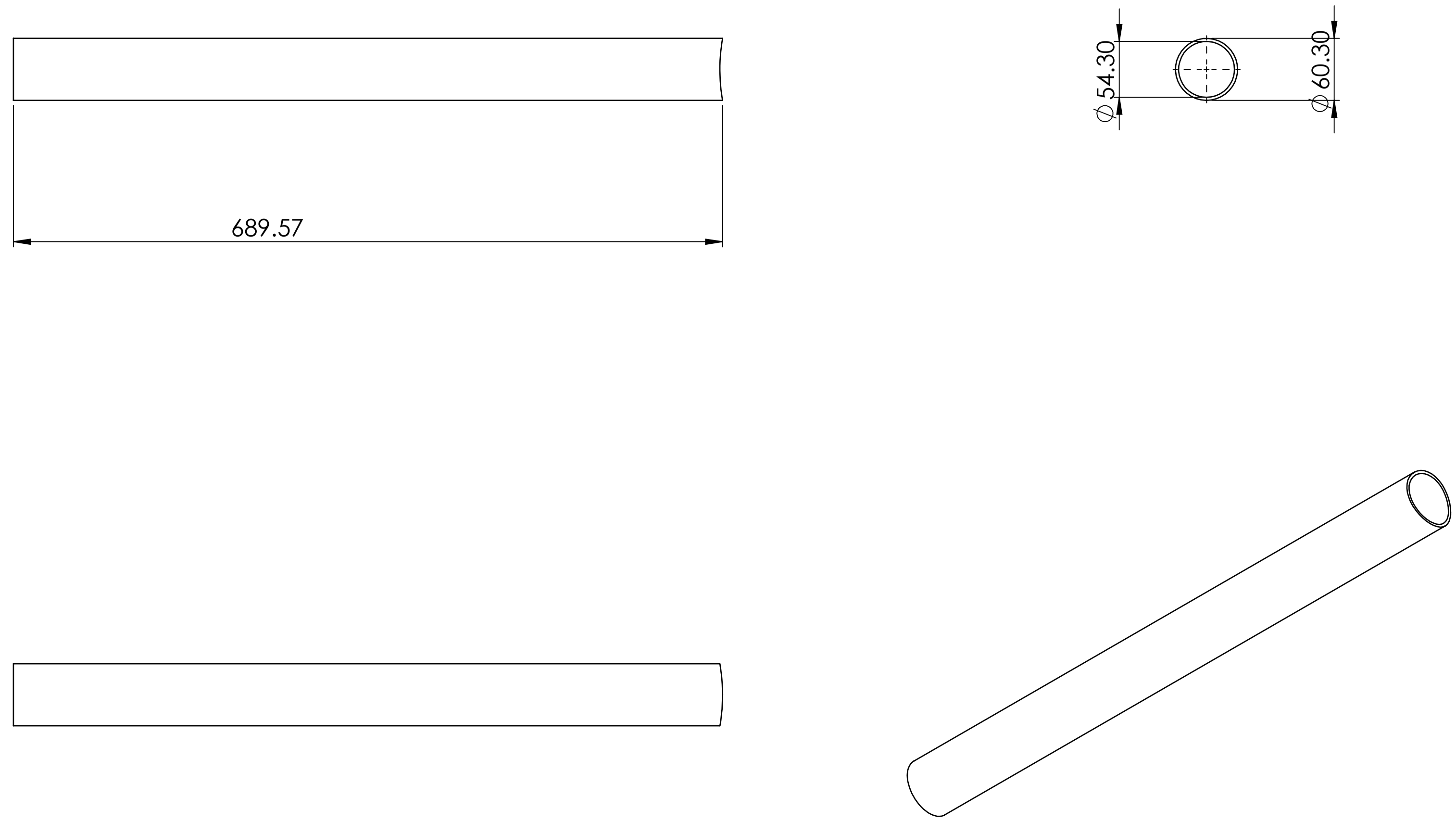

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DWG NO. Top pipe	A3
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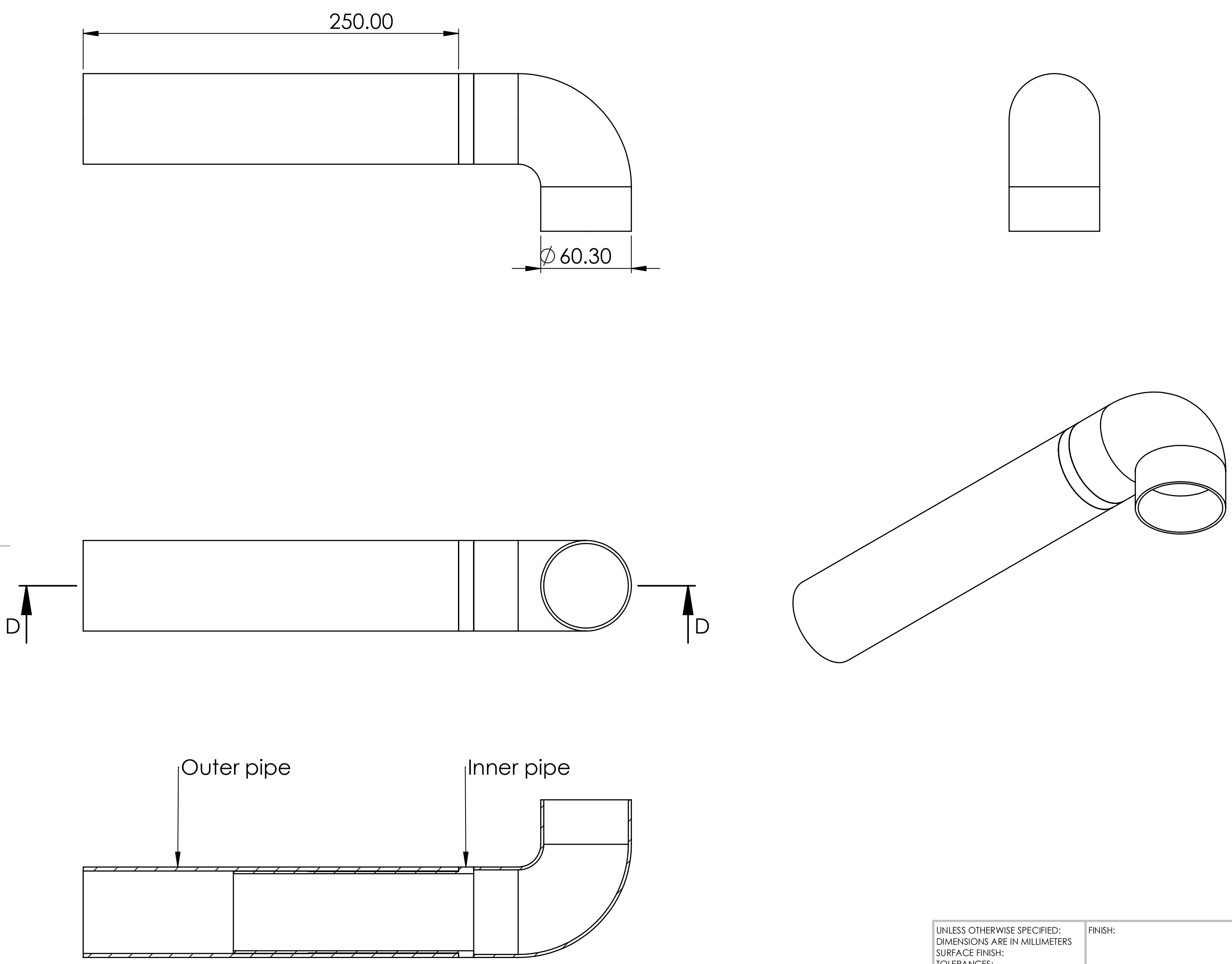

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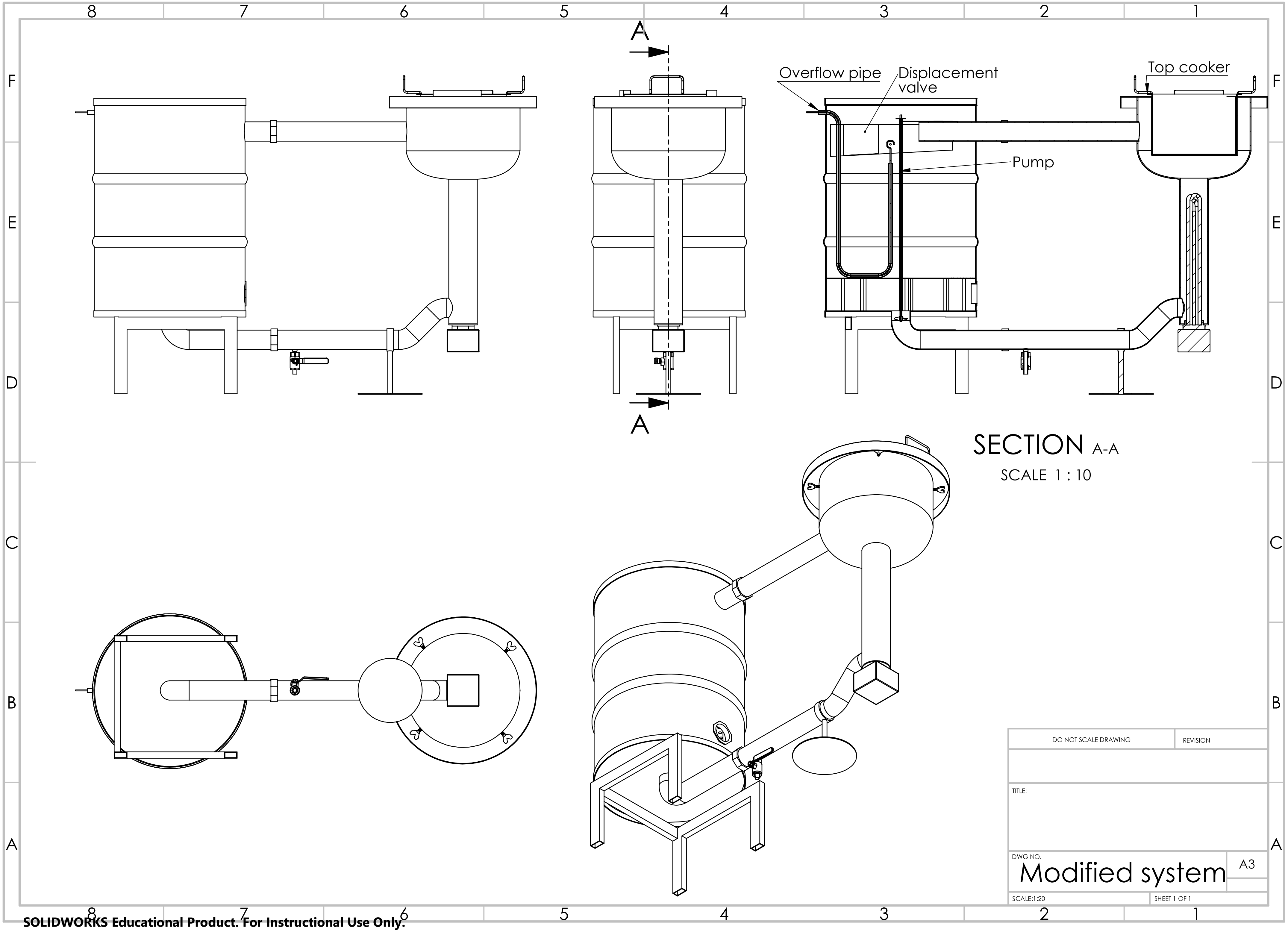
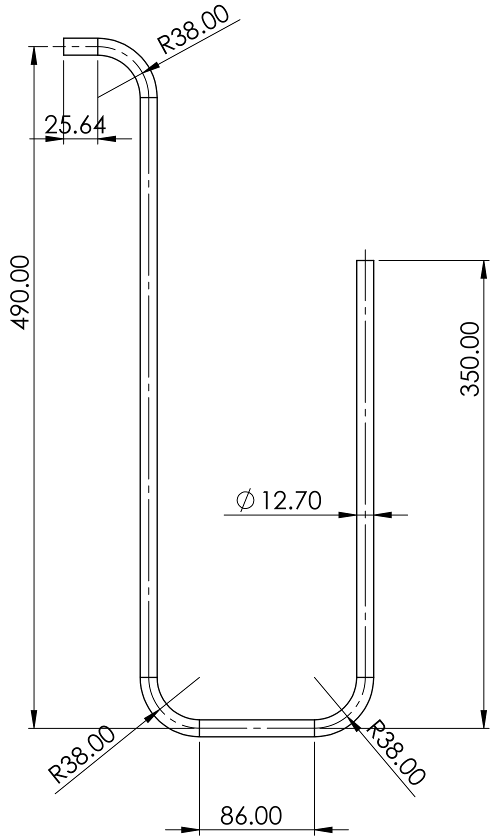
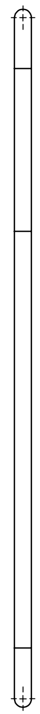
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO. Turning valve	A3
			WEIGHT:	SCALE:1:2	SHEET 1 OF 1

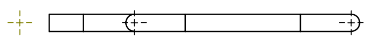
A3.2 Modified system

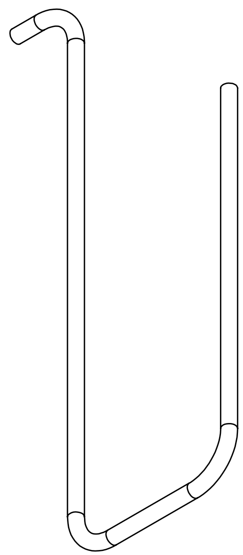


A
A
Overflow pipe
Displacement valve
Pump
Top cooker
SECTION A-A
SCALE 1 : 10
DO NOT SCALE DRAWING
REVISION
TITLE:
DWG NO.
Modified system
A3
SCALE:1:20
SHEET 1 OF 1









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DWG NO. Guide tube	A3
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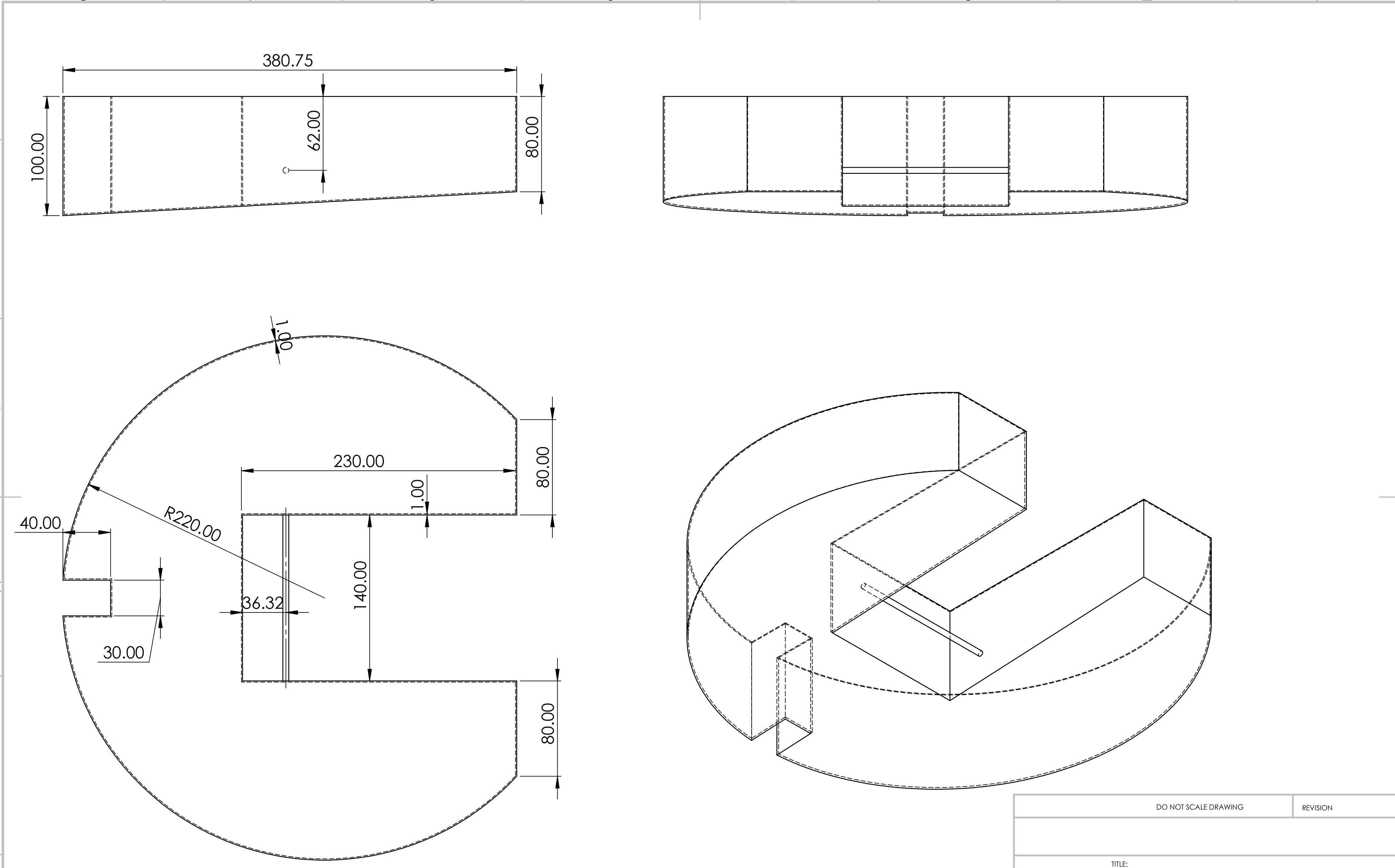

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REVISION

TITLE:

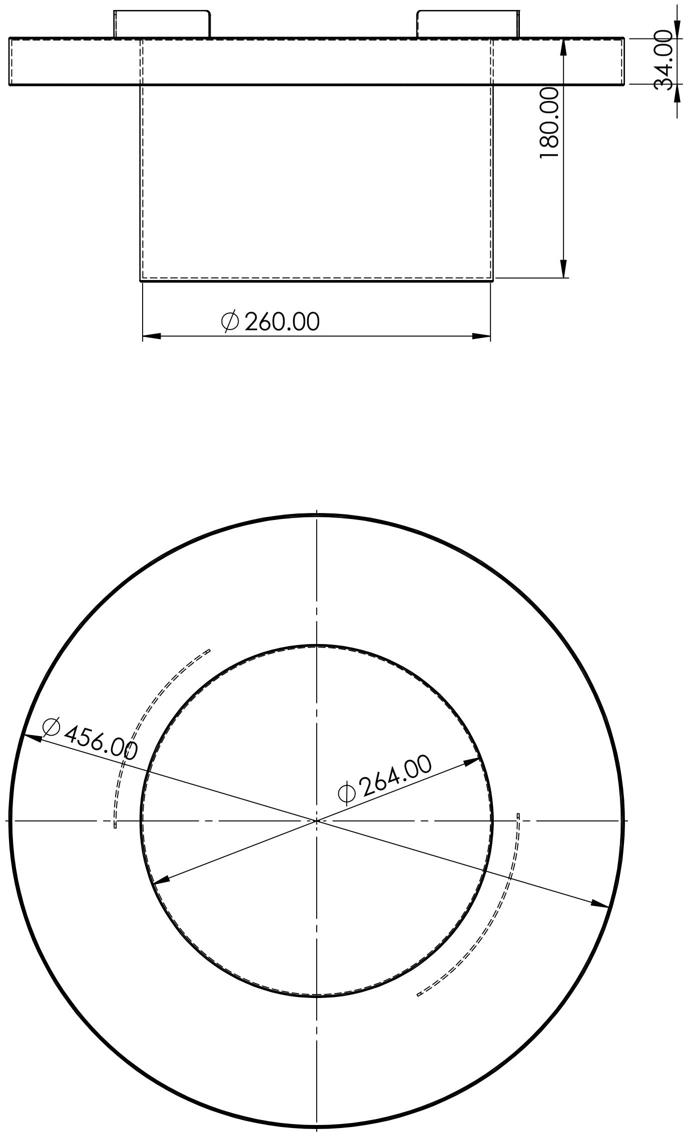
DWG NO.

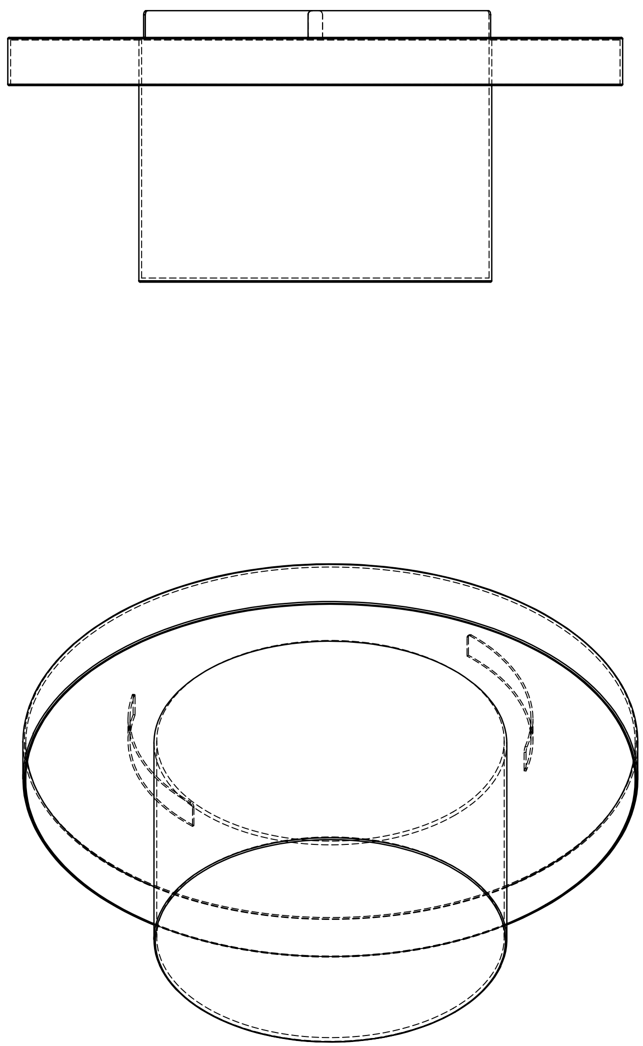
Displacement volume

A3

SCALE:1:5

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

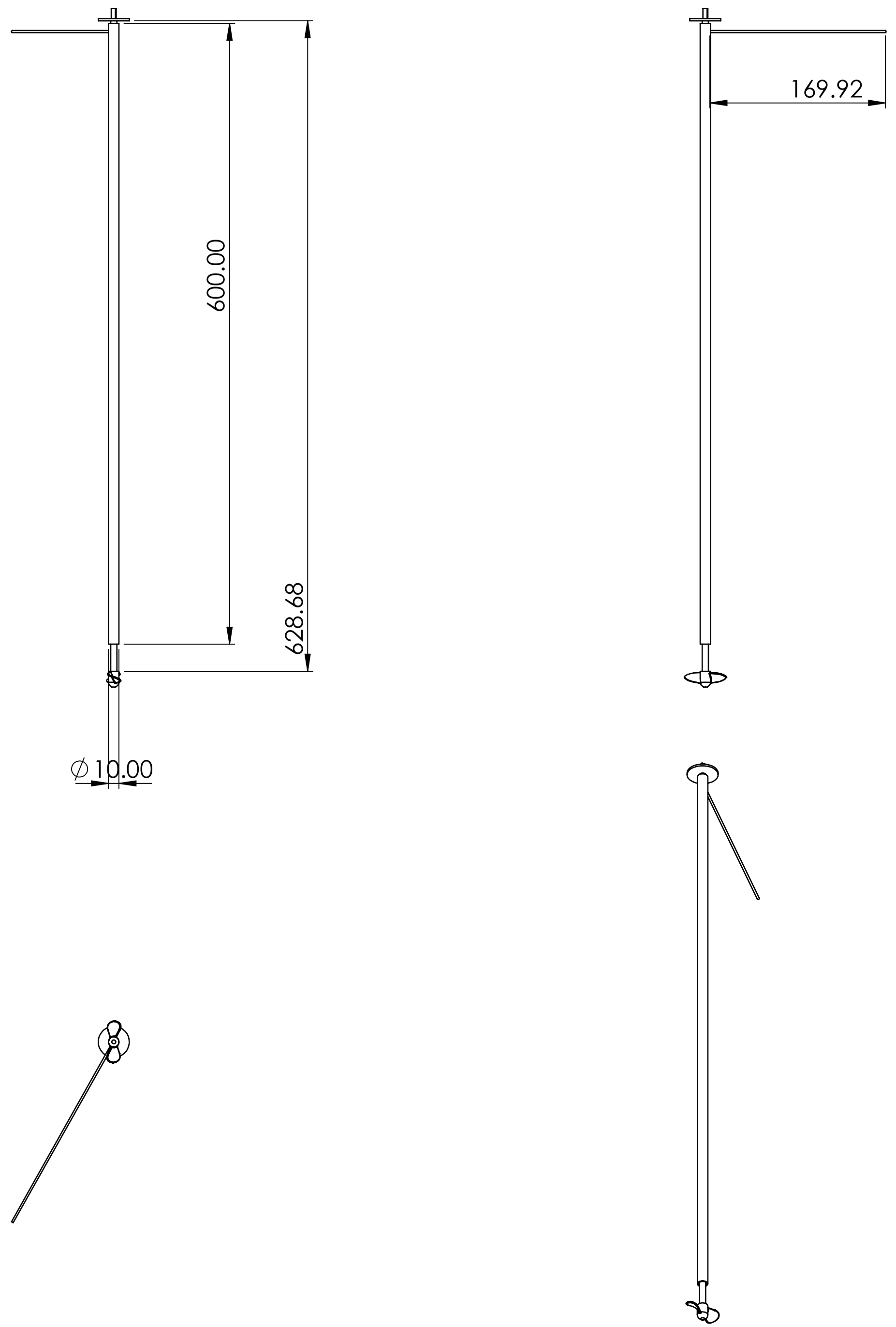
DWG NO.

Top cooker V2

A3

SCALE:1:5

SHEET 1 OF 1



DO NOT SCALE DRAWING	REVISION
TITLE:	
DWG NO. Pump	A3
SCALE:1:10	SHEET 1 OF 1

A4 Duratherm-630 product sheet [40]

DURATHERM
Heat Transfer Fluids

DURATHERM 630

A high performance, efficient and environmentally friendly thermal fluid engineered for applications requiring high temperature stability to 332°C (630˚F). Offering precise temperature control it's a great alternative to aromatic/synthetic fluids, at a fraction of the cost.

It is ideal for a wide range of applications including, high temperature batch processing, chemical reactions, pharmaceutical and resin manufacturing among others.

APPLICATION

Duratherm 630 is a high performance, efficient and environmentally friendly fluid engineered for applications requiring high temperature stability to 332°C (630˚F). Offering precise temperature control it's a great alternative to high temperature aromatic fluids, at a fraction of the cost.

It is ideal for a wide range of applications including, high temperature batch processing, chemical reactions, pharmaceutical and resin manufacturing among others.

THE DIFFERENCE

Our exclusive additive package, including a proprietary dual stage anti-oxidant, ensures long trouble free operation. **Duratherm 630** also incorporates metal deactivators, a seal and gasket extender, de-foaming and particle suspension agents.

LASTS LONGER

Oxidation can cripple your system. Left unchecked, it will ultimately cause catastrophic failure and costly downtime. That's why **Duratherm 630** offers unsurpassed levels of protection against oxidation, and a service life that other fluids simply can't match.

RUNS CLEANER

Duratherm 630 delivers superior resistance to sludging, a problem plaguing most other fluids. That makes it the best defense against extreme oxidation found in many of today's demanding manufacturing environments.

ENVIRONMENTAL

Duratherm 630 is environmentally friendly, non-toxic, non-hazardous and non-reportable. It poses no ill effect to worker safety and does not require special handling. After its long service life, **Duratherm 630** can easily be disposed of with other waste oils.

SYSTEM CLEANING

If your existing fluid has let you down and left you with a system full of sludge or carbon, we've developed a full line of heat transfer system cleaners to get your system back to like-new condition. Contact us for complete details.

1 800 446 4910

www.durathermfluids.com

DURATHERM 630

- Maximum temperature: 332°C / 630°F
- Flash point 229°C / 444°F
- Alternative to chemical aromatic fluids
- Non-toxic/non-hazardous
- Includes free fluid analysis and tech support

1 800 446 4910

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TEMPERATURE RATINGS

Maximum Bulk/Use Temp.	332°C	630°F
Maximum Film Temp.	354°C	670°F
Pour Point ASTM D97	-18°C	-1°F

SAFETY DATA

Flash Point ASTM D92	229°C	444°F
Fire Point ASTM D92	244°C	472°F
Autoignition ASTM E-659-78	368°C	693°F

THERMAL PROPERTIES

Thermal Expansion Coefficient	0.1011 %/°C	0.0562 %/°F
Thermal Conductivity	W/m K	BTU/hr F ft
38°C / 100°F	0.143	0.083
260°C / 500°F	0.131	0.076
316°C / 600°F	0.128	0.074
332°C / 630°F	0.127	0.073
Heat Capacity	kJ/kg K	BTU/lb F
38°C / 100°F	1.991	0.475
260°C / 500°F	2.724	0.650
316°C / 600°F	2.908	0.694
332°C / 630°F	2.962	0.707

PHYSICAL PROPERTIES

Appearance: colorless, clear and bright liquid		
Viscosity ASTM D445		
cSt at 40°C / 104°F	42.31	
cSt at 100°C / 212°F	6.82	
cSt at 316°C / 600°F	0.79	
cSt at 332°C / 630°F	0.74	
Density ASTM D1298	kg/m3	lb/ft3
38°C / 100°F	853.39	53.29
260°C / 500°F	702.45	43.85
316°C / 600°F	665.74	41.50
332°C / 630°F	652.5	40.79
Vapor Pressure ASTM D2879	kPa	psi
38°C / 100°F	0.00	0.00
260°C / 500°F	2.28	0.33
316°C / 600°F	9.75	1.40
332°C / 630°F	14.2	2.04
Distillation Range ASTM D2887	10%	383°C (721°F)
	90%	494°C (921°F)
Average Molecular Weight	395	

The values quoted are typical of normal production. They do not constitute a specification.

DURATHERM 630

PROPERTY VS. TEMPERATURE CHART
METRIC

TEMPERATURE (Celsius)	DENSITY (kg/m^3)	KINEMATIC VISCOSITY (Centistoke)	DYNAMIC VISCOSITY (Centipoise)	THERMAL CONDUCTIVITY (W/m-K)	HEAT CAPACITY (kJ/kg-K)	VAPOR PRESSURE (kPa)
-5	882.63	683.16	602.98	0.146	1.849	0.00
5	875.83	307.70	269.49	0.145	1.882	0.00
15	869.03	156.16	135.71	0.145	1.915	0.00
25	862.23	87.38	75.34	0.144	1.948	0.00
35	855.43	52.97	45.31	0.144	1.981	0.00
45	848.63	34.31	29.11	0.143	2.014	0.00
55	841.84	23.47	19.76	0.142	2.047	0.00
65	835.04	16.81	14.04	0.142	2.080	0.00
75	828.24	12.51	10.37	0.141	2.113	0.00
85	821.44	9.62	7.90	0.141	2.146	0.00
95	814.64	7.60	6.19	0.140	2.179	0.00
105	807.84	6.15	4.97	0.140	2.212	0.00
115	801.04	5.08	4.07	0.139	2.245	0.01
125	794.24	4.26	3.39	0.138	2.278	0.01
135	787.44	3.64	2.86	0.138	2.311	0.02
145	780.64	3.14	2.45	0.137	2.344	0.03
155	773.84	2.75	2.13	0.137	2.377	0.05
165	767.04	2.43	1.86	0.136	2.410	0.08
175	760.24	2.16	1.65	0.135	2.443	0.12
185	753.45	1.95	1.47	0.135	2.476	0.18
195	746.65	1.76	1.32	0.134	2.509	0.26
205	739.85	1.61	1.19	0.134	2.542	0.38
215	733.05	1.47	1.08	0.133	2.575	0.54
225	726.25	1.36	0.99	0.133	2.608	0.77
235	719.45	1.26	0.91	0.132	2.641	1.06
245	712.65	1.17	0.84	0.132	2.674	1.45
255	705.85	1.10	0.78	0.131	2.707	1.96
265	699.05	1.03	0.72	0.130	2.740	2.60
275	692.25	0.97	0.67	0.130	2.773	3.44
285	685.45	0.92	0.63	0.129	2.806	4.49
295	678.65	0.87	0.59	0.129	2.839	5.82
305	671.86	0.83	0.56	0.128	2.872	7.47
315	665.06	0.79	0.53	0.128	2.905	9.51
325	658.26	0.76	0.50	0.127	2.938	12.00
332	653.39	0.74	0.48	0.126	2.960	15.03

The values quoted are typical of normal production.
They do not constitute a specification.

DURATHERM 630

PROPERTY VS. TEMPERATURE CHART
STANDARD

TEMPERATURE (Fahrenheit)	DENSITY (lb/ft^3)	KINEMATIC VISCOSITY (Centistoke)	DYNAMIC VISCOSITY (Centipoise)	THERMAL CONDUCTIVITY (BTU/hr-F-ft)	HEAT CAPACITY (BTU/lb-F)	VAPOR PRESSURE (Psia)
15	55.29	1018.91	902.98	0.084	0.438	0.00
25	55.06	621.05	548.04	0.084	0.443	0.00
35	54.82	395.64	347.63	0.084	0.447	0.00
45	54.58	262.15	229.35	0.084	0.451	0.00
55	54.35	179.91	156.72	0.084	0.456	0.00
65	54.11	127.41	110.51	0.084	0.460	0.00
75	53.88	92.80	80.14	0.083	0.464	0.00
85	53.64	69.32	59.60	0.083	0.469	0.00
95	53.40	52.97	45.34	0.083	0.473	0.00
105	53.17	41.31	35.20	0.083	0.478	0.00
115	52.93	32.81	27.83	0.083	0.482	0.00
125	52.70	26.49	22.38	0.082	0.486	0.00
135	52.46	21.72	18.26	0.082	0.491	0.00
145	52.23	18.04	15.10	0.082	0.495	0.00
155	51.99	15.18	12.65	0.082	0.499	0.00
165	51.75	12.91	10.71	0.082	0.504	0.00
175	51.52	11.09	9.16	0.082	0.508	0.00
185	51.28	9.62	7.91	0.081	0.513	0.00
195	51.05	8.42	6.89	0.081	0.517	0.00
205	50.81	7.42	6.04	0.081	0.521	0.00
215	50.57	6.59	5.34	0.081	0.526	0.00
225	50.34	5.88	4.75	0.081	0.530	0.00
235	50.10	5.29	4.25	0.080	0.534	0.00
245	49.87	4.78	3.82	0.080	0.539	0.00
255	49.63	4.34	3.46	0.080	0.543	0.00
265	49.40	3.97	3.14	0.080	0.548	0.00
275	49.16	3.64	2.87	0.080	0.552	0.00
285	48.92	3.35	2.63	0.080	0.556	0.00
295	48.69	3.09	2.42	0.079	0.561	0.01
305	48.45	2.87	2.23	0.079	0.565	0.01
315	48.22	2.67	2.06	0.079	0.569	0.01
325	47.98	2.49	1.92	0.079	0.574	0.01
335	47.75	2.33	1.79	0.079	0.578	0.02
345	47.51	2.19	1.67	0.079	0.583	0.02
355	47.27	2.06	1.56	0.078	0.587	0.02
365	47.04	1.95	1.47	0.078	0.591	0.03
375	46.80	1.84	1.38	0.078	0.596	0.03
385	46.57	1.74	1.30	0.078	0.600	0.04
395	46.33	1.66	1.23	0.078	0.604	0.05
405	46.09	1.58	1.16	0.077	0.609	0.06
415	45.86	1.50	1.10	0.077	0.613	0.08
425	45.62	1.43	1.05	0.077	0.618	0.08
435	45.39	1.37	1.00	0.077	0.622	0.11
445	45.15	1.31	0.95	0.077	0.626	0.13
455	44.92	1.26	0.91	0.077	0.631	0.15
465	44.68	1.21	0.87	0.076	0.635	0.19
475	44.44	1.17	0.83	0.076	0.639	0.22
485	44.21	1.12	0.80	0.076	0.644	0.26
495	43.97	1.08	0.76	0.076	0.648	0.31
505	43.74	1.05	0.73	0.076	0.653	0.36
515	43.50	1.01	0.71	0.076	0.657	0.42
525	43.26	0.98	0.68	0.075	0.661	0.48
535	43.03	0.95	0.65	0.075	0.666	0.56
545	42.79	0.92	0.63	0.075	0.670	0.66
555	42.56	0.89	0.61	0.075	0.674	0.76
565	42.32	0.87	0.59	0.075	0.679	0.87
575	42.09	0.84	0.57	0.074	0.683	1.00
585	41.85	0.82	0.55	0.074	0.688	1.14
595	41.61	0.80	0.53	0.074	0.692	1.31
605	41.38	0.78	0.52	0.074	0.696	1.49
615	41.14	0.76	0.50	0.074	0.701	1.69
625	40.91	0.74	0.49	0.074	0.705	1.92
630	40.79	0.74	0.48	0.073	0.707	2.04

The values quoted are typical of normal production.
They do not constitute a specification.

A5 Risk Assessment Report

NTNU

Risk Assessment Report

[Dual Tank System]

Project name	Rock based heat storage for cooking
Facility name	Dual Tank Cooker
Building and room number	Varmeteknisk C164
Project leader	Ole Jørgen Nydal
Facility responsible	Ole Jørgen Nydal
HES coordinator	Morten Grønli
HES responsible	Terese Løvås
Risk assessment performed by	Alexander Peter Olsen

Approval:

Apparatur kort (UNIT CARD) valid for:	6 months
Forsøk pågår kort (EXPERIMENT IN PROGRESS) valid for:	6 months

Role	Name	Date	Signature
Project leader	Ole Jørgen Nydal		
HES coordinator	Morten Grønli		
HES responsible	Terese Løvås		

TABLE OF CONTENTS

1 INTRODUCTION

A system utilizing heat storage for cooking will be tested in the lab. The experimental plans include heating and storage tests where oil and rocks will be heated to 220 C while being closely monitored. The sensible heat in the oil and rocks will then be used for tests with cooking. The system is electrically heated with either PV solar panels or power from the grid.

2 DESCRIPTIONS OF EXPERIMENTAL SETUP

Setup:
The heat storage for cooking system is shown in the figures below:

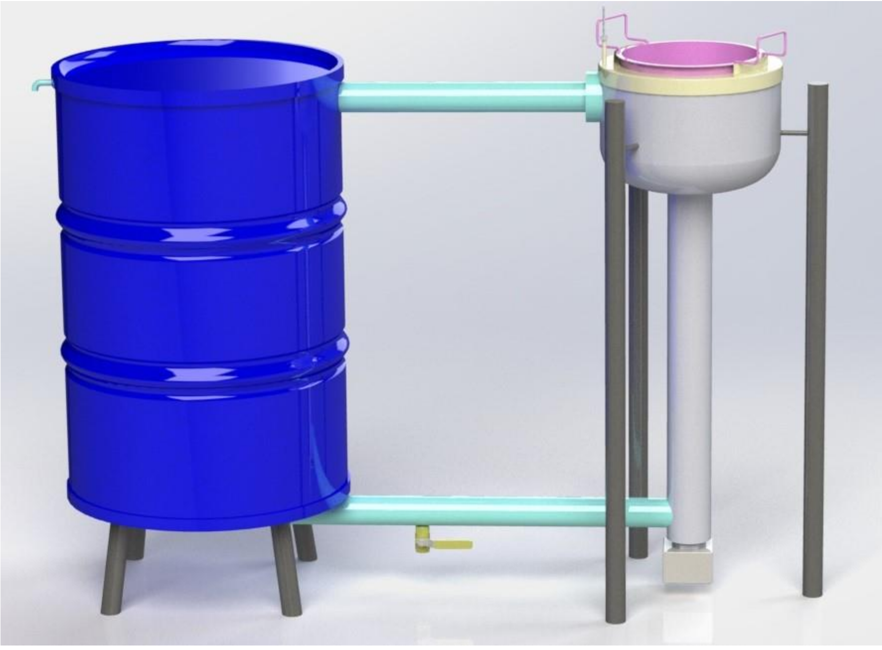


Figure 1: System overview

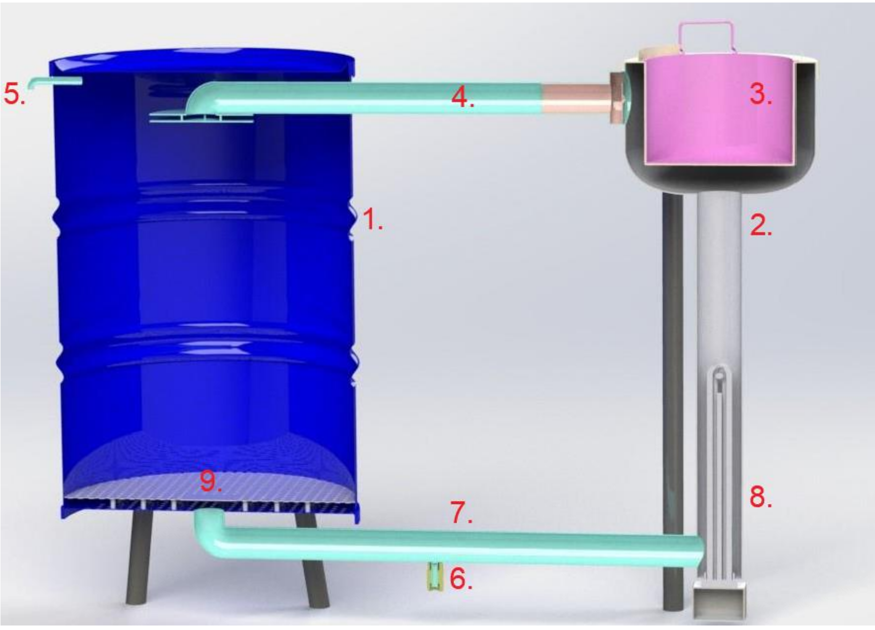


Figure 2: System half view with component numbering

Part	Part description
1.	216L barrel
2.	Funnel
3.	Cooking pot
4.	Top pipe
5.	Overflow pipe
6.	Drainage valve
7.	Bottom pipe
8.	Heating element (1800W)
9.	Bottom plate

As can be seen in figure 1 the system consists of two separate tanks connected through pipes. The barrel is filled with rocks and oil, and the rest of the system is only filled with oil. The oil is of the type Duratherm-630. By supplying electrical energy to the heating element placed in the funnel the oil is heated. The hot oil then flows upwards heating the pot, which can be used for cooking, before flowing into the barrel. Cold oil is sucked into the funnel from the bottom of the barrel, due to induced natural circulation. The process is controlled by the valve placed in the top pipe which controls the heigh level of when oil is allowed to flow between the two tanks.

The system is monitored by a series of thermocouples placed in the system, as well as a thermostat placed inside the heating element, ensuring temperatures stay below safe limits. An overflow pipe is also installed in the barrel to protect from over expansion of oil, and a drainage valve is also placed to empty the system. The entire system will be insulated to reduce heat loss to the environment and protect the operator.

Safety:
When conducting experiments, the operator will be close to the experimental setup and monitor the system. The area around the system should be clear of objects such that a safe escape is ensured in case of emergency. The system is not connected to any external utilities such as gas or water except electricity.

- *Process and Instrumentation Diagram (PID) with list of components*

3 EVACUATION FROM THE EXPERIMENTAL AREA

Evacuate at signal from the alarm system or local gas alarms with its own local alert with sound and light outside the room in question

Evacuation from the rigging area takes place through the marked emergency exits to the assembly point, (corner of Old Chemistry Kjelhuset or parking 1a-b.)

Action on rig before evacuation:
If evacuation is necessary, the electrical supply of the system will be disconnected before leaving the lab. This will ensure temperatures in the system will not increase after leaving, drastically lowering the dangers of fire.

4 WARNING

4.1 Before experiments

Send an e-mail with information about the planned experiment to:
experiments@ept.ntnu.no

The e-mail must include the following information:

- Name of responsible person:
- Experimental setup/rig:
- Start Experiments: (date and time)
- Stop Experiments: (date and time)

You must get the approval back from the laboratory management before start up. All running experiments are notified in the activity calendar for the lab to be sure they are coordinated with other activity.

4.2 Abnormal situation

FIRE

If you are NOT able to extinguish the fire, activate the nearest fire alarm and evacuate area. Be then available for fire brigade and building caretaker to detect fire place.
If possible, notify:

NTNU
Morten Grønli, Mob: 918 97 515
Terese Løvås: Mob: 918 97 007
NTNU – SINTEF Beredskapstelefon: 800 80 388

GAS ALARM

If a gas alarm occurs, close gas bottles immediately and ventilate the area. If the level of the gas concentration does not decrease within a reasonable time, activate the fire alarm and evacuate the lab. Designated personnel or fire department checks the leak to determine whether it is possible to seal the leak and ventilate the area in a responsible manner.

PERSONAL INJURY

- First aid kit in the fire / first aid stations
- Shout for help
- Start life-saving first aid
- **CALL 113** if there is any doubt whether there is a serious injury

OTHER ABNORMAL SITUATIONS

NTNU:

You will find the reporting form for non-conformance on:

https://innsida.ntnu.no/wiki/-/wiki/Norsk/Melde+avvik

5 ASSESSMENT OF TECHNICAL SAFETY

5.1 HAZOP

The experiment set up is divided into the following nodes:

Node 1	Barrel
Node 2	Piping
Node 3	Funnel

ATTACHMENTS B: HAZOP
Conclusion: When operating and completing tests on the system safety equipment should always be worn. This includes safety glasses, protective gloves and shoes and full coverage clothing. The temperature in the system should constantly be monitored to stay below the flash point of the

5.2 Flammable, reactive and pressurized substances and gas

Are any flammable, reactive and pressurized substances and gases in use?

NO	

Attachments: EX zones?
Conclusion:

5.3 Pressurized equipment

Is any pressurized equipment in use?

NO	

ATTACHMENTS D: TEST CERTIFICATE FOR LOCAL PRESSURE TESTING
Conclusion:

5.4 Effects on the environment (emissions, noise, temperature, vibration, smell)

Will the experiments generate emission of smoke, gas, odour or unusual waste?
Is there a need for a discharge permit, extraordinary measures?

YES	

Attachments:
Conclusion: The system will at temperatures close to the flash point of 230 C produce smoke with a mild odour. A ventilation hood should therefore be used when conducting experiments, with no further actions required.

5.5 Radiation

NO	

Attachments:
Conclusion:

5.6 Chemicals

Will any chemicals or other harmful substances be used in the experiments? Describe how the chemicals should be handled (stored, disposed, etc.) Evaluate the risk according to safety datasheets, MSDS. Is there a need for protective actions given in the operational procedure?

YES	Duratherm 630 oil

Attachments: MSDS
Conclusion: The oil is non-toxic, non-hazardous and non-reportable. After use the oil is discarded as special waste. The oil is not safe for consumption.

5.7 Electricity safety (deviations from the norms/standards)

NO	

Attachments:
Conclusion:

6 ASSESSMENT OF OPERATIONAL SAFETY

Ensure that the procedures cover all identified risk factors that must be taken care of. Ensure that the operators and technical performance have sufficient expertise.

6.1 Procedure HAZOP

The method is a procedure to identify causes and sources of danger to operational problems.

To identify causes and sources of danger the procedure is:

1. After filling the system with oil the system is to be checked for leaks before heat is supplied to the system
2. The entire system is to be insulated to protect the operator from contact with hot surfaces (For system efficiency as well)
3. Contain the system inside a box to prevent oil from contact with the floor
4. Test system with low temperatures before gradually increasing

ATTACHMENT C: HAZOP PROCEDURE

6.2 Operation procedure and emergency shutdown procedure

The operating procedure is a checklist that must be filled out for each experiment. Emergency procedure should attempt to set the experiment set up in a harmless state by unforeseen events.

ATTACHMENT E: PROCEDURE FOR RUNNING EXPERIMENTS
Emergency shutdown procedure: Disconnect the power source to the system

6.3 Training of operators

A Document showing training plan for operators

- *What are the requirements for the training of operators?*
- *What it takes to be an independent operator*
- *Job Description for operators*

Attachments*:* Training program for operators

6.4 Technical modifications

-

Conclusion:

6.5 Personal protective equipment

- It is mandatory use of eye protection in the rig zone
- It is mandatory use of protective shoes in the rig zone.
- Use gloves when there is opportunity for contact with hot/cold surfaces.
- Use protective clothing when conducting experiments

Conclusion: Full protective equipment is necessary when conducting experiments.

6.6 General Safety

- The area around the staging attempts shielded.
- Gantry crane and truck driving should not take place close to the experiment.
- The system should be constantly monitored by an operator during experiments
- Experiment under progress sign should always be posted when conducting experiments

6.7 Safety equipment

- Warning signs, see the Regulations on Safety signs and signalling in the workplace
- Foam fire extinguisher should always be available
- Fire blanket should always be available

6.8 Special predations

-

7 QUANTIFYING OF RISK - RISK MATRIX

The risk matrix will provide visualization and an overview of activity risks so that management and users get the most complete picture of risk factors.

IDnr	Activity	Consequence	Likelihood	RV
1	Skin contact with hot oil	D	2	D2
2	Skin contact with hot surfaces	A	4	A4
3	Water entering tank	D	2	D2
4	Overflow of oil	A	3	A3
5	Overheating of system	D	1	D1

Conclusion:
From the Risk Matrix it becomes apparent that none of the activities are of unacceptable risk, and actions therefore don't necessarily needs to be made, but should be considered. For all risks preventive measures such as temperature monitoring, protective safety equipment and fire suppression equipment has been implemented. The risks of the system is therefore considered acceptable.

RISK MATRIX

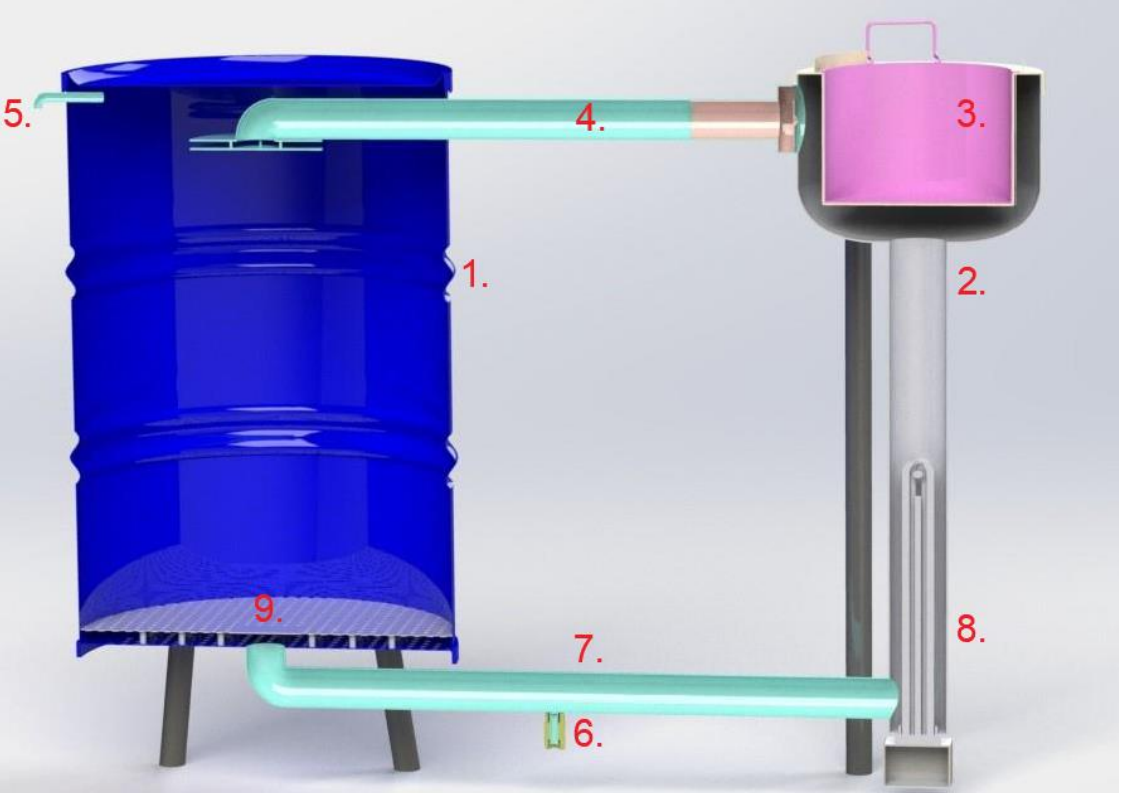
CONSEQUENSE	(E) Very critical	E1	E2	E3	E4	E5
	(D) Critical	D1	D2	D3	D4	D5
	(C) Dangerous	C1	C2	C3	C4	C5
	(B) Relatively safe	B1	B2	B3	B4	B5
	(A) Safe	A1	A2	A3	A4	A5
		(1) Minimal	(2) Low	(3) Medium	(4) High	(5) Very high
		LIKELIHOOD				

The principle of the acceptance criterion. Explanation of the colors used in the matrix

COLOUR		DESCRIPTION
Red		Unacceptable risk Action has to be taken to reduce risk
Yellow		Assessment area. Actions has to be considered
Green		Acceptable risk. Action can be taken based on other criteria

ATTACHMENT A: PROCESS AND INSTRUMENTATION DIAGRAM (PID)

Part	Part description
1.	216L barrel
2.	Funnel
3.	Cooking pot
4.	Top pipe
5.	Overflow pipe
6.	Drainage valve
7.	Bottom pipe
8.	Heating element (1800W)
9.	Bottom plate



ATTACHMENT B: HAZOP TEMPLATE

Project: **Node: 1**						**Page**	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	No flow	Blockage of pipe	Overheating of oil in funnel	Perforated bottom plate to hinder rocks, temperature control		Unplug power supply	
	Reverse flow	NA					
	More flow	NA					
	Less flow	Blockage of pipe	Overheating of oil in funnel	Perforated bottom plate to hinder rocks, temperature control		Unplug power supply	
	More level	Initial overfilling of oil and rocks	Hot oil overflowing system	Overflow pipe to control location	Heat oil gradually and monitor oil level		
	Less level	Initial underfilling of oil and rocks	Overheating of oil in funnel	Temperature control	Heat oil gradually and monitor oil level		
	More pressure	NA					
	Less pressure	NA					
	More temperature	Temperatures above flash point 229C with spark	Fire	Temperature control	Fire suppression apparatus at hand	Use of fire suppression apparatus	
	Less temperature	NA					
	More viscosity	NA					
	Less viscosity	NA					
	Composition Change	NA					

Project: **Node: 1**						**Page**	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Contamination	Temperature close to flash point with insufficient ventilation	Smoke as well as smell in the laboratory	Temperature control	Use oil with low contamination properties and ventilation hood	Duratherm 630	
	Relief	Overflow and leaks	Oil leakage in lab	Inspection of system		Place system in leak proof container	
	Instrumentation	NA					
	Sampling	NA					
	Corrosion/erosion	NA					
	Service failure	Heating element	No temperature increase in system	Temperature control			
	Abnormal Operation	NA					
	Maintenance	Leaks	Oil leakage in lab	Inspection of system		Place system in leak proof container	
	Ignition	Exceed flash point with spark, exceed autoignition point	Fire	Temperature control	Fire suppression apparatus at hand	Use of fire suppression apparatus	
	Spare equipment	NA					
	Safety	Fire and burns	Human and material danger	Use of safety equipment, temperature control		Use of safety equipment	

ATTACHMENT C: HAZOP PROCEDURE (TEMPLATE)

Project: **Node: 1**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Not clear procedure	Procedure is to ambitious, or confusingly					
	Step in the wrong place	The procedure can lead to actions done in the wrong pattern or sequence					
	Wrong actions	Procedure improperly specified					
	Incorrect information	Information provided in advance of the specified action is wrong					
	Step missing	Missing step, or step requires too much of operator					
	Step unsucessful	Step has a high probability of failure					
	Influence and effects from other	Procedure's performance can be affected by other sources					

ATTACHMENT D: TEST CERTIFICATE FOR LOCAL PRESSURE TESTING

Printed equipment:	
Used in rig:	
Design print for equipment (bara):	
Maximum permissible pressure: (i.e. burst pressure if known)	
Maximum operating pressure in this rig	

The proof pressure must be determined according to the standard and with respect to the maximum permissible pressure.

Test pressure (bara):			
1,5 times maximum operating pressure			
Test medium:			
Temperature (°C)			
Start time:		Pressure (bara):	
Stop time:		Pressure (bara):	
Maksimum driftstrykk i denne rigg:			

Any repetitions from atm. press to maximum proof-no

Test pressure, date of testing and maximum permissible operating pressure should be marked on (separated or switched on)

Location and date　　　　　　　　　　Signature

ATTACHMENT E: PROCEDURE FOR RUNNING EXPERIMENTS

Project	**Date**	**Signature**
Facility Dual Tank Cooker		
Project leader Ole Jørgen Nydal		

	Conditions for the experiment:	**Completed**
	Experiments should be run in normal working hours, 08:00-16:00 during winter time and 08.00-15.00 during summer time. Experiments outside normal working hours shall be approved.	
	One person must always be present while running experiments, and should be approved as an experimental leader.	
	An early warning is given according to the lab rules, and accepted by authorized personnel.	
	Be sure that everyone taking part of the experiment is wearing the necessary protecting equipment and is aware of the shut down procedure and escape routes.	
	Preparations	**Carried out**
	Post the “Experiment in progress” sign.	
	Turn on the ventilation hood and place it close to the funnel	
	Locate fire suppression apparatus	
	Clear an escape path if things were to go wrong	
	Prepare equipment for monitoring temperatures in the system	
	During the experiment	
	Control temperatures in the system	
	Control leaks in the overflow pipe in case of high oil levels	
	Carefully fill cooking pots with intended cooking medium ensuring the content will not overflow with boiling	
	End of experiment	
	Unplug the power supply	
	Monitor the temperature in the system to ensure the temperature is below the safe limit of 220 C (Below flash point)	
	Leave the ventilation hood running to remove fumes	
	Remove all obstructions/barriers/signs around the experiment.	
	Tidy up and return all tools and equipment.	
	Tidy and cleanup work areas.	
	Return equipment and systems back to their normal operation settings (fire alarm)	
	To reflect on before the next experiment and experience useful for others	
	Was the experiment completed as planned and on scheduled in professional terms?	

	Was the competence which was needed for security and completion of the experiment available to you?	
	Do you have any information/ knowledge from the experiment that you should document and share with fellow colleagues?	

Operator(s):

Navn	Dato	Signatur
Alexander Peter Olsen		

ATTACHMENT F: TRAINING OF OPERATORS

Project	Date	Signature
Facility Dual Tank Cooker		
Project leader Ole Jørgen Nydal		

	Knowledge about EPT LAB in general	
	Lab • Access • routines and rules • working hour	
	Knowledge about the evacuation procedures.	
	Activity calendar for the Lab	
	Early warning, experiments@ept.ntnu.no	
	Knowledge about the experiments	
	Procedures for the experiments	
	Emergency shutdown.	
	Nearest fire and first aid station.	

I hereby declare that I have read and understood the regulatory requirements has received appropriate training to run this experiment and are aware of my personal responsibility by working in EPT laboratories.

Operator(s):

Navn	Dato	Signatur
Alexander Peter Olsen		

NTNU

APPARATURKORT / UNITCARD

Dette kortet SKAL henges godt synlig på apparaturen!

This card MUST be posted on a visible place on the unit!

Apparatur (Unit)	
Prosjektleder (Project Leader)	**Telefon mobil/privat** (Phone no. mobile/private)
Apparaturansvarlig (Unit Responsible)	**Telefon mobil/privat** (Phone no. mobile/private)
Sikkerhetsrisikoer (Safety hazards)	
Sikkerhetsregler (Safety rules)	
Nødstopp prosedyre (Emergency shutdown)	

Her finner du (Here you will find):

Prosedyrer (Procedures)	aaa
Bruksanvisning (Users manual)	bbb

Nærmeste (Nearest)

Brannslukningsapparat (fire extinguisher)	aaaa
Førstehjelpsskap (first aid cabinet)	bbbb

NTNU
Institutt for energi og prosessteknikk

Dato

____

Signert

____

NTNU

FORSØK PÅGÅR /EXPERIMENT IN PROGRESS

Dette kortet SKAL henges opp før forsøk kan starte!
This card MUST be posted on the unit before the experiment startup!

Apparatur (Unit)	
Prosjektleder (Project Leader)	**Telefon mobil/privat** (Phone no. mobile/private)
Apparaturansvarlig (Unit Responsible)	**Telefon mobil/privat** (Phone no. mobile/private)
Godkjente operatører (Approved Operators)	**Telefon mobil/privat** (Phone no. mobile/private)
Prosjekt (Project)	
Forsøkstid / Experimental time (start - stop)	
Kort beskrivelse av forsøket og relaterte farer (Short description of the experiment and related hazards**)**	

NTNU
Institutt for energi og prosessteknikk

Dato

____

Signert

____

ATTACHMENT H GUIDANCE TO RISK ASSESSMENT

Chapter 5 Assessment of technical safety.

Ensure that the design of the experiment set up is optimized in terms of technical safety.
Identifying risk factors related to the selected design, and possibly to initiate re-design to ensure that risk is eliminated as much as possible through technical security.
This should describe what the experimental setup actually are able to manage and acceptance for emission.

5.1 HAZOP

The experimental set up is divided into nodes (eg motor unit, pump unit, cooling unit.). By using guidewords to identify causes, consequences and safeguards, recommendations and conclusions are made according to if necessary safety is obtained. When actions are performed the HAZOP is completed.
(e.g. "No flow", cause: the pipe is deformed, consequence: pump runs hot, precaution: measurement of flow with a link to the emergency or if the consequence is not critical used manual monitoring and are written into the operational procedure.)

5.2 Flammable, reactive and pressurized substances and gas.

According to the Regulations for handling of flammable, reactive and pressurized substances and equipment and facilities used for this:

Flammable material: Solid, liquid or gaseous substance, preparation, and substance with occurrence or combination of these conditions, by its flash point, contact with other substances, pressure, temperature or other chemical properties represent a danger of fire.
Reactive substances: Solid, liquid, or gaseous substances, preparations and substances that occur in combinations of these conditions, which on contact with water, by its pressure, temperature or chemical conditions, represents a potentially dangerous reaction, explosion or release of hazardous gas, steam, dust or fog.
Pressurized : Other solid, liquid or gaseous substance or mixes having fire or hazardous material response, when under pressure, and thus may represent a risk of uncontrolled emissions

Further criteria for the classification of flammable, reactive and pressurized substances are set out in Annex 1 of the Guide to the Regulations "Flammable, reactive and pressurized substances"
http://www.dsb.no/Global/Publikasjoner/2009/Veiledning/Generell%20veiledning.pdf
http://www.dsb.no/Global/Publikasjoner/2010/Tema/Temaveiledning_bruk_av_farlig_stoff_Del_1.pdf

Experiment setup area should be reviewed with respect to the assessment of Ex zone

- Zone 0: Always explosive atmosphere, such as inside the tank with gas, flammable liquid.
- Zone 1: Primary zone, sometimes explosive atmosphere such as a complete drain point
- Zone 2: secondary discharge could cause an explosive atmosphere by accident, such as flanges, valves and connection points

5.4 Effects on the environment

With pollution means: bringing solids, liquid or gas to air, water or ground, noise and vibrations, influence of temperature that may cause damage or inconvenience effect to the environment.
Regulations: http://www.lovdata.no/all/hl-19810313-006.html#6
NTNU guidance to handling of waste:http://www.ntnu.no/hms/retningslinjer/HMSR18B.pdf

5.5 Radiation

Definition of radiation

Ionizing radiation: Electromagnetic radiation (in radiation issues with wawelength <100 nm) or rapid atomic particles (e.g. alpha and beta particles) with the ability to stream ionized atoms or molecules.
Non ionizing radiation: Electromagnetic radiation (wavelength >100 nm), og ultrasound[1] with small or no capability to ionize.
Radiation sources: All ionizing and powerful non-ionizing radiation sources.
Ionizing radiation sources: Sources giving ionizing radiation e.g. all types of radiation sources, x-ray, and electron microscopes.
Powerful non ionizing radiation sources: Sources giving powerful non ionizing radiation which can harm health and/or environment, e.g. class 3B and 4. MR[2] systems, UVC[3] sources, powerful IR sources[4].
[1]Ultrasound is an acoustic radiation ("sound") over the audible frequency range (> 20 kHz). In radiation protection regulations are referred to ultrasound with electromagnetic non-ionizing radiation. [2]MR (e.g. NMR) - nuclear magnetic resonance method that is used to "depict" inner structures of different materials. [3]UVC is electromagnetic radiation in the wavelength range 100-280 nm. [4]IR is electromagnetic radiation in the wavelength range 700 nm - 1 mm.

For each laser there should be an information binder (HMSRV3404B) which shall include:

- General information
- Name of the instrument manager, deputy, and local radiation protection coordinator
- Key data on the apparatus
- Instrument-specific documentation
- References to (or copies of) data sheets, radiation protection regulations, etc.
- Assessments of risk factors
- Instructions for users
- Instructions for practical use, startup, operation, shutdown, safety precautions, logging, locking, or use of radiation sensor, etc.
- Emergency procedures
- See NTNU for laser: http://www.ntnu.no/hms/retningslinjer/HMSR34B.pdf

5.6 The use and handling of chemicals.

In the meaning chemicals, a element that can pose a danger to employee safety and health
See: http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20010430-0443.html
Safety datasheet is to be kept in the HSE binder for the experiment set up and registered in the database for chemicals.

Chapter 6 Assessment of operational procedures.

Ensures that established procedures meet all identified risk factors that must be taken care of through operational barriers and that the operators and technical performance have sufficient expertise.

6.1 Procedure Hazop

Procedural HAZOP is a systematic review of the current procedure, using the fixed HAZOP methodology and defined guidewords. The procedure is broken into individual operations (nodes) and analyzed using guidewords to identify possible nonconformity, confusion or sources of inadequate performance and failure.

6.2 Procedure for running experiments and emergency shutdown.

Has to be prepared for all experimental setups.
The operating procedure has to describe stepwise preparation, startup, during and ending conditions of an experiment. The procedure should describe the assumptions and conditions for starting, operating parameters with the deviation allowed before aborting the experiment and the condition of the rig to be abandoned.

Emergency procedure describes how an emergency shutdown have to be done,

- *what happens when emergency shutdown, is activated. (electricity / gas supply) and*
- *which events will activate the emergency shutdown (fire, leakage).*

Chapter 7 Quantifying of RISK

Quantifying of the residue hazards, Risk matrix.

To illustrate the overall risk, compared to the risk assessment, each activity is plotted with values for the likelihood and consequence into the matrix. Use task IDnr.
Example: If activity IDnr. 1 has been given a probability 3 and D for consequence the risk value become D3, red. This is done for all activities giving them risk values.

In the matrix are different degrees of risk highlighted in red, yellow or green. When an activity ends up on a red risk (= unacceptable risk), risk reducing action has to be taken

RISK MATRIX

CONSEQUENSE	(E) Very critical	E1	E2	E3	E4	E5
	(D) Critical	D1	D2	D3	D4	D5
	(C) Dangerous	C1	C2	C3	C4	C5
	(B) Relatively safe	B1	B2	B3	B4	B5
	(A) Safe	A1	A2	A3	A4	A5
		(1) Minimal	(2) Low	(3) Medium	(4) High	(5) Very high

		LIKELIHOOD

The principle of the acceptance criterion. Explanation of the colors used in the matrix

COLOUR		DESCRIPTION
Red		Unacceptable risk Action has to be taken to reduce risk
Yellow		Assessment area. Actions has to be considered
Green		Acceptable risk. Action can be taken based on other criteria

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once every 50 years or less	Once every 10 years or less	Once a year or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E **Very critical**	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D **Critical**	Permanent injury, may produce serious serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C **Dangerous**	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B **Relatively safe**	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A **Safe**	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

Alexander Peter Olsen

Design and testing of a natural-circulating heat storage for cooking

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