Eindhoven University of Technology

MASTER

The cooling of a High-Energy Laser on a naval surface combatant

Havermans, Sabine D.C.

Award date:
2023

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 25. Mar. 2025

Technische Universiteit
Eindhoven
University of Technology

De Rondom 70, 5612 AP Eindhoven P.O.
Box 513, 5600 MB Eindhoven
The Netherlands
www.tue.nl

Author
Sabine Havermans

Date
May 2, 2023

The cooling of a High-Energy Laser on a naval surface combatant

Graduation Project - Sabine Havermans

Master	Mechanical Engineering
Department	Mechanical Engineering
Research Group	Power and Flow
Student	S.D.C. Havermans
Identity number	1245093
Thesis supervisor TU/e	Nico Dam & Noud Maes
Thesis supervisor Ministry of Defense	Huibert-Jan Verbaan
Date	May 2, 2023

This report was made in accordance with the TU/e Code of Scientific Conduct for the Master thesis.

Abstract

Title
The cooling of a High-Energy Laser on a naval surface combatant

The implications of cooling a High-Enery Laser on a naval surface combatant are investigated. Different cooling methods are reviewed by literature research, and the best options are further explored. The implications of using a chiller, ice water cooling system, and magnetic refrigeration are gathered from the information of manufacturers and literature research. The implications of using a heat battery made from phase change material are researched by a computational fluid dynamics simulation in COMSOL. Using magnetic refrigeration gives the best results considering the implications; weight, volume and power demand. However, there are no working systems of the required size. Therefore, using a heat battery combined with the existing chillers is the most feasible option, considering it has to be implemented with the midlife update of the vessel.

Table of contents

Title
The cooling of a High-Energy Laser on a naval surface combatant

Table of contents

Title
The cooling of a High-Energy Laser on a naval surface combatant

Table of contents

Title
The cooling of a High-Energy Laser on a naval surface combatant

List of symbols

Title
The cooling of a High-Energy Laser on a naval surface combatant

Symbol	Description	Unit
ρ	Density	[kg/m^3]
t	Time	[s]
$\mathbf{u}$	Velocity profile	[m/s]
p	Pressure	[Pa]
μ	Kinematic viscosity	[Pa s]
$\mathbf{F}$	External forces	[Pa/m]
D_H	Hydraulic diameter	[m]
Re	Reynolds number	[-]
e	Internal Energy	[J]
$\mathbf{q}$	Conductive heat flux	[W/m^2]
σ	Total stress tensor	[Pa]
τ	Viscous stress tensor	[Pa]
h	Enthalpy	[J]
C_p	Specific heat capacity	[J/kg]
T	Temperature	[K]
d_{bc}	Channel thickness	[m]
$\dot{m}$	Mass flow	[kg/s]
$\mathbf{n}$	Normal vector	[-]
A	Area	[m^2]
P	Perimeter	[m]
H	Magnetic field	[T]
$\mathcal{Q}$	Internal heat source	[J]
$L_{1\rightarrow 2}$	Latent heat	[J/kg]
Δx	Distance to middle of material	[m]
k	Conductivity	[W/mK]
r	Radius	[m]
L	Length	[m]
g	Gravitational constant	[m/s^2]
z	Height	[m]
$\mathbf{I}$	Unity vector	[-]
u	Velocity	[m/s]
β	Bulk expansion coefficient	[-]
Q_{HEL}	Dissipated heat by the HEL	[J]
V	Volume	[m^3]
D	Diameter	[m]

1 Introduction

The ongoing development of weapon systems induces the development of renewed defense systems. Currently, kinetic energy weapon systems are used for counterattacks in naval combat on naval ships. This means that when a naval surface combatant is attacked, it will defend itself using a weapon system that fires ammunition toward the threat. This ammunition needs a finite time to reach the threat and then explodes, which has an instant effect but could also bring collateral damage.

The Dutch Ministry of Defense has explored new options to defend its naval surface combatants. One of these options is a High-Energy Laser (HEL). The HEL weapon system can defend the vessel by sending a lethal amount of electromagnetic energy toward the threat. This energy reaches the threat with the speed of light, and within a finite time, it will disarm the threat. Since the beam of the HEL system can be directed very precisely, collateral damage is limited[1]. Besides limiting collateral damage, another advantage is that no expensive and voluminous ammunition is needed on the vessel. The HEL can be used indefinitely as long as it is powered and cooled[2].

Considering above mentioned advantages, the Dutch Ministry of Defense has decided that the HEL weapon system should be integrated into the naval surface combatant in the future. However, some issues must be looked into before integration is possible.

As the name already mentions, the High-Energy Laser weapon system needs a lot of energy. And where a lot of energy is needed, waste heat is generally produced: an inherent issue caused by finite efficiencies. Therefore, some challenges are imposed on the vessel by integrating this weapon system. In this research, the challenge associated with cooling will be looked into.

1.1 High-Energy Laser

Several challenges must be faced to use a High-Energy Laser as a defense weapon system, such as the power demand and cooling. Even though this research is only on cooling the High-Energy Laser, it helps to know more about the whole system. To understand the challenges and their constraints, challenges concerning the deposit of sufficient energy on the target in varying atmospheric conditions will be explained. Then the challenges of getting the weapon system “plugged into the vessel” will be discussed.

1.1.1 Operation of a High-Energy Laser

As researched by TNO[3], creating a high enough power density on a target at a stand-off distance is difficult due to atmospheric attenuation, turbulence, scattering, and thermal blooming. Combining multiple (weaker) laser beams to create a single, powerful beam is a promising solution for these atmospheric effects. From multiple beam combining techniques, “coherent beam combining” shows the most promising result in tests with above mentioned atmospheric effects. However, “spectral beam combining” is more robust for military applications. The definition of “spectral beam combining” according to Scheers et al. (2020)[3] is: “A class of methods for beam combining, based on wavelength-sensitive beam combiners”. Or in other words, several beams with small differences in wavelength are combined into one big powerful beam using a diffraction grating, shown in Figure 1.1. When creating this single output beam, the smaller beams have to pass (or be reflected by) multiple volume gratings and steering mirrors, which can decrease the efficiency of the laser. Decreasing efficiency is not only seen at the beam combining part of the HEL. The HEL has a wall-plug efficiency of 33%, which means that 67% of the total input energy to the complete system is converted into waste heat.

The High-Energy Laser weapon system poses two important requirements to be able to work on a vessel [2]. First, it needs lots of energy in a short amount of time. For the application on the Navy vessel, this energy will come from the onboard battery combined with a capacitor for fast release during the first seconds. Then the generator will start up to support the battery. With the power of this battery and generator, the HEL system should be deployable for 10 minutes per hour, which is assumed to be enough for most battle scenarios.

The second thing the High-Energy Laser weapon system needs for proper use is cooling. Cooling is essential

---

[1] Joung R. Cook/John R. Albertine: The Navy’s high-energy laser weapon system, in: Patrick G. O’Shea/Harold E. Bennett (eds.), May 1997, p. 264.

[2] Michael Hafften/Robert Stratton: High-Energy Laser Weapon Integration with Ground Vehicles, in.

[3] ir. L.C.W. Scheers/ir. P.J. van den Berg/dr. A.S. Stodolna: Beam combining techiniques for high energy lasers, tech. rep., Den haag: TNO, 2020.

because of the way the beams are combined. When the temperature variations are too big, the diffraction gratings cannot combine the different beams into one beam since the diffraction gratings are specific for certain wavelength ranges. When the temperature difference is too big, the laser diodes create beams with wavelengths that do not correspond with the diffraction gratings. Therefore, they cannot combine the different beams into one. As a result, there would be several small beams that are not directed to the target.
The consequence of putting a lot of energy into the weapon system is also creating a lot of waste heat. This waste heat has to be extracted from the system instantly to ensure the constant temperature needed for the beam combining. There are some chillers on the vessel, but these are not big enough to do their regular task and cool the HEL system simultaneously. On the other hand, only a limited volume is available for the HEL system and auxiliary equipment. Therefore, an optimization problem arises around the cooling of the weapon system.

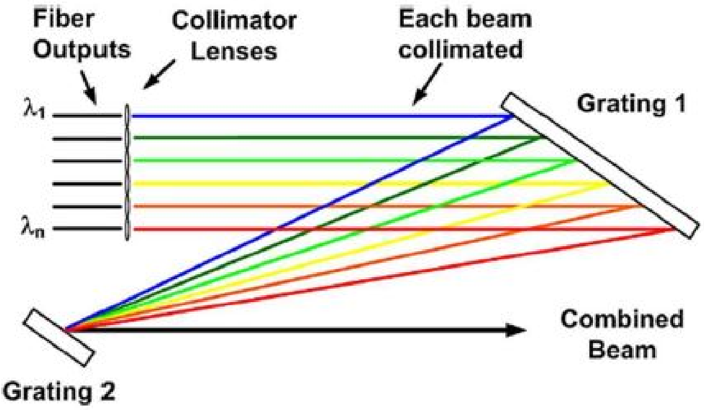


Figure 1.1: Schematic of the dual-grating SBC concept for a high-power fiber laser[4].

1.1.2 Previously researched solutions for cooling HEL systems

There are some developments around the High-Energy Laser. However, according to the author, an operational HEL weapon system in the size range needed on the operational naval vessel does not exist yet. Below, a few studies of smaller implementations will be explained to show what options already exist.

In the article of Hafften et al.[5], a study discusses integrating a HEL system on a ground vehicle. The thermal management system is based on storing heat. This is efficient since there is a cyclic operation of the system. The stored heat will then be rejected over a recovery period. The heat storage in a phase change material will significantly reduce volume and weight.

Another researched option is to use heat pipes to dissipate the waste heat[6]. Heat pipes are used instead of water cooling since it is more lightweight and a compact way of direct cooling.

The US military already uses the CLaWS (Compact Laser Weapon System). This is a High-Energy Laser of 25 kW, which is used in ground-based platforms. This HEL system is cooled directly by cooling water in a phase-transition cycle.

1.2 Problem definition and research question

Looking at previous Sections, the High-Energy Laser weapon system shows extraordinary potential for the naval vessel. However, before integration is possible, the cooling of the HEL system should be solved, among other challenges.

---

[4] ir. L.C.W. Scheers/ir. P.J. van den Berg/dr. A.S. Stodolna: Beam combining techiniques for high energy lasers, tech. rep., Den haag: TNO, 2020.

[5] Michael Hafften/Robert Stratton: High-Energy Laser Weapon Integration with Ground Vehicles, in.

[6] Shili Shu et al.: Heat dissipation in high-power semiconductor lasers with heat pipe cooling system, in: Journal of Mechanical Science and Technology 31.6 (June 2017), pp. 2607–2612.

1.2.1 Requirements, preferences, and constraints

At the start of this chapter, the term “naval surface combatant” is mentioned. Since quite a few of the requirements, preferences, and constraints (RPCs) are determined because the HEL system has to be integrated into this kind of vessel, a short explanation will follow.
The naval surface combatants are vessels that have armaments. These vessels are optimized for maximum sustained speed, acceleration, and maneuverability to be in the best shape to find and act against threats, including submarines, ground attacks, naval surface attacks, and other threats. Optimizing those features also introduces drawbacks, including negative effects on the size, logistics, and manning of the ship’s platform[7]. Also, since it is a warfare ship, the equipment should not fail because one part of the (auxiliary) equipment fails (redundancy), and the equipment should be shock resistant. Finally, signatures should be minimized. This means the ship should not become easier to find because of (additional) equipment. In short, the naval surface combatant poses extra challenges to solving the cooling of the HEL system, which are included in the RPCs.

Below, the requirements, preferences, and constraints of the cooling system for the HEL weapon system on a naval surface combatant are listed. The requirements capture the features and function of the system, whereas the constraints capture the restrictions of the surroundings and define the non-functional aspects of the system. The preferences list the features that would be nice to have but are not necessary for the system’s working. Since the High-Energy Laser is a system that cannot be changed (this is out of the scope of the project), the High-Energy Laser is simplified to a black box which creates a heat problem, as indicated in Figure 1.2. Also, some of the requirements are stated as: “as low as possible” because the exact requirements are not allowed in the report. Therefore, the goal is to create something with a low weight, volume demand, and power demand, and in a later stage, it will be integrated into the vessel demands itself.

Requirements:

- The incoming cooling water into the HEL system shall be kept stable at 20 °C with a tolerance of 0.5 °C at all times
- The cooling water coming out of the system has a temperature of 26 °C
- The cooling system should have the lowest weight possible
- The cooling system should use the existing structure if possible
- The cooling should have a minimal signature
- The cooling hardware should fit in the ammunition storage of the current weapon system and auxiliary machinery spaces (pump rooms)
- The system should use as little as possible energy for the cooling process
- After an hour, the laser should be fully cooled and operational again
- There cannot be a single source of failure in the auxiliary equipment
- The cooling mechanism should be shock resistant or resilient mounted
- The HEL system should be integrated on a ship in 15-20 years

Preferences

- Lifetime cooling mechanism
- Energy neutrality
- Smart usage of seawater
- Universality

Constraints:

- The system has to be able to endure seawater temperatures between -6 °C and 38 °C and has to function with seawater temperatures between -2 °C and 35 °C[8]
- The system has to be able to endure outside air temperatures between -35 °C and 50 °C and has to function in outside air temperatures between -20 °C and 48 °C[8]
- The maximum temperature of incoming water to the onboard chiller is 16 °C
- The chilled water supply temperature from the onboard chiller is 10 °C

---

[7] Jeffrey A Koleser/Jeffrey Kline: Determining surface combatant characteristic requirements through a mission effectiveness analysis framework, in: 2007.

[8] AECTP-200 - 3 Environmental Conditions. URL: `http://everyspec.com/NATO/NATO-AECTP/AECTP-200-3_3976/`.

- Safety regulations of naval vessels should be followed

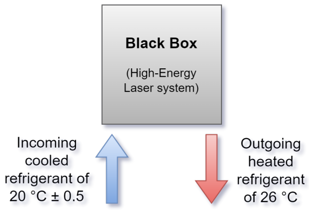


Figure 1.2: Representation of the simplified heat problem.

1.2.2 Problem definition

The cooling of the High-Energy Laser system is so important because of the tolerance of only 0.5 °C that the system needs for optimal operation. To comply with this requirement, the waste heat should be transported away from the system immediately. When it is away from the system, it could be cooled directly or stored and then cooled in a certain recovery time, as stated in Section 1.2.1. Finally, this design challenge's requirement, preferences, and constraints, mentioned in Section 1.2.1, must be integrated.

To solve this challenge, it should be known in what ways the system can be cooled, how big the cooling installation will be, what weight is added to the vessel by integrating this system, and what power demand is needed by the cooling system. To combine all these questions, the definition of implications is used: "the effect that an action or decision will have on something else in the future." Consequently, the following research question is composed:

"What are the implications of cooling a High-Energy Laser weapon system on a naval surface combatant?"

The research question has several aspects. These aspects are cooling a High-Energy Laser weapon system, implications, and naval surface combatant. In Section 1.2.3, these aspects are further elaborated, and sub-questions are derived from them.

1.2.3 Breaking down the research question

The research question can be divided into sub-questions using the RPCs from Section 1.2.1. In Figure 1.3, this is visualized. The first three sub-questions are derived from the requirements, which together will give the first conclusion on what method and configuration should be used for the cooling. The last four questions are derived from the preferences. Those questions will each lead to their conclusion on how the "extra" can be integrated. The seven questions all have to comply with the stated constraints. When the separate conclusions are combined, a complete recommendation will be given to answer the research question.

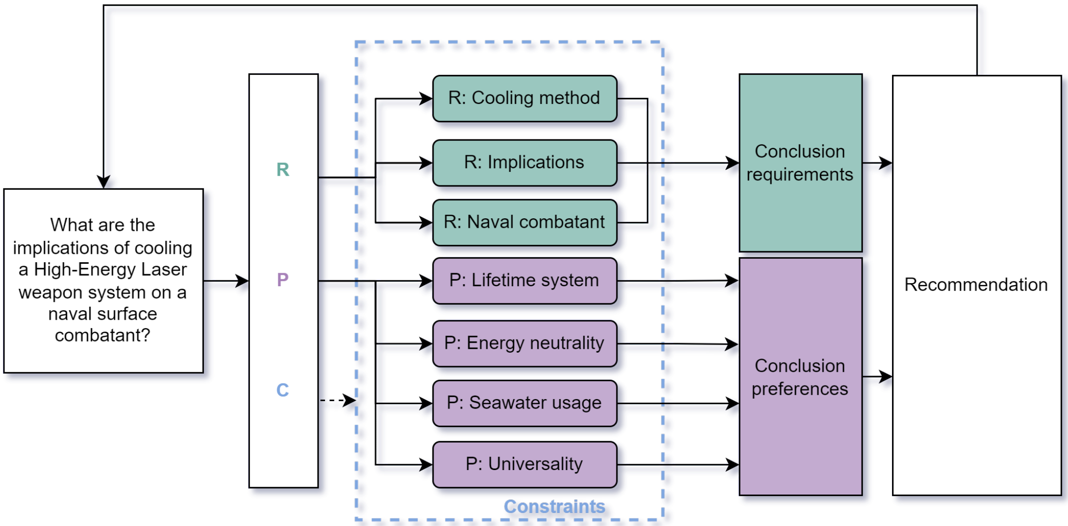


Figure 1.3: Relation between the research question and sub-questions.

The "how" in cooling a High-Energy Laser weapon system is left open. Therefore, there is freedom in how the cooling can be done as long as it cools the High-Energy Laser so that the temperature requirements are met.

The implications mentioned in the question can be seen broadly. However, the subjects considered here are weight, volume and power demand. All three of these subjects have to be optimized.

Finally, the aspect of the naval surface combatant. Section 1.2.1 states the constraints around a naval surface combatant. The extra challenges in constraints should be taken into account when designing the cooling system. The focus is on the redundancy, shock resistance, signatures, safety regulations, and temperature restrictions of the surroundings.

Besides the aspects of the research question, some other subjects can be researched to end up with a sustainable system. These subjects are the preferences of Section 1.2.1. First, the lifetime of the cooling mechanism can restrict the usage of the HEL system, and it is, therefore, essential to be as high as possible.

Another preference is that the system would include energy neutrality. The High-Energy Laser generates a lot of waste heat, so if this waste heat could be used for something else, the total efficiency of power demand will go up.

Connected to this subject and sustainability in general, it is also a preference to use seawater when the seawater temperature is low enough. If this is done, less additional cooling would be needed, and therefore less power demand is necessary.

Finally, the last preference is universality. This research could be used in more situations if the final result could also be used in applications other than only this specific naval surface combatant.

To give an overview of the sub-questions:

1. "Which cooling methods are possible and comply with the RPCs?"
2. "How to provide sufficient cooling of a High-Energy Laser weapon system, with as little as possible additional weight, volume and power demand?"
3. "How can the cooling method be implemented while in compliance with the design constraints of a naval surface combatant?"
4. "What is the lifetime of the cooling mechanism, and how does the usage of the HEL system influence this?"
5. "How can the configurations be adjusted to recover energy?"
6. "How can the smart usage of seawater be integrated into the cooling configurations?"

7. “How can the cooling configuration be implemented in other vessels?”

The bigger picture should be considered when considering the sub-questions: Implement the cooling of a High-Energy Laser weapon system on a naval surface combatant. Therefore, not all questions can be seen apart from each other. Also, clear prioritizing can be done since it is a warfare vessel, and performance is essential. Nevertheless, sustainability cannot be forgotten these days. Therefore, implementing sustainable procedures should not affect performance too much. Therefore, the research will first focus on the performance, weight, volume and power demand optimization and the design constraints of a naval surface combatant before looking at the sustainability part of the research. Therefore, answering the first three questions will already answer the research question. Consequently, the four additional questions will be an extension to the conclusion of the first questions, as presented in Figure 1.3.

1.2.4 Research plan

In Chapter 1, the operation of the High-Energy Laser is shortly explained, the problem definition is mentioned, and the research question is formulated. In the following Chapter, Chapter 2, the literature research on different cooling methods is elaborated on, and the research on the impact of building this system on a naval surface combatant is explained. In Chapter 3, the research method on the implications of the cooling methods is explained with, in particular, the explanation of the computational fluid dynamics simulation. In Chapter 4, the results of the previously explained research are shown and elaborated. Then, in Chapter 5, the assumptions and future work are discussed. Finally, in Chapter 6, the research conclusion is presented.

2 Background

This chapter presents the literature research on the different cooling methods, and the design choice is made and explained. Finally, the influence of building this cooling system on a naval surface combatant is elaborated.

2.1 Cooling methods

The introduction shows the importance of a cooling system for the High-Energy Laser. To investigate the different cooling methods, a literature study is carried out. This shows that there are two classes of cooling methods: direct and indirect cooling[1]. Figure 2.1 shows the cooling method classification.
Direct cooling means that the waste heat from the High-Energy Laser, in the form of heated cooling water, is cooled instantly. This can be done in several different ways. One possibility is to use a chiller with a specific refrigerant, coming from a natural source or manufactured synthetically[2]. Also, ice water cooling is an option, where an ice bank is built to cool the heat load instantly. Another option is to cool the heated cooling water with magnetic refrigeration, a new method that uses the magnetocaloric effect[3]. Finally, air-atomized spray cooling could also be used. This is a method that uses pressurized air and water combined to increase heat absorption[4].
Indirect cooling means that the waste heat will first be stored. The advantage of this is that the peak load will be much lower since the cooling system can store the heat and cool over a specific period instead of cooling the system directly. For this method, a heat storage medium is needed. There are several kinds of heat storage. First, sensible heat storage could be used. One example of this method is heating water[5]. Secondly, latent heat storage is an option too. In such a system, heat is extracted around the melting point of a solid material while remaining at about constant temperature, using the latent heat of a material[6]. Finally, heat storage can be created by storing heat in chemical reactions[7]. In all indirect cooling cases, the heat storage will be cooled afterward by the existing onboard cooling structure as indicated in Figure 2.1.

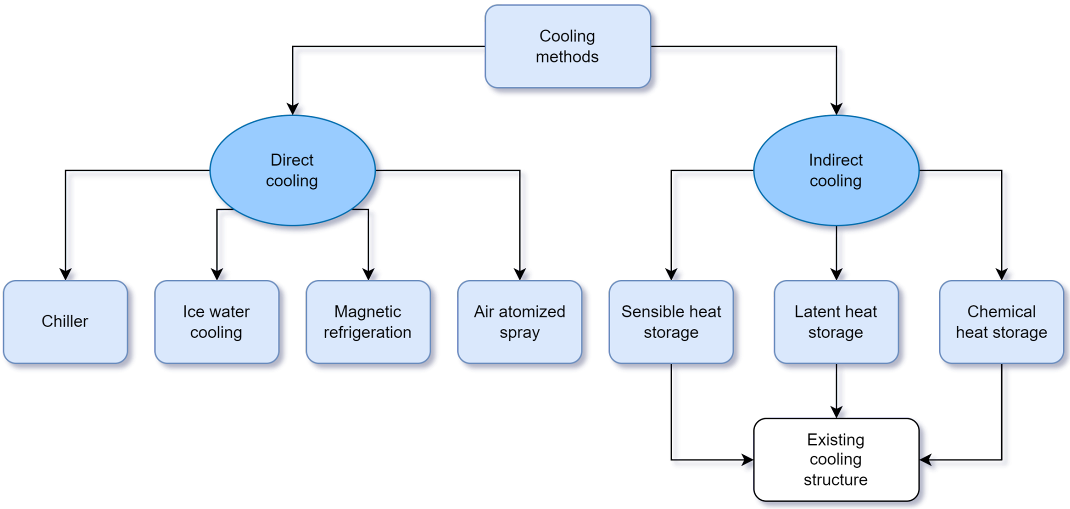


Figure 2.1: Overview of cooling methods.

---

[1] Andrei Blinov/Dmitri Vinnikov/Tõnu Lehtla: Cooling Methods for High-Power Electronic Systems, in: Scientific Journal of Riga Technical University. Power and Electrical Engineering 29.1 (Oct. 2011), pp. 79–86.

[2] Saad Dilshad et al.: Review of carbon dioxide (CO 2) based heating and cooling technologies: Past, present, and future outlook, in: Int J Energy Res 44 (2020), pp. 1408–1463.

[3] Andrej Kitanovski/Peter W. Egolf: Application of magnetic refrigeration and its assessment, in: Journal of Magnetism and Magnetic Materials 321.7 (Apr. 2009), pp. 777–781.

[4] S S Mohapatra/S Chakraborty/S K Pal: Experimental Studies on Different Cooling Processes to Achieve Ultra-Fast Cooling Rate for Hot Steel Plate, in: Experimental Heat Transfer 25.2 (2012), pp. 111–126, URL: `https://www.tandfonline.com/action/journalInformation?journalCode=ueht20`.

[5] T Dawe/MEng CEng MIMechE: The potential of Thermal Storage Tanks to assist in managing Peak Heat Loads on Naval Ships, in: URL: `https://doi.org/10.24868/issn.2515-818X.2020.037`.

[6] H. Xu et al.: Towards higher energy efficiency in future waste-to-energy plants with novel latent heat storage-based thermal buffer system, in: Renewable and Sustainable Energy Reviews 112 (Sept. 2019), pp. 324–337.

[7] T. Yan et al.: A review of promising candidate reactions for chemical heat storage, in: Renewable and Sustainable Energy Reviews 43 (2015), pp. 13–31.

Below, the seven cooling methods are discussed in more detail. First, the working principle of each method is explained, then the possible configurations are elaborated, and finally, the method is reviewed to see if it could work in this application. The points of review are the RPCs mentioned in Section 1.2.1. After explaining the seven methods, the methods will be evaluated by a design choice matrix. This will result in an overview of the methods applied in this situation.

2.1.1 Chiller

Cooling is always needed on board a vessel for air conditioning, radar systems, and other equipment. The cooling system that is currently used is the chiller. There are two chillers on the vessel, each able to cool all needed equipment in a critical situation. Therefore, redundancy is included: when one of the two chillers fails, the other can still cool all the critical equipment. Currently, the chillers are oversized, which means that the load, stable over time, can be cooled on the current structure. However, the peak loads of the HEL are too large to include in this structure.

Working principle

A chiller is used to cool water or a refrigerant by exploiting the refrigeration cycle shown in Figure 2.2. The cycle starts at the evaporator. Here, the heat of a system, such as the HEL, will be transferred, causing the cooling water to evaporate. Then, the low-temperature vapor will enter the compressor, where it will be compressed into high-temperature vapor. In the condenser, it changes phase into liquid, releasing heat that is carried away by the seawater, in the case of the chiller on the vessel. The final step is when the expansion valve releases pressure, and the cycle can restart[8].

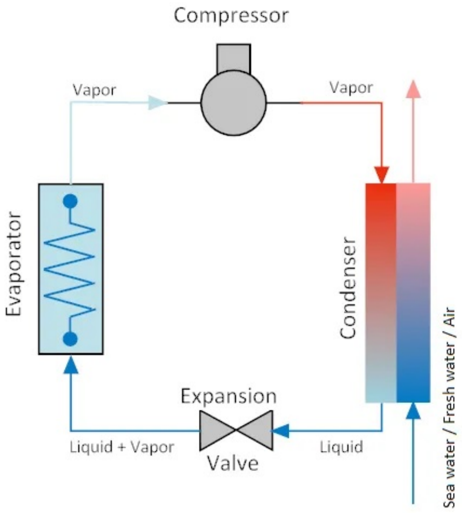


Figure 2.2: Chillers use this refrigeration cycle to remove heat from water[9].

Possible configurations

A chiller can be used to cool the HEL system with several configurations. First, the refrigerant could be changed from the standard. Appendix A presents that 515B is the most optimal refrigerant since it is non-flammable, has the normal pressure point, and has a relatively low global warming potential.

Other configurations can be made by increasing the size of the chillers at the bottom of the vessel or adding a chiller below the HEL system. When the chillers at the bottom of the vessel are increased, the HEL system will be connected to the current cooling structure. An important design implication then becomes that when the HEL system is initiated, the cooling water temperature may not be higher than 16 °C when entering the chiller. When

---

[8] How a Chilled Water System Works | HVAC Training Shop, URL: `https://hvactrainingshop.com/how-a-chilled-water-system-works/`.

[9] Cooling Plant - Heinen & Hopman, URL: `https://www.heinenhopman.com/knowledge/cooling-plant/#overview`.

cooling water of higher temperature enters the chiller, it will not be able to cool to 10 °C, consequently overheating the other equipment connected to the cooling structure. Using the current structure also implies that a heat exchanger will be used to to use the chiller at the right temperatures. When a separate chiller is installed underneath the HEL system, a chiller with a different temperature range must be chosen.

Review of the method

Looking at the RPCs of Section 1.2.1, the first requirement is the stable temperature. The vessel is already equipped with radar systems that also need such tolerance on temperature, so this is not a problem when using the chiller. Being able to use the current structure does give an advantage in terms of weight and volume demand. However, since the heat has to be cooled away instantly, the chiller has to have a big capacity, and in other words, large parts, and a high volume of cooling water. A chiller induces acceptable signatures on the ship by the vibration and noise of the equipment. It does not have one point of failure, either by increasing the size of both the chillers at the bottom of the vessel or placing the new chiller underneath the HEL system. Since the chiller is already used, it is also proven resiliently mounted and market ready.
The preferences are energy neutrality, which is hard to implement with direct cooling. However, universality could be an option. Finally, seawater usage is already integrated into the current cooling system by cooling directly with the seawater when the temperature is low enough.

2.1.2 Ice water cooling

Ice water cooling is a cooling method extensively used in the dairy sector. As a result of high amounts of milk at once, high cooling capacities are needed. However, after the peak load, usually, for quite some time, there is no cooling load needed. Hence, building a buffer ice bank is a good solution in the dairy sector, as well as it can be a good solution for the High-Energy Laser.

Working principle

Ice water cooling is a method of direct cooling. In contrast to using a chiller, the power needed for cooling can be divided over a longer time. This is done by creating an ice bank. When no cooling load is needed, the ice bank is built up to a specific volume and a certain heat capacity. Afterwards, it only needs to keep the ice bank from melting. When the cooling capacity is needed, ice water (at a temperature of 0.5°C) is taken from the ice bank. This water then cools the other fluid through a heat exchanger, as presented in Figure 2.3. The advantage of using ice water, instead of directly cooling with this ice bank, is that there is no risk of freezing the other fluid and the system.

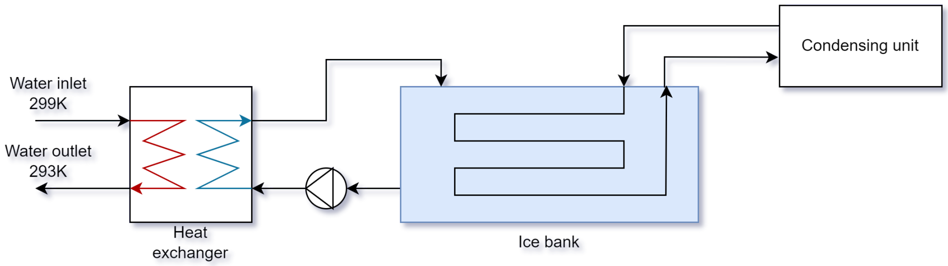


Figure 2.3: Schematic overview of an ice water cooling system.

Configurations

Since the ice bank should be created by a system that can freeze instead of only cool, the system cannot be connected to the current cooling system of the naval vessel. However, due to implementing an existing product in the dairy sector, the system will already be optimized for its use.

Review of the method

This method can give high precision to the temperature of the refrigeration fluid. Even though the system cannot use the current cooling structure, the cooling capacity can be spread over time, which will be better for weight, volume and power demand. The system has no signature and will be placed underneath the High-Energy Laser to make it redundant. The system can be mounted resilient to be shock resistant. Finally, seawater can be used to cool down the first peak, if not everything, before the ice has to be broken down.

2.1.3 Magnetic refrigeration

Magnetic refrigeration is a cooling method that is not in practical use at room temperature yet. Nevertheless, it is an auspicious method and will, therefore, be considered in this research.

Working principle

Magnetic refrigeration is based on the magnetocaloric effect. The magnetocaloric effect is a phenomenon that iron, among others, shows in a varying magnetic field. In essence, the paramagnetic or soft ferromagnetic materials expel heat, and their magnetic entropy decreases when the magnetic field is applied isothermally. The other way around works too; when they absorb heat, their magnetic entropy increases provided that the magnetic field is reduced isothermally[10].

The magnetocaloric effect can create a cycle, leading to magnetic refrigeration. Two cycles can be used at room temperature: The Ericsson and Brayton cycles, shown in Figure 2.4a. As shown in Figure 2.5, the Ericsson cycle proceeds as follows: Going from A to B is the isothermal magnetization process. When the magnetic field increases from H_0 to H_1, the heat transferred from magnetic cooling water (fluid below the electromagnet, shown in Figure 2.5) to regenerator fluid (fluid above the electromagnet) makes the upper fluid increase in temperature and thus release heat from the process. The isofield (constant magnetic field) cooling process is from B to C. The magnetic cooling water and electromagnet move downward to the bottom, transferring heat from the magnetic cooling water to the regenerator fluid. Then from C to D is the isothermal demagnetization process. Here the magnetic field decreases from H_1 to H_0, which causes the magnetic cooling water to absorb heat from the part that should be cooled. Finally, from D to A is the isofield heating process. The magnetic cooling water and electromagnet move upward to the top, and the regenerator fluid absorbs heat.

The Brayton cycle consists of two adiabatic and two isofield processes, as shown in Figure 2.4b. During the adiabatic magnetization process (D→A) and adiabatic demagnetization process (B→C), no heat flows from and out of the magnetization cooling water. The magnetic cooling water expels heat during the isofield cooling process A→B. During the isofield heating process C→D, the magnetic cooling water absorbs heat[10]. These two cycles can be optimal if the T-S curves are parallel, which can only be realized with composite materials.

In designing a magnetic refrigeration system, the following factors should be considered[11]: First, the device configuration (rotary, reciprocating), then the thermodynamic cycle (Ericsson or Brayton). Preceding, the selection of the working material depends on the operating temperature of the system and the form of the active material matrix, which must allow good heat transfer and low-pressure drop. Next, the heat conduction in the regenerator and the regenerator fluid mixing should be minimized since they tend to degrade temperature gradients. Also, the regenerator fluid should be selected (large volumetric heat capacity and low viscosity), and the magnet configuration and magnetic field profile should be chosen (in a way that the T-S curves obtained are properly parallel). Finally, cryogenic heat leaks should be minimized.

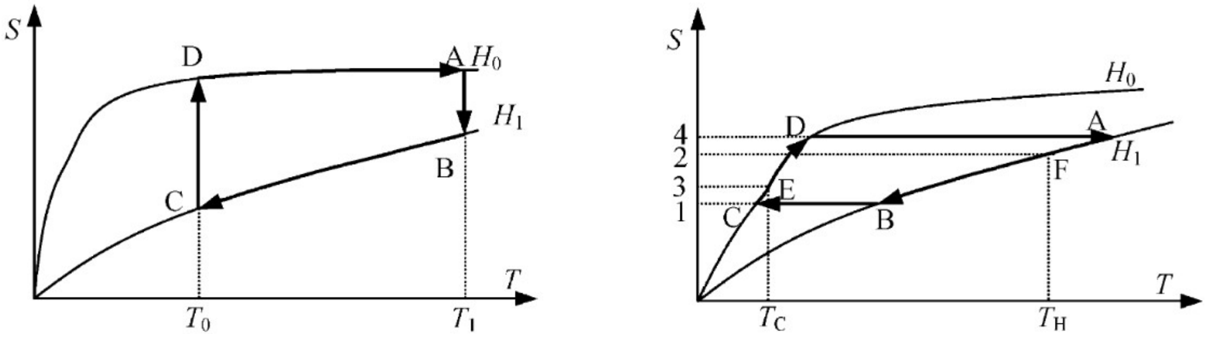
Configurations

Similarly as for the ice water cooling, the magnetic refrigeration system should be placed directly underneath the HEL system. In this position, the system will have the needed volume and redundancy.

---

[10] B. F. Yu et al.: Review on research of room temperature magnetic refrigeration, in: International Journal of Refrigeration 26.6 (Sept. 2003), pp. 622–636.

[11] Jay F Kunze: Magnetic Refrigeration Feasibility in Aircraft 7-24-1987, in: 2013, URL: `https://www.researchgate.net/publication/236586376`.



(a) Magnetic Ericsson cycle. (b) Magnetic Brayton cycle.

Figure 2.4: Magnetic refrigeration cycles at room temperature where H_0 and H_1 indicate two different magnetic fields ($H_0 < H_1$), T is the temperature, and S is the entropy.

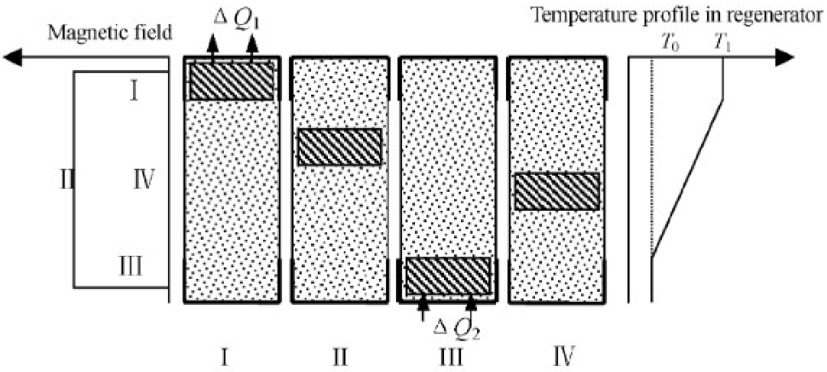


Figure 2.5: Schematic representation of magnetic Ericsson cycle [10].

Review of the method

Magnetic refrigeration is likely to have no to small signatures. There are minor pressure differences, no hotspots, and low noise, according to Egolf et al.[12]. The HEL system needs a stable temperature feasible with magnetic refrigeration[13]. In Kunze et al.[14], a magnetic refrigeration system for a fighter aircraft is designed. Here it is presented that the size of a magnetic refrigeration system will be close to a chiller system. Also, with the information that 4 kW/kg can be cooled and that the system weighs 13.2 kg per kg Gd, the required weight of the system can be calculated. There is no usage of dangerous liquids, and there is no single point of failure in the auxiliary equipment. However, at this moment, as mentioned before, there is no operational magnetic refrigeration system at room temperature. In about ten years, this device is expected to exist[15].

2.1.4 Air-atomized spray cooling

The fourth and last considered direct cooling method is air-atomized spray cooling. This method is currently used to cool high-temperature steel plates quickly after rolling to increase the tensile strength, but also for cooling vegetables in the store and in firefighting as water mist[16].

---

[12] P. W. Egolf/R.E. Rosensweig: Bulletin 2007-5 Magnetic Refrigeration at Room Temperature, tech. rep., 2007.

[13] Andrej Kitanovski/Peter W. Egolf: Application of magnetic refrigeration and its assessment, in: Journal of Magnetism and Magnetic Materials 321.7 (Apr. 2009), pp. 777–781.

[14] Jay F Kunze: Magnetic Refrigeration Feasibility in Aircraft 7-24-1987, in: 2013, URL: `https://www.researchgate.net/publication/236586376`.

[15] Andrej Kitanovski et al.: Present and future caloric refrigeration and heat-pump technologies, in: International Journal of Refrigeration 57 (Oct. 2015), pp. 288–298.

[16] Soumya S. Mohapatra et al.: Ultra fast cooling of a hot steel plate by using high mass flux air atomized spray, in: Steel Research International 84.3 (Mar. 2013), pp. 229–236.

[17] Santosh Kumar Nayak/Purna Chandra Mishra/Sujay Kumar Singh Parashar: Influence of spray characteristics on heat flux in dual phase spray impingement cooling of hot surface, in: Alexandria Engineering Journal 55.3 (Sept. 2016), pp. 1995–2004

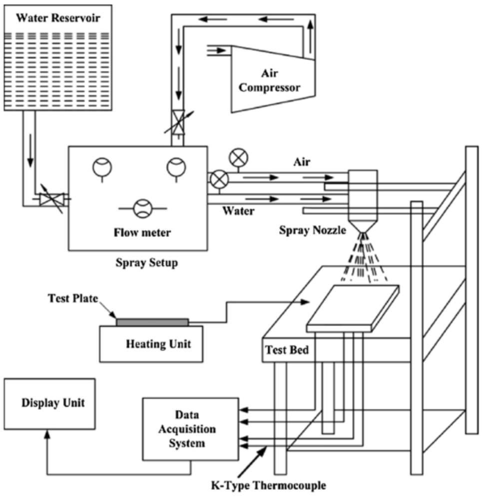


Figure 2.6: Schematic overview of an air-water spray cooling test setup. [17]

Working principle

In essence, air-atomized spray cooling involves nothing more than blowing air with tiny droplets against a hot plate to decrease the temperature of the hot plate. Figure 2.6 shows the setup of air-atomized spray cooling. The particles can be just water, but they can also be salt solutions. The droplet size can be influenced by changing the liquid-to-air ratio and the air and liquid pressure[18]. When a droplet is smaller, evaporating is easier, increasing the heat transfer effectiveness. However, too small particles will not reach the surface at all. Realizing a balance between those two is therefore very important[19].

Configurations

To use this method with the High-Energy Laser system, the heat from the HEL system should flow through a steel plate. Then this plate can be cooled by the air-atomized spray. This would take place underneath the High-Energy Laser system. The needed parts are two pressurized tanks, one with air and one with pressurized fluid. These two can be combined in the nozzle and directly sprayed onto the steel plate, just like the experimental setup in Mohapatra et al.[19].

Review of the method

When comparing the RPCs of Section 1.2.1 and the properties of this method, it is clear that air atomized spray cooling does give signatures: hot spots and pressure differences. This is created since the heat from the plate is released into the air instead of into the seawater, for example. However, the method can be used well to reach a stable temperature by influencing the particle size until the suitable heat transfer is realized [18]. Also, the required amount of cooling is possible with this method, and there will not be one single point of failure in the auxiliary equipment. Usage of weight and volume can be determined when looking at the weight of two pressurized containers filled with air and water combined with the steel plate. To have a shock-resistant system, the system as a whole or the separate parts should be placed on springs. Since this system has several separate parts, making the whole system shock-resistant will be more challenging. Many studies are still going on about air-atomized cooling and how this can be applied in a cooling system. However, it is not market-ready yet[19]. Finally, there is no use of the current chiller system and no use of dangerous liquids. However, the pressurized containers imply additional risks for danger to the vessel.

---

[18] Roy J.: Multiphase Spray Cooling Technology in Industry, in: Advanced Technologies, Oct. 2009.

[19] Soumya S. Mohapatra et al.: Ultra fast cooling of a hot steel plate by using high mass flux air atomized spray, in: Steel Research International 84.3 (Mar. 2013), pp. 229–236.

2.1.5 Sensible heat storage

Sensible heat storage is one of the three options for indirect cooling. The indirect cooling methods discussed in the following subsections are based on storing the waste heat of the HEL and then cooling the heat battery over a longer period with the existing cooling structure onboard.

Working principle

Sensible heat storage is storing heat in a material by increasing its temperature. Then, a suitable material can be chosen depending on the working temperatures. A sensible heat storage device consists of in- and outlets (from the HEL system to the chiller at the bottom of the vessel), a container (which has to retain the medium and prevent thermal loss), and the medium. For storage and cooling efficiency reasons, a thermal gradient in the container is desirable[20].

Configurations

To implement this method of cooling, two parts should be integrated. The sensible heat storage is the first part, whereas the cooling of the sensible heat storage is the second part.
Sensible heat storage should be placed inside the ammunition storage under the HEL system. The medium in which the heat is stored will not affect this, but here are the considerations: solid media could be concrete or ceramics since they both have low cost and high heat capacity. The fluid medium could be water, soil, sodium, and as the best-chosen medium, molten salts. However, water is still used most of the time because of its compromise between heat storage capacity, costs, density, and environmental impact[21].
The second part, cooling the sensible heat storage, will be done by connecting the storage to the cooling system that is already on board. The current chillers will have to increase in size to some extent to cool the storage within the set time.

Review of the method

Looking at the RPCs of Section 1.2.1, sensible heat storage can comply to maintain the temperature as long as the heat storage is sufficiently large. Table 2.1 lists the physical and chemical properties of some potential sensible heat storage media. In addition to these volumes and weights in the table, the tank around it should not be forgotten, resulting in a bigger and heavier solution than the table first indicates. The existing cooling structure is used, which makes the HEL system part of the other systems on the vessel. As a disadvantage, the heat storage will heat up when storing the heat of the HEL system, which could lead to a heat signature.
Finally, looking at the preferences of this project, the principle of a heat battery could make the option to recover energy more feasible.

Material	Density [kg/m^3]	Heat capacity [kJ/kgK]	Volumetric heat capacity [kJ/m^{3}K]
Concrete	2240	1.13	2531
Ceramics	1600	0.84	1344
Water	1000	4.18	4180
Soil	1300	0.46	598
Sodium	968	1.23	1191

Table 2.1: Physical properties of promising sensible heat storage materials[22].

2.1.6 Latent heat storage

The second indirect cooling method that is discussed is latent heat storage.

---

[20] Ibrahim Dincer/Sadik Dost/Xianguo Li: Performance analyses of sensible heat storage systems for thermal applications, tech. rep., 1997, pp. 1157–1171.

[21] Deepesh Sonar: Renewable energy based trigeneration systems—technologies, challenges and opportunities, in: Renewable-Energy-Driven Future 2021, pp. 125–168.

[22] Devrim Aydin/Sean P. Casey/Saffa Riffat: The latest advancements on thermochemical heat storage systems, in: Renewable and Sustainable Energy Reviews 41 (2015), pp. 356–367

(a) Block. (b) Cylinder. (c) Ball.

Figure 2.7: Representation of how the different shapes of phase change material would look.

Working principle

Latent heat storage consists of the same parts as sensible heat storage: in- and outlets, a container, and the medium. As a result of the usage of latent heat, the container will be smaller and with less insulation in contrast to the sensible heat container[23].

The medium used is called phase change material (PCM). The most crucial property of PCM is that when heat is stored in the material, the temperature of the PCM will stay close to constant, during which it melts. Depending on the working temperature, a suitable medium can be chosen. Phase change materials can be categorized into eutectics, salt hydrates, and organic materials[24]. For this application, the operating temperature is below 100 °C, which removes eutectics as an option.

Configurations

The way this cooling method can be integrated into the vessel is very similar to that of sensible heat storage. However, the container will be smaller, increasing the chance of fitting inside the existing structure. The conductivity, heat capacity and point of latent heat absorption can be determined depending on the kind of PCM. Therefore, the choice of PCM is critical in the configuration.

The inside of the container can be filled in very different ways. One option is to have an inside just as a shell-in-tube heat exchanger. This means that the cooling water will flow through tubes, while the tubes are covered on the outside with a shell of phase change material. The opposite option is to contain the phase change material, and the fluid will flow freely through the tank. This way, having as much heat transfer surface as possible is essential since the phase change material generally has low conductivity. Hence, several shapes of the contained phase change material are possible. In practice, three shapes are used: The cubed way, called blocks (Figure 2.7a), the cylinders (Figure 2.7b), and the balls (Figure 2.7c). All have different heat transfer surfaces and different heat capacities dependent on time. In all configurations, one challenge is known, phase change material expands during the phase change. Therefore, the tank should have a buffer for the pressure created and space for the increasing volume of the phase change material. Looking at the shell-in-tube configuration, the tubes must be vertical, so the expansion will not interfere with the tubes.

Review of the method

The review of the latent heat storage is comparable to that of the sensible heat storage, yet there are two significant differences. First, the latent heat storage does (almost) not increase in temperature, and the cooling liquids do

---

[23] Guruprasad Alva/Yaxue Lin/Guiyin Fang: An overview of thermal energy storage systems, in: Energy 144 (Feb. 2018), pp. 341–378.

[24] S. Wu: Heat energy storage and cooling in buildings, in: Materials for Energy Efficiency and Thermal Comfort in Buildings 2010, pp. 101–126.

not have significant temperature differences; therefore, the system has no signature. Second, the PCMs have high latent heat, which makes it possible to store a high amount of heat in a small and light volume.

2.1.7 Chemical heat storage

Finally, the third indirect cooling method is chemical heat storage, which indicates storing energy in chemical reactions.

Working principle

A chemical reaction or sorption can be initiated whenever heat is added to a specific material. Aydin et al.[25] discusses the ongoing studies on chemical heat storage. The layout of the chemical heat storage depends on the kind of chemical reaction or sorption. For example, figure 2.8 shows the layout for the lead(II)carbonate reaction. For the storage, a vacuum pump is needed to extract the CO_2 from the tank with $PbCO_3$ and PbO. Then, a valve is opened to release the heat, cool it, or use it for something else on the vessel. Finally, the CO_2 flows back to the other container, releasing heat.

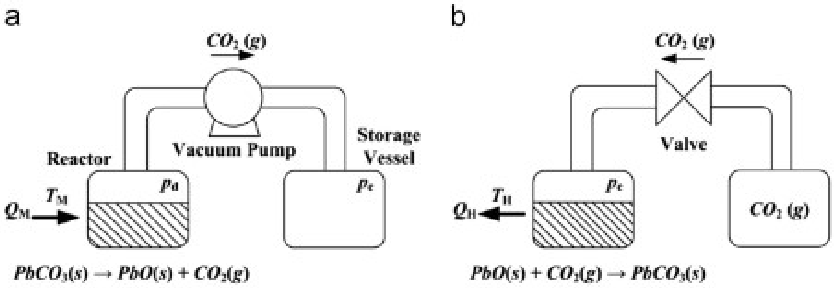


Figure 2.8: Principle of PbO/CO_2 chemical reaction heat storage system: (a) heat storage mode; (b) heat supply mode[26].

Configurations

In most cases, the chemical heat storage will need two containers with some extraction equipment in between. Since the temperature will not vary, the containers do not need insulation. These containers can be placed underneath the HEL system. The configuration does vary with the chemical reaction, which in most cases is determined by the presence of H_2O or NH_3. H_2O is the ideal working gas in many ways since it has the highest latent heat and is non-toxic. However, it has low vapor pressure, which can present problems. In addition, the hydration process can be limited by mass transfer. Ammonia does not have this disadvantage[27].

Review of the method

Looking at the RPCs, the review will be almost the same as for the latent heat storage. The biggest difference is the size and weight of the systems. To summarize, this system causes no signatures and can be built redundant and shock-resistant. When the right chemical reaction is chosen, the direct capacity and stable temperatures will also be good. Besides, the usage of dangerous liquids is not needed if the used reaction does not have dangerous reactants. One difference is that the separate containers, and therefore the heat can be transported without losing energy. Also, energy recovery is feasible with this method. This system is still new, nevertheless already in use, which makes it possible to integrate it into the naval vessel in the future.
However, there is one challenge. When looking into the different reactions that can be used for this application, no

---

[25] Devrim Aydin/Sean P. Casey/Saffa Riffat: The latest advancements on thermochemical heat storage systems, in: Renewable and Sustainable Energy Reviews 41 (2015), pp. 356–367.

[26] T. Yan et al.: A review of promising candidate reactions for chemical heat storage, in: Renewable and Sustainable Energy Reviews 43 (2015), pp. 13–31.

[27] T. Yan/R. Z. Wang/T. X. Li: Experimental investigation on thermochemical heat storage using manganese chloride/ammonia, in: Energy 143 (Jan. 2018), pp. 562–574.

reaction is found that is applicable within the temperature range of the High-Energy Laser. In Appendix B, Table B.2 shows several different options for chemical reactions. To the author's knowledge, the lowest temperature used for TCES is 90 °C. There are some developments to lower this to 45 °C[28], yet this is still far from the 20-26 °C needed for this application. Therefore, this cooling method will not be possible to cool the High-Energy Laser weapon system.

2.1.8 Design choice

In previous Sections, the seven cooling methods are explained and reviewed. The cooling methods will be compared in this Section. The most important reviewing point for each cooling method is if they comply with the RPCs elaborated in Section 1.2.1. Table 2.2 summarizes the review paragraphs of previous Sections by giving +/++ to good/excellent compliance, -/- - too bad/very bad compliance, and ± to undetermined compliance.

The chiller is a cooling method that is very well-known for the naval vessel, which is an advantage. However, since it cannot use the current structure and has to cool the peak load, it will increase the weight, volume and power demand. The ice-water cooling method is also unable to use the current structure. However, since it can prepare for the peak loads of waste heat, the system can have less capacity, which will probably decrease the weight, volume and power demand. Magnetic refrigeration is known for being very efficient and therefore uses less power. However, the system still needs to be market ready. Air-atomized spray cooling is also an upcoming cooling method that is not market-ready yet. Besides, it also increases the chance of having signatures on the naval vessel, and it cannot use the current structure of the vessel. Sensible heat storage gives the option to use the current cooling structure of the naval vessel. As a disadvantage, a large volume and weight are needed to store all the waste heat in water, which is one of the best fluids to store heat in. On the other hand, latent heat storage can store much heat in small volume and weight and can use the current structure to cool down again. Finally, chemical heat storage can store heat without changing temperature, giving excellent options for recovering energy. However, there are no chemical reactions, to the author's knowledge, that can be used for this at the low temperature of 20 °C.

Comparing the above advantages and disadvantages, and in combination with Table 2.2, the cooling methods, air atomized spray cooling, sensible heat storage, and chemical heat storage seem to have too big challenges or disadvantages. The other four cooling methods: Chiller, ice water cooling, magnetic refrigeration, and latent heat storage, have attractive advantages and properties. Therefore, these four methods will be investigated further in this research.

		Requirements								Preferences			Constraints	
Category	Method	Stable temperature	Weight	Existing structure	Signatures	Volume	Cooling time/capacity	Shock-resistant	Market ready	Energy neutrality	Universality	Seawater	On board chiller	Safety regulations
Direct	Chiller	++	±	++	++	-	+	+	++	- -	-	++	+	+
	Ice water cooling	++	±	- -	++	±	++	+	++	-	++	++	- -	++
	Magnetic refrigeration	+	±	- -	++	±	++	-	- -	-	+	++	-	++
	Air atomized spray	+	±	- -	-	±	+	-	+	-	-	++	-	++
Indirect	Sensible heat storage	++	-	++	-	-	+	+	++	+	+	++	++	++
	Latent heat storage	++	+	++	+	+	++	±	++	+	+	++	++	+
	Chemical heat storage	++	+	++	+	++	++	±	- -	++	+	++	++	±

Table 2.2: Decision matrix of the investigated cooling methods.

---

[28] Amirhoushang Mahmoudi et al.: A thorough investigation of thermochemical heat storage system from particle to bed scale, in: Chemical Engineering Science 246 (Dec. 2021).

2.2 Naval surface combatant

In Chapter 1, it became clear that not only the cooling problem is a challenge, but specifically solving the cooling problem on a naval surface combatant. This increases the complexity of the cooling problem. The most crucial part of introducing something on the naval vessel is the weight, volume and power demand increase. These three values all have a direct influence on the overall performance of the ship. This research focuses on finding the optimal cooling method for the High-Energy Laser with those three implications in mind. However, besides those three implications, additional design rules are induced while adding something to the navel vessel. In this Section, these additional design rules are explained and elaborated on how they can be obeyed.

2.2.1 Redundancy

First is the system's redundancy, which is the constraint that the system should not fail if only one part of the (auxiliary) equipment fails, emphasizing damage by war activities. This gives the configuration two options: making sure that the cooling system will not be destroyed before the High-Energy Laser itself is destroyed or having two different locations of the cooling system, which can both cool the High-Energy laser on its own. If one of these two options is implemented, it should not be possible for the High-Energy Laser itself to be operational, but it cannot be used because the cooling equipment is broken.

In this application, the most significant part of the cooling system will be placed underneath the High-Energy Laser. This means that if the High-Energy Laser is hit when the ship is attacked, the cooling system is also hit. Therefore, this configuration is acceptable from a redundancy point of view. When the cooling structure of the ship is used, it is essential that if one of the chillers is shut down, the other chiller can take the total load.

2.2.2 Shock resistance

Secondly, the shock resistance of the system. If the ship is in battle, there could be an impact on the vessel. This will cause a shock wave. Therefore, all the equipment inside the vessel should be able to endure this shock wave at least once. Also for this design rule there are two options: the equipment can endure shock waves independently, which will depend on its properties and build. The other option is that the complete system will be placed on special springs, which will take up the shock wave and most likely break after one time. Such springs are used widely on naval surface combatants.

Depending on if the system is, for example, very brittle, the choice should be made to use the springs. However, the use of springs will increase the volume demand of the system since the system should not touch any of the walls and floor except through the springs.

2.2.3 Signatures

Thirdly, the signature of the vessel is essential. This means that the cooling system should not increase the visibility of the vessel to its enemies. This restricts the possibility of heat spots, pressure differences, and noise. In Thompson et al.[29], the author explains how vital the suppression of signatures is to be less visible and detectable. Looking at the cooling system, the most important, and most likely, signature is the visibility through infra-red because of temperature differences, called hotspots.

There are several options to have a low signature. One way is to suppress the hot spot, which can be done by, for example, a layer of cold air around the heated equipment, as explained in Thompson et al.[29]. However, an even easier option is to have a cooling system that does not involve too significant temperature differences and thus will not create hot spots in the first place.

2.2.4 Temperature restrictions

Fourthly, the vessel has regulations in which temperatures it should endure and in which to function. These temperatures are derived from the regions the vessel has to sail and the common temperature. Therefore, the cooling system should be prepared to endure and function in these temperatures of the seawater and the air. As mentioned in Section 1.2.1, the water temperatures it should endure are -6 °C to 38 °C, and it shall function in

---

[29] J Thompson/D Vaitekunas/B Brooking: Signature management- The persuit of stealth lowering warship signatures: Electromagnetic and infrared, tech. rep., 2000, URL: `www.davis-eng.on.ca`.

seawater temperature of -2 °C to 35 °C. For the air the temperature to endure is -35 °C to 50 °C and it shall function in -20 °C to 48 °C.

For the seawater temperature, these temperatures imply that cooling the High-Energy Laser with the seawater directly will be hard since the seawater temperature can rise above the maximum temperature of the High-Energy Laser. However, since most of the temperatures and, most of the time, the seawater temperature is below the maximum temperature of the HEL system, the seawater could be used to decrease the power demand of the cooling system.

For the air temperatures, it is less critical since the ammunition room where the cooling system should be built will be kept stable at around 20 °C. However, it is worth looking into the case where the temperature does not stay stable to see if the equipment will not fail immediately.

2.2.5 Safety regulations

Finally, the vessel poses several safety regulations. This could be about which kind of liquids are allowed on the vessel but also about the risk of explosion of the system. Therefore, these safety regulations should be considered during the design period.

In Andrews et al.[30], it is explained that the common threat in safety rules on the naval vessel is that the risk should weigh up against the benefit. Therefore there are four classifications of risks:

- Class A, which is intolerable
- Class B, which is undesirable and only accepted when risk reduction is impractical
- Class C and D, which are both deemed tolerable.

However, to be more specific on the critical risks on a naval vessel and specifically looking at the cooling system that should be integrated, the most critical risks are fire, explosion, and toxicity. Therefore, to comply with these safety rules, all used fluids and materials should be checked for (long-term) toxicity, explosiveness, and low flash points. Also, if there are processes that are sensitive to catching fire, they should be suppressed too.

---

[30] David Andrews: Recent developments in the Safety Regime for Naval Ship design, in: Quality and Reliability Engineering International, vol. 22, Feb. 2006, pp. 21–30.

3 Research Methods

In this Chapter, the research methods will be explained. The research methods means that for every cooling method chosen at the end of Chapter 2, the way of finding the implications will be explained. The implications are, in particular: weight, volume and power demand. The simulation and optimization process will be explained for the latent heat cooling method. A model will determine the power demand for several cooling methods, which will also be elaborated. Finally, the method behind answering the sustainability questions will be explained.

3.1 Chiller

As explained in Chapter 2, the chiller onboard the naval vessel in the standard structure does not have enough capacity left to cool the High-Energy Laser too. However, much information is already known since the chiller is already used on the naval vessel. Therefore, the information of the current manufacturer will be used to find the implications; weight, volume and power demand of this chiller. The current manufacturer has several types of chillers. It could be that a different chiller is better for this case since a lower load is needed. Therefore, the optimization of the chiller cooling method will be on choosing the most optimal, but existing chiller. Optimization, in this case, means choosing the chiller with enough capacity in the temperature range mentioned, with as low as possible use of weight, volume and power demand. Finding the implications by using the manufacturers' information has as advantage that the information provided is accurate. However, looking at only one manufacturer can give a situation where the most optimal chiller of this manufacturer is chosen, while another manufacturers may have even better chillers. The same manufacturer is usually used for specific parts in the design of new naval surface combatants. The advantage is that not only the manufacturer provides information, but there is also experience in the own organization. So, even though the choice of chillers is minimized by looking at only one manufacturer, the chiller's implications are very reliable. Using the manufacturer's information is, therefore, a suitable research method.

3.2 Ice water cooling

The ice water cooling method is derived from an existing application. This application is the milk tank in the dairy sector since peak heat loads must be extracted from the milk quickly. The implications will be taken from the dairy sector's existing ice water cooling machine. Optimizing the existing product will take place in choosing the appropriate machine with as little as possible usage of weight, volume and power demand and enough capacity to cool the peak loads of the High-Energy Laser. The choice of using an existing product instead of designing and optimizing an ice water cooler in this research is made because the existing product is used for a similar situation. The quality of the existing product is therefore expected to be better than when a self-made product is designed in this research. The disadvantage of using an existing product, and the manufacturer's information, is the same as for the chiller; it could be that a different manufacturer has a better machine without the author's knowledge. Still, using the manufacturer's information is a common way of finding the first implications of a specific method.

3.3 Magnetic refrigeration

The cooling method of magnetic refrigeration is not an existing cooling method. As explained in Chapter 2, there are working prototypes. However, these are not of the range of capacity to cool the High-Energy Laser. Still, based on these prototypes, there is a belief that this cooling method is up-and-coming. The implementation of the High-Energy Laser on the new naval surface combatant will be in at least 15 years. If the developments of magnetic refrigeration increase in the coming years, the cooling method could be used on a naval vessel. However, since there are no working systems yet of the needed capacity, the implications must be approximated by looking at different systems in the literature and comparing them to the theoretical efficiencies of this system. The implications of working magnetic refrigeration systems will be compared and scaled to the capacity needed for the High-Energy Laser. The result will be a range of used weight, volume and power demand that the working magnetic refrigeration system needs on the naval vessel. With this research method, the implications can be determined up to a range based on several literature sources. However, the scaling does imply uncertainty in the result, and no specific values can be determined. Since there are no existing products of this size, it is a good and common way to find information, despite the uncertainty.

(a) Chilled water unit [1]. (b) Ice water cooling system [2]. (c) Magnetic refrigeration prototype [3].

Figure 3.1: Example products/prototypes of the first three cooling methods.

3.4 Latent heat storage

The fourth cooling method involves a heat battery of phase change material. Many variations can be made on this heat battery; no existing product could be used, like in the other cooling methods. First, a comparison between phase change materials will be made to find the optimal usage of PCM. Then the different application methods will be compared—these vary from shell-in-tube tanks to tanks filled with blocks and cylinders of PCM. Finally, the COMSOL simulation of the heat battery will be elaborated. With this order of finding information, the final goal, the implications, can be determined efficiently. The Computational Fluid Dynamics (CFD) model needs a starting point from where the optimization can start. The model can focus on the details by determining the (range of) best materials and shapes by literature and hand-calculations. Also, the end product is focused on this application particularly, instead of having a generally used solution, which could imply that it is not efficient for this usage. The disadvantage of a CFD model is that it is uncertain how much difference there is between reality and the model. These points of uncertainty will be elaborated on throughout the following sections. In comparison to a model, testing in real life is costly and time-consuming. Also, CFD is a common way of researching the implications of a specific system in heat transfer-fluid flow situations. To conclude, the research method of doing literature research to implement the findings in the CFD model does limit the certainty. However, it is less expensive and will indicate the implications well.

3.4.1 Phase change material

There are several essential aspects to choosing this heat battery's optimal phase change material. First, the conductivity should be as high as possible as it accounts for how fast heat can be taken from the cooling water. Second, the volume change should be as little as possible, as it contributes to challenges in the tank design and can decrease the amount of heat transfer surface when it is in the smallest volume. Third, the heat the material can absorb at the melting point should be as high as possible to have less volume of material for the same amount of heat. Finally, the melting point should be at a favorable temperature. After the material is chosen, a check should be done on the safety rules explained in Section 2.2.5.

Three types of phase change materials are commonly used in heat batteries: paraffin wax, non-paraffin organics, and hydrated salts. Non-paraffin organics are highly flammable, and unsuitable for naval surface combatant use. Hydrated salts have a too high melting point for this application, and are therefore unsuited. On the contrary, paraffin wax is stable, has the right melting point, and has a high latent heat. In Table B.1, in Appendix B, several paraffin wax materials are compared. At first, a melting point in the range of 20 °C to 26 °C seemed suitable. Later, in Chapter 4, this will prove to be wrong. The PCM's low conductivity makes a lower melting point much more interesting. When ΔT is high, the material will absorb faster.

The RT series, presented in Table B.1, has chemical stability over time and is not flammable, making it suitable for the heat battery that will cool the High-Energy Laser. From this series, the optimal material will be chosen by iterating in the simulation regarding latent heat and melting point.

---

[1] Heinen Hopman: Ventilation Air Conditioning Refrigeration Heating provided by 22 ° C, tech. rep.

[2] IJsaccumulator PIB 25-160, tech. rep., URL: `www.packocooling.com`.

[3] Bingfeng Yu et al.: A review of magnetic refrigerator and heat pump prototypes built before the year 2010, 2010.

Shape	Amount needed	Size	Δ x [mm]	Volume [m^3]	Volume PCM [m^3]	Weight PCM [kg]
Shell-in-tube	10600 m	D=15mm	2.0	3.4	1.53	1200
Blocks	1500 blocks	8 mm thick	1.0	2.6	1.5	1600
Cylinders	13300 cylinders	D=24 mm	1.0	3.3	3.0	1400
Balls	450000 balls	D=20 mm	4.0	3.44	1.2	1000

Table 3.1: Comparison of the different arrangements of PCM tanks. The calculation behind these numbers is incorporated in Appendix C.

3.4.2 Shape phase change material

In previous sections, it became clear that the contact surface with the cooling water should be as high as possible because of the low conductivity of the phase change material. Therefore, the different arrangements of a tank are compared in Table 3.1. Here, the optimal hand-calculated size of the pipes, blocks, cylinders, or balls is shown and the calculation is presented in Appendix C. From there, the tank's total volume, as presented in Figure 3.2, the volume of phase change material, and the tank's weight inside are calculated because it is likely that conductivity will be the limiting factor. Nevertheless, it should be checked with the simulation to see if the hand calculation is indeed the most optimal situation.

To achieve the most optimal heat battery, a balance should be created between having a low total volume of a tank, a high volume of PCM, and a high amount of contact surface between the fluid and the PCM. Table 3.1 presents that the ball-shaped PCM uses a total volume smaller than the block but close to the cylinders, while it does not have much volume of PCM. The high volume is due to many balls; therefore, a lot of "free" space is needed to have enough heat transfer surface. On the contrary, shell-in-tube tanks need a lot less volume and have more PCM volume. This is because both blocks and cylinders need more volume as the shell-in-tube while also having more volume PCM. Consequently, the ball-shaped PCM will be left out of this research as it comes out as least optimal, whereas the other three tank arrangements will be further investigated throughout the research.

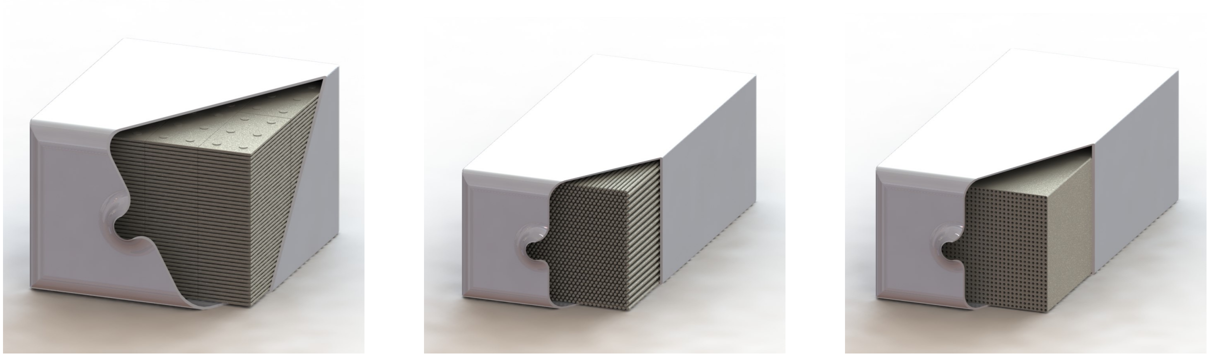

(a) Block tank.
(b) Cylinder tank.
(c) Shell-in-tube tank.

Figure 3.2: Schematic visualization of the tanks with the different shapes of phase change material.

3.4.3 COMSOL

In contrast to the three direct cooling methods, all existing products or concepts, the heat battery of phase change material does not have given parameters for weight, volume and power demand. Hence, a Computational Fluid Dynamics simulation is needed to find the optimal configuration of a heat battery in this application. In this Section, the equations used in the simulation and the initial and boundary conditions will be presented. Furthermore, the simplifications of the model, the mesh, and the used 3D models will be explained.

Governing equations

The model is based on the three equations for conservation of mass, momentum, and energy[4]. The conservation of mass can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{3.1}$$

where ρ is the density of the material [kg/m^3], t is the time [s], and $\mathbf{u}$ is the velocity profile [m/s]. When the material derivative is now applied to the above equation, the result is:

$$\frac{D\rho}{Dt} + \rho(\nabla \cdot \mathbf{u}) = 0. \tag{3.2}$$

The fluid can be assumed incompressible at the temperatures used in this application since the Mach number is smaller than 0.3. Consequently, the first term of the above equation is equal to zero. So, the conservation of mass is

$$\rho(\nabla \cdot \mathbf{u}) = 0 \Rightarrow \nabla \cdot \mathbf{u} = 0, \tag{3.3}$$

which is also known as the continuity equation. The Navier-Stokes equation is used with the continuity equation to solve the fluid flow. The Navier-Stokes equation is derived from the conservation of momentum, which is:

$$\underbrace{\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right)}_{1} = \underbrace{-\nabla p}_{2} + \underbrace{\nabla \cdot \left(\mu\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I}\right)}_{3} + \underbrace{\mathbf{F}}_{4}. \tag{3.4}$$

Here, p is the pressure [Pa], μ the viscosity [Pa s], $\mathbf{I}$ a unit vector [-], and $\mathbf{F}$ a tensor of externally applied forces [Pa/m]. The first term corresponds to the inertia forces, the second to the pressure forces, the third to the viscous forces, and the last to the externally applied forces. The model simulates the fluid flow in a stationary situation. Thus the time-dependent term in the inertia forces term can be neglected. Similarly, the term

$$-\frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I}, \tag{3.5}$$

can be removed since Equation 3.3 shows that the velocity profile's divergence is zero. Implementing discussed alterations gives

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F}, \tag{3.6}$$

which is the equation that the model uses for the fluid flow simulation. In this equation $\mathbf{K} = \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$. A variation of these equations is the Reynolds-averaged Navier-Stokes equations, which include the turbulence of a flow. The Reynolds number can be calculated with

$$Re = \frac{u \rho D_H}{\mu}, \tag{3.7}$$

where $D_H = \frac{4A}{P}$ of which u is the velocity of the fluid [m/s], A is the area [m^2], and P is the perimeter of the cross-section of one fluid passage [m]. When the Reynolds number for the tank with blocks is calculated, the result is about 1000, which indicates a laminar flow. Consequently, the flow can be calculated as a laminar flow as in equation 3.6.

After the stationary fluid flow simulation, the heat transfer between fluid and solids is simulated in a time-dependent situation. Similar to fluid flow is heat transfer based on a conservation law. The most general form of the conservation of energy can be written as

$$\underbrace{\frac{\partial}{\partial t}\left[\rho\left(e + \frac{1}{2}u^2\right)\right]}_{1} + \underbrace{\nabla \cdot \left[\rho \mathbf{u}\left(e + \frac{1}{2}u^2\right)\right]}_{2} = \underbrace{-\nabla \cdot \mathbf{q}}_{3} + \underbrace{\nabla \cdot (\sigma \cdot \mathbf{u})}_{4} + \underbrace{\rho \mathbf{u} \cdot \mathbf{F}}_{5}, \tag{3.8}$$

where e is internal energy per unit mass [J/kg], u^2 is the square of the velocity magnitude [m^2/s^2], $\mathbf{q}$ is the conductive heat flux vector [W/m^2], and σ is the total stress tensor [Pa]. In this equation, the first term corresponds to the rate of increase of energy per unit volume, the second term to the convection of energy into a point by flow,

---

[4] Heat Transfer: Conservation of Energy, URL: `https://www.comsol.com/multiphysics/heat-transfer-conservation-of-energy?parent=fluid-flow-heat-transfer-and-mass-transport-0402-442`.

the third term to the net heat flux, the fourth to the work of surface forces, and the last term to the work of body forces. The total stress tensor can also be written as

$$\sigma = -p\mathbf{I} + \tau, \tag{3.9}$$

of which τ is the viscous stress tensor [Pa]. Using the above notation, the fourth term of equation 3.8 can be rewritten as follows:

$$\nabla \cdot (\sigma \cdot \mathbf{u}) = -\nabla \cdot (p\mathbf{u}) + \nabla \cdot (\tau \cdot \mathbf{u}). \tag{3.10}$$

Here, the first term on the right side is known as pressure work, and the second is viscous work. As a result of the fluid being incompressible and the viscous heating of the system being neglected, both parts will be removed from equation 3.8. Instead of expressing the thermodynamic state in internal energy, which is rarely used, the thermodynamic state can also be expressed in enthalpy, h [J], which is related to internal energy as follows:

$$e = h - \frac{p}{\rho}. \tag{3.11}$$

Using this equation in equation 3.8, together with removing above mentioned elements, gives

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho \mathbf{u} h) = -\nabla \cdot \mathbf{q} + \mathcal{Q}. \tag{3.12}$$

Here, the term $\mathcal{Q}$ is added too [J], where a possible internal heat source can be implemented. Although enthalpy is a commonly used term in engineering language, expressing the energy in temperature gives better insight into the behavior of systems since all engineers are familiar with the concept of temperature. The following differential relations exist between enthalpy, temperature, and pressure:

$$dh = C_p dT + \frac{1}{\rho}\left[1 + \frac{T}{\rho}\frac{\partial \rho}{\partial T}\bigg|_p\right] dp = C_p dT + \frac{1}{\rho}[1 - T\beta]dp. \tag{3.13}$$

From these equations, C_p is the heat capacity at constant pressure [J/K], and β is the bulk expansion coefficient [-]. Implementing these differential relations into equation 3.12 gives the final version of the conservation of energy equation that the model uses:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = \mathcal{Q}, \tag{3.14}$$

where $\mathbf{q}$ can be written as $\mathbf{q} = -k\nabla T$, where k is the thermal conductivity [W/mK].

One-way coupling combines the two final equations, equations 3.6 and 3.14. One-way coupling means that when the fluid flow is modeled stationary, this flow is used without considering the temperature difference over time. This can be done since the temperature differences are so minor that the flow will not vary because of those differences. However, unlike the fluid flow, the heat transfer does consider that the flow will carry heat from and towards the PCM. Hence, it is a one-way coupling.

Initial and boundary conditions

For the model to have a starting point, initial conditions are implemented. Also, to have a realistic simulation, boundary conditions are given.
First, the fluid flow is calculated. This is done with initial conditions of $\mathbf{u} = 0$ and $p = 0$, ensuring that the model starts to build up from a zero velocity. Also, the initial temperature is given as $T = 283K$. When the model starts, it has inlet conditions.
The fluid inlet has a mass flow condition. This condition is written as

$$-\int \rho(\mathbf{u} \cdot \mathbf{n}) d_{bc} dS = \dot{m} \tag{3.15}$$

in which d_{bc} is the channel diameter [m], and $\dot{m}$ is the mass flow per second [kg/s]. The inlet temperature is described by a step-function which has a baseline of 283 K, increasing to 299 K. The step function has a smoothing of the increase over 120 seconds to have a realistic start of the heat flow. Therefore, the time is started after 1 minute. Another inlet boundary condition is that one point on the inlet has a pressure equal to zero, giving the effect of being able to calculate the pressure difference over the inlet and outlet of the system.

On the contrary to the inlet, the outlet has no prescribed flow. It uses the constant pressure point, p_0, at the inlet and states

$$[-p\mathbf{I} + \mathbf{K}]\mathbf{n} = -\hat{p}_0\mathbf{n}, \tag{3.16}$$

where $\hat{p}_0 \leq p_0$, while the pressure and viscous forces should be equal to p_0. For the heat transfer, the situation applies that there cannot be conductive heat transfer through the outlet, given by:

$$-\mathbf{n} \cdot \mathbf{q} = 0. \tag{3.17}$$

Next, there are boundary conditions on the walls of the simulation. For the fluid flow, the wall boundary is a no-slip boundary, which indicates:

$$\mathbf{u} = 0. \tag{3.18}$$

Thus, a velocity of zero at the wall. On the outside walls, there would be thermal insulation, which is the same condition as for the outlet in equation 3.17, which says that there cannot be heat transfer in the average direction of the wall. Nevertheless, this boundary condition is only applied on the front and back end of the simulation. The sides of the model are covered by the symmetry boundary conditions, which means the same as the wall boundary condition in the case of solid parts. On the contrary, for fluid flow with a symmetry boundary, the following is applied:

$$\mathbf{u} \cdot \mathbf{n} = 0, \mathbf{K_n} - (\mathbf{K_n} \cdot \mathbf{n})\mathbf{n} = 0, \mathbf{K_n} = \mathbf{K}\mathbf{n}, \tag{3.19}$$

which says in the first part that in the normal direction of the symmetry boundary, the velocity profile is zero. The second and third parts say that the velocity profile is the same on the other side of the symmetry boundary.

Simplifications

The shapes of the PCM and tanks are shown in the previous Section. With these shapes, the models are also built. However, the model would become very large and highly demanding from a calculation perspective. To decrease this demand, the models will have several simplifications. Since the PCM shapes are the same pattern throughout the whole tank, it is possible to take small parts of the tank and scale this to the whole tank.
Looking at the blocks in a square tank, the model can be scaled by looking at a 2D model of three layers: on top, half the PCM block, then the fluid flow, and at the bottom, another half PCM block, as can be seen in Figure 3.3a. On the contrary, with the cylindrical PCM and the tube-in-tank model, 2D is not representative. Consequently, another pattern is found. In the case of the tank with cylinders, this can be done with a 3D model in a triangular shape, covering a part of the tank which repeats itself constantly, as presented in Figure 3.3b. The last model is made from squares, which shows one-quarter of a pipe of the shell-in-tube tank, as presented in Figure 3.3c.
Preceding the simplifications of the model for the computational load to decrease is the inlet, a vital subject. As a result of having ample open space in the inlet of the tank, as presented in Figure 3.2, and small spaces between the PCM shapes, some meshing issues occur. These issues are caused by the fact that the mesh can only increase with 1.4 per step, which gives a tiny mesh at a position where a big mesh gives better results with a reduced computational load. With this in mind, a small study is done on the influence of the size and position of the inlet and outlet of the tank in Appendix D. Because of the high pressure in the inlet part of the tank and the high-pressure drop throughout the pipes between the PCM, the result is that neither the position nor the inlet's size influences the fluid's spread or speed. Hence, the model will not contain an inlet and outlet, and thus the mass flow per entrance between the PCM shapes will be used.
Finally, the situation modeled has a high Peclet number, which is the ratio between diffusion and convection times. The high number means that convection happens faster than diffusion, which creates a heat front. A heat front is hard to simulate since, with every time step, the same particle has to move but also has a significant temperature gradient with the sides and therefore transfers heat. To decrease the temperature gradient of the heat front, the simulation will increase the temperature slowly over 2 minutes. To determine the time it takes for the tank to saturate, the first minute will be neglected because only a small amount of hot water has reached the tank at that time.

Mesh

For all models counts: The mesh is made based on the physics computed in that specific study. Therefore, in the first study step, the mesh is based on laminar flow combined with heat transfer since the fluid and PCM both have a temperature. However, this temperature stays stable at 283 K. In the second study step, the mesh is based on heat transfer between fluids and solids and nonisothermal flow. Figure 3.4 shows the difference between the two

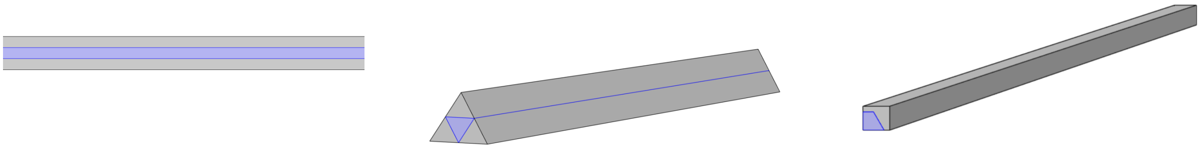
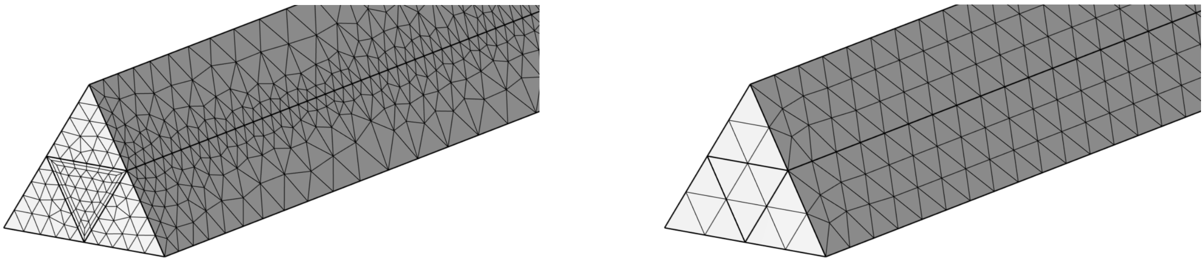

(a) Block model. (b) Cylinder model. (c) Shell-in-tube model.

Figure 3.3: Visualization of the used models and how they look after the simplifications are implemented. The blue highlighted parts are fluid.

meshes. In Figure 3.4a, it is visible that there are boundary layers to be able to simulate the no-slip boundary condition. Also, the size of the mesh's tetrahedral parts is much smaller, which is needed to simulate the particles moving through the tank.
To continue on the last paragraph, another computational load-reducing simplification is done in the mesh. As a consequence of the shape of the mesh, primarily triangles, covering a round-shaped figure on all sides gives complications. Changing the cylinders to hexagons solves the meshing problem and decreases the computational load. Appendix E compares circles and hexagonal shapes regarding the perimeter and area. They result in deviations of less than 5% in the volume of the hexagon and the same perimeter. Therefore, the assumption of using hexagons instead of circles is acceptable.


(a) Mesh made for physics laminar flow and heat transfer.

(b) Mesh made for physics heat transfer and nonisothermal flow.

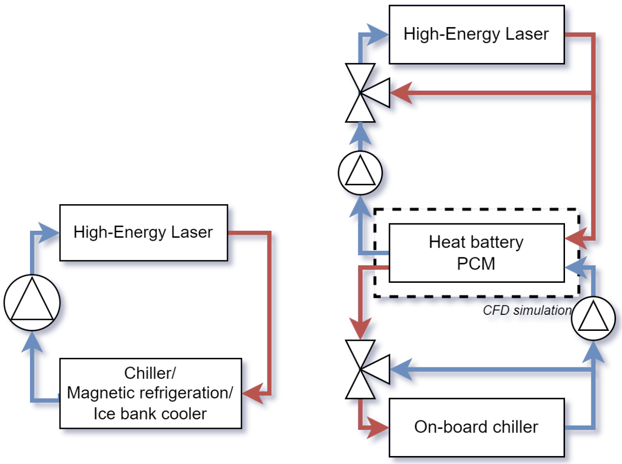
Figure 3.4: Mesh on the model for the tank with cylindrical PCM parts.

3.5 Power demand

The sections above explain how to find the volume and weight of the different cooling methods. In contrast, nothing has been said about the power demand of the cooling methods. A modeling tool will be used since several factors influence the power demand of pumps and chillers. This simulation will use as input: What is the cooling method used, what is the efficiency curve of the pump(s) and chiller, and what is the load on the system. Combining these information sources, the power demand of the single machines can be derived and thus also the total power demand of the cooling system.
From Figure 3.5, it can be interpreted that when the cooling method is the chiller, the magnetic refrigeration, or the ice water cooler, there is only one pump needed, additional to the cooling system itself. On the other hand, two pumps are needed for the cooling with a heat battery of phase change material; one for the cycle between the High-Energy Laser and the heat battery and one between the heat battery and the onboard chiller. Unlike direct cooling methods, the heat battery can use the onboard chiller, which is added to the vessel's load. Adding up the power demands in specific scenarios will show the total power demand per cooling method, which can then be compared.

3.6 Sustainable solutions

In Chapter 1, seven sub-questions are defined. The last four are all connected to having a sustainable solution. First, the lifetime of a cooling system is important, especially when the naval surface combatant is deployed for a



(a) Cooling cycle using a chiller, magnetic refrigeration, or ice water cooling.

(b) Cooling cycle using a heat battery with PCM.

Figure 3.5: Schematic overview of the cooling cycles with different cooling methods.

longer time. It should not be the case that halfway through the mission, the cooling system is not usable anymore. For longer deployments, it is also important to think about energy usage. Energy neutrality should be desired where possible, and using natural resources, such as seawater, can be part of this solution. Finally, from a different sustainable perspective, the possibility of repeating the same system on different vessels is also sustainable.

3.6.1 Lifetime system

The lifetime of the cooling system for the High-Energy Laser can depend on the cycles it has cooled the HEL, on the influences from the outside, or on other properties of the system. For the chiller and ice water cooling system, the lifetime can be derived from the meantime to break down and the mean time between failure. However, magnetic refrigeration is still new and will not have these numbers available. Therefore, the lifetime will be derived from the shortest lifetime of one of the parts inside the magnetic refrigeration system. Finally, the lifetime of the heat battery of phase change material will be derived from the degradation of phase change material. This information will be gathered from a literature study on the subject.

3.6.2 Energy neutrality

In order to achieve energy neutrality, or at least a more energy-efficient system, the waste heat of the HEL should be recovered and used for something else. With the heat battery, the advantage is that the heat is stored and, therefore, can be used over a more extended period instead of only when the HEL is activated. The maximum temperature of the heated cooling water is 26 °C. Literature research will show how to recover the energy for the different cooling systems. Also, it will give an overview of things that can be done with the recovered energy.

3.6.3 Seawater usage

A known method on naval vessels to have more efficient cooling is to use the seawater at moments it is cool enough. Using seawater means that a heat exchanger is used to transport the heat from the cooling water into the seawater, which will then be dumped back into the sea again. However, because of the different temperatures, the vessel has to be able to function in, cooling by seawater cannot be a standard cooling method. To see what is possible for cooling the HEL with seawater, literature research will be done on the possibilities and how much of the time the seawater is cool enough to use.

3.6.4 Universality

Finally, a preference is to have universality in the cooling system. With universality is meant that a standardized cooling system can be integrated into different kinds of vessels. In order to do this, an overview of the demands that must be met should be presented. Then, the standardized cooling system can be integrated when a vessel complies with these demands. The demands will be gathered and presented in the results section using the implications derived from this research.

4 Results

In Chapter 1, the research question, together with its seven sub-questions, is presented. In Chapter 2, the first question, "which cooling methods exist", and the third question, "the influence of the naval surface combatant", are answered. In Chapter 3, research methods for the other five sub-questions are explained. This Chapter continues the research methods by giving the results per question. First, the volume and weight of the four cooling methods will be presented, including the results of the COMSOL model for latent heat storage. Then, the power demand of the four cooling methods is explained. The weight, volume and power demand together answer the second question. Finally, the results of the sustainability questions are presented.

4.1 Weight and volume demand

First, the chiller is evaluated. As explained in Chapter 3, the implications will be gathered from the manufacturer's information on the already onboard chillers. To immediately cool the High-Energy Laser, the chiller should have a cooling capacity equal to– or bigger than—the waste heat produced. Also, the flow rate that comes from the HEL should be processed by the chiller too. Hence, the chiller with a flow rate of 58 m^3/h is chosen, whereas the flow rate from the HEL is 57 m^3/h. This chiller has a cooling capacity of 400 kW, weighs 3200 kg, and the volume is 3.30 x 1.20 x 1.66 m, corresponding to 6.6 m^3[1].

The ice water cooling system will be directly taken from the dairy sector. Hence, the implications of using this system are directly known. The needed capacity is calculated using the peak load of the waste heat multiplied by the amount of time it will be turned on. Consequently, the ice water cooling system from Packo of 82 kWh will be used for the implications[2]. The weight of a fully loaded system will be 3627 kg, and the system's volume is 5.32 m^3.

Next, the implications of magnetic refrigeration are shown. In contrast to the previous two cooling methods, there is no existing product yet. Therefore, as explained in Chapter 3, the implications must be approached by comparing several smaller prototypes and scaling these to the appropriate size. Appendix F presents data about the evaluated prototypes of several articles. However, since most of the evaluated prototypes must be increased by a factor of 100 or more, linear scaling is irrelevant. One prototype of a bigger size is known and has a cooling capacity of 48kW. In this article[3], all the design parts are mentioned, including their weights. In contrast, the system's size is only said to be the same as a vapor-compression system of the same capacity. Scaling only one system to the correct size brings uncertainty. However, scaling such small systems to the correct size does not give realistic results. Hence, the comparison will be made with the scaled version of the weight and volume of the article as mentioned earlier [3]. As the scaling shows in Appendix F, the weight will be 1060.5 kg, and the volume will be the same as the chiller, 6.6 m^3.

4.1.1 Latent heat storage

The results of the COMSOL simulation are gathered according to the test plans in Appendix G. The goal is to achieve a state of heat storage in which the waste heat of the High-Energy Laser can be taken up with some buffer while also having a low weight and volume demand of the heat storage. In the final test plan, where the flow rate for cooling is determined, the goal is to achieve the lowest flow rate possible to cool the heat storage within the given time. A low flow rate corresponds to a low power demand, which is the third implication that is optimized.

The same order of tests is carried out in all three situations, block-shaped PCM, cylinder-shaped PCM, and shell-in-tube. First, the material is determined based on the time it takes until the tank is saturated, or in other words, the water of a temperature of 293 K or higher flows out, as seen in Figure 4.1. Also, it considers how much time it takes to change the PCM in a saturated tank back to solid, for 90%, as presented in Figure 4.3. Then, the thickness of the blocks, cylinders, or tubes is determined, again based on the time it takes till the tank is saturated. The most significant difference is how fast solid PCM decreases, as shown in Figure 4.2. If there is not much difference, the tank's volume also plays a role. Next, the length, and therefore the height and width of the tank, are determined. Again on the time to saturate and total volume of the tank. Fourth, the amount of tanks is determined.

---

[1] Cooling Plant - Heinen & Hopman, URL: `https://www.heinenhopman.com/knowledge/cooling-plant/#overview`.

[2] IJsaccumulator PIB 25-160, tech. rep., URL: `www.packocooling.com`.

[3] Jay F Kunze: Magnetic Refrigeration Feasibility in Aircraft 7-24-1987, in: 2013, URL: `https://www.researchgate.net/publication/236586376`.

It is researched if it has advantages to have two tanks of, for example, 1 meter long, instead of one tank of 2 meters. One advantage is inevitable when two or more tanks are used; it is possible to cool one tank while the other is used to cool the HEL. The amount of tanks is chosen based on the time to saturate and the time to cool down the storage. Finally, the flow rate to cool down the tank is determined. The flow rate should be as low as possible to decrease the power demand while still being able to cool the tank up to the point where 90% of the phase change material is changed back to solid. This point should be reached before the 50 minutes, which are reserved for cooling, are over. The starting point of this optimization is determined by the amount of water needed to take up all the waste heat. Figure 4.3 shows how solid PCM increases while cooling the tank. It is visible that when most of the PCM is already changed, the rate of change to solid is slowing down. Also, appendix H shows that it does not matter if the PCM is 100% solid or 90% solid when the heating starts since the cycle result is both 90%. Therefore, in all cases, cooling down means reaching the point where 90% of the PCM is back to solid.

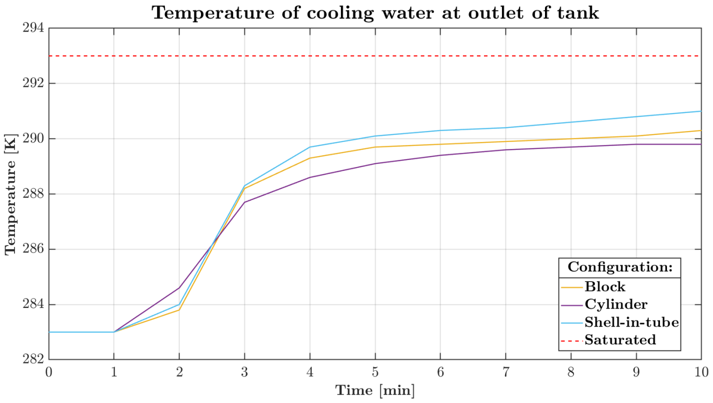


Figure 4.1: The temperature at the outlet of the tank during cooling of the High-Energy Laser.

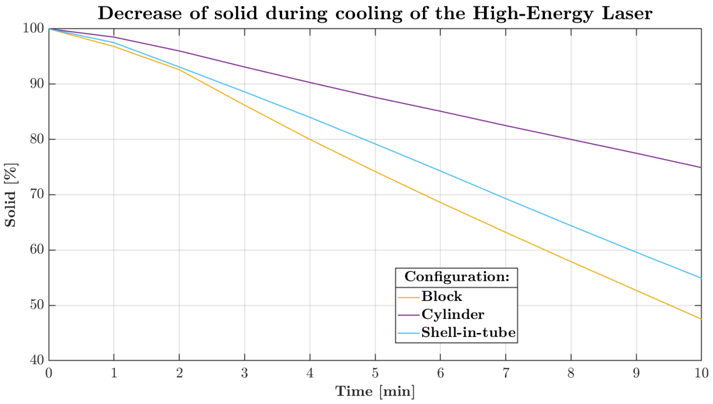


Figure 4.2: The decrease of solid during the cooling of the High-Energy Laser with the heat battery.

The starting point of the optimizations is related to the hand calculations, as presented in Appendix C. Several thicknesses and amounts of PCM shapes are then tried around the hand-calculated values. It shows that the material's conductivity is leading in all cases, as long as the PCM shapes contain enough volume of phase change material. A new flow rate is calculated for all situations in the test plans. First, the overall flow rate is calculated by what flow rate comes from the High-Energy Laser. The in- and outlet temperatures are known, and the amount of heat dissipated per second is known. With the heat capacity of water, 4184 J/kgK, a flow rate of 15.93 kg/s is needed. As presented in Figure 3.5b, the hot water flow is used to heat the water that is cooled too far down by the heat battery. The average temperature coming from the heat battery is 291 K. To make sure that a flow rate of 15.93 kg/s of 293 K goes into the HEL, a flow rate of 11.95 kg/s goes through the heat battery. However, the simulation exists only as a repeating unit from the whole tank. Therefore, the flow rate used in the model is based on how many inlets exist as the inlet used in the simulation.

Figure 4.1 and Figure 4.3 show no direct correlation between the amount of solid PCM and the outlet temperature. The main reason for this is that the conductivity of the phase change material is low. Therefore, the time for the phase change material to give the temperature through the whole material takes more time than the flow of the

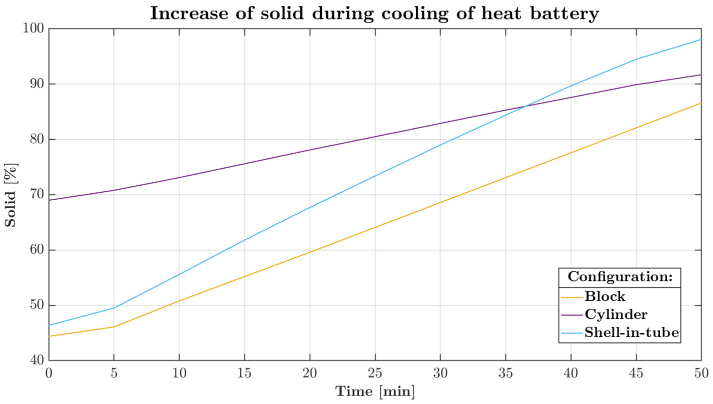
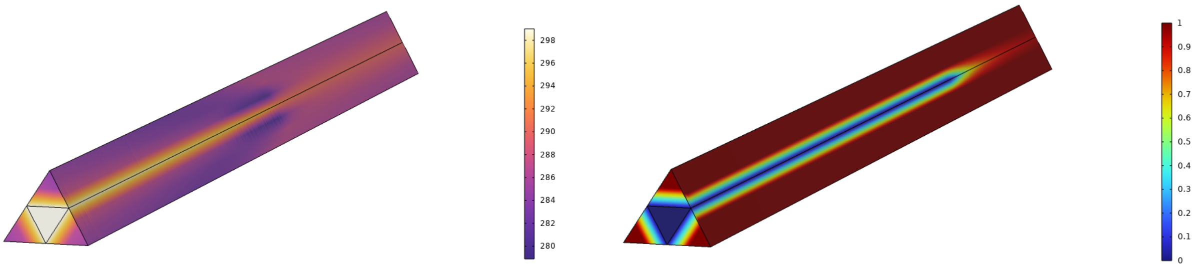


Figure 4.3: The increase of solid during the cooling of the heat battery.

water. When the material is thinner, the distance to the middle of the PCM is shorter; therefore, less time is needed to reach the inner part.

As mentioned before, the conductivity of the phase change material limits the water's cooling speed. In Figure 4.4a, it is visible that the phase change material directly touching the water is the same temperature as the water. However, the temperature is still low further to the middle of the phase change material—the same counts for Figure 4.4b where the phase indication is shown. The blue parts are fully liquid, and the red parts are fully solid; everything in between is in transition. The phase change material changes over a few degrees; therefore, a temperature gradient can be seen during phase transition. Another thing that can be seen in Figure 4.4a is that there is darker purple in the middle of the tank, indicating lower temperature. The overshoot of the phase change material probably causes this small temperature drop. The latent heat of the phase change material is so much bigger than the heat capacity of the material that with too large timesteps, it gathers too much heat. Because of the energy balance, the overshoot of heat at one point creates a undershoot of temperature at another, hence the dark purple spots.



(a) Temperature throughout the tank with cylindrical shapes.

(b) Phase indication of PCM shapes.

Figure 4.4: Figures of the temperature and phase indication at minute 5 of a simulation of a tank with cylindrical PCM shapes.

As a result of the test plans, the optimized tanks are gathered and shown in Table 4.1. The same phase change material with a melting point at 18 °C was the best option in all cases. The most probable reason for this is that the low conductivity has less effect if the temperature gradient is big. Therefore, the melting point should be as low as possible with cooling the HEL. However, when the heat battery should be cooled and the temperature gradient is small, changing the material back to solid is almost impossible. Therefore, a middle point had to be chosen: the melting point of 18 °C. The choice for the thickness of the phase change material was, in all cases, between having enough time till the battery is saturated and having a low volume. Then the length of the tank is determined by the time to saturate. For all shapes, the length has only minimal influence. Therefore, if a different length is more optimal for fitting into the ammunition storage onboard, it will not affect the cooling capacity drastically. Determining the number of used tanks is the final step in shaping the tank. In all cases, the cooling capacity decreases slightly with an increasing amount of tanks. The cooling capacity decreased too much for the shell-in-tube heat battery and, therefore, should be used in one tank. The other two heat batteries can be split into two tanks, which gives the advantage of cooling one tank while cooling the HEL with the other.

Combining the above results, the total volume of the tanks, the total volume of phase change material, and the

total weight of the tanks can be determined. Table 4.1 shows that the tank with the block-shaped phase change material has both the lowest volume of tanks and the lowest weight.
Finally, the flow rate while cooling the heat battery is determined. For the blocks and cylinders, the calculated flow rate, based on the conductivity of water, is the minimum flow rate needed to cool down the heat battery in the given time. However, a higher flow rate is needed for the shell-in-tube since the calculated flow rate only changes the phase change material back to 86 % solid.

Shape	Blocks	Cylinders	Shell-in-tube
Material	RT 18 HC	RT 18 HC	RT 18 HC
Length single tank	2 m	3 m	4 m
Amount of tanks	2	2	1
Total volume tank	2.99 m^3	3.62 m^3	3.65 m^3
Total volume PCM	1.50 m^3	3.00 m^3	1.53 m^3
Total weight	2806 kg	3267 kg	3513 kg
Flow rate cooling	2.39 kg/s	2.41 kg/s	3.18 kg/s

Table 4.1: Comparison of the different arrangements of PCM tanks. The numbers from this table are the simulation results shown in Appendix H.

Looking at Table 4.1, it is clear that the block tank has the smallest weight and volume. On the other hand, the shell-in-tube tank has the biggest weight and volume.

4.2 Power demand

Not only the weight and volume are essential in the comparing process, but also the power demand of the cooling method is important. However, in contrast to the weight and volume, the power demand is not one fixed parameter throughout time. Hence, an approach is made by adding up the different power demands while using a cooling method. Figure 4.5 shows power demand per minute for the different cooling methods. Below, the explanation of the origin of these numbers is given.
For all the cooling methods counts, the pump between the HEL and the cooling system must run during the first ten minutes of a cycle. This pump should create a flow rate of 15.93 kg/s. A suitable pump is a centrifugal pump combined with a frequency regulator, with efficiency curves shown in Appendix I, Figure I.1, which uses 1.336 kW.
For the heat battery configurations, another pump is needed between the heat battery and the chiller for minutes 11-50. The simulations of the heat batteries determine the flow rate of this cycle. For the blocks, a flow rate of 2.39 kg/s is preferred. Similarly, for the configuration of the cylinders, a flow rate of 2.41 kg/s is desired. The pump in Appendix I, Figure I.2 will be used for both. The power demand of this pump is 261 W. Finally, the pump for the shell-in-tube tank should create a flow rate of 3.18 kg/s. It uses 360 W and is displayed in Appendix I, Figure I.3.
However, the two pumps are not all that is needed for the heat battery cooling systems, as presented in Figure 3.5b. The onboard chiller is the final part of the cycle. However, the efficiency curve cannot be adjusted to the HEL since the chiller is already on the vessel when the HEL is implemented. Also, other equipment will need cooling when the HEL is used. Therefore, the power demand of the chiller will depend on the current efficiency curve, combined with the cooling load of the vessel. Appendix I elaborates on this, but to conclude, the chiller has a power demand of 18.6 kW.

	Method	Weight [kg]	Volume [m^3]	Power demand per cycle [MJ]
Direct cooling	Chiller	3200	6.6	79.5
	Ice water cooling	3627	5.3	96.8
	Magnetic refrigeration	1061	6.6	20.6
Latent heat	Blocks	2806	2.99	57.4
	Cylinders	3267	3.6	57.4
	Shell-in-tube	3513	3.7	57.7

Table 4.2: Overview of the weight, volume and power demand of the different cooling methods.

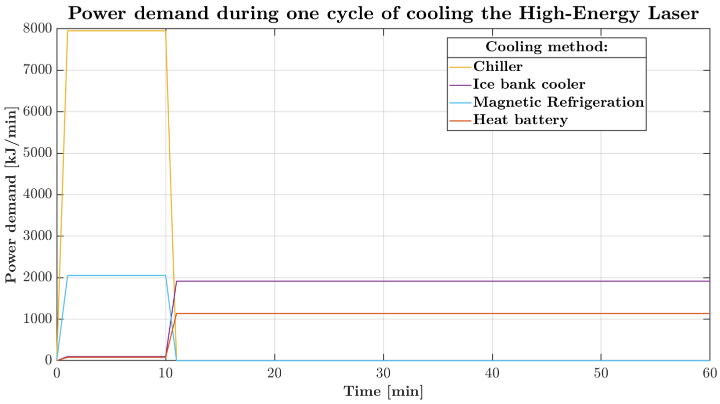


Figure 4.5: Overview of power demand per cooling method over time.

For the chiller, ice water cooling system, and magnetic refrigeration counts that the pump to get the cooling water to the cooling system is needed, and the power demand of the cooling system itself is needed. The chiller has a power demand of 131.2 kW, the cooling water system has a power demand of 31.9 kW, and magnetic refrigeration has a power demand of 32.9 kW.

Power demand also differs in how long a system has to work. The chiller has to be turned on, together with the pump, for 10 minutes and is then turned off. The ice water cooling system has the HEL pump and a small pump inside the ice water system for the first 10 minutes. In the following 50 minutes, the ice bank has to be built up again and should therefore be turned on. Magnetic refrigeration is only turned on with the HEL pump when the HEL is on during the first 10 minutes. Afterwards, it can be turned off again. Only the HEL pump is needed for the first ten minutes for the heat battery configurations. In the fifty minutes following, the pump between the chiller and the heat battery is needed, and some load of the existing chiller too. If everything is put together, the total power demand for a complete cycle of cooling the High-Energy Laser demands is given in Table 4.2. It shows that magnetic refrigeration is the most efficient, followed by the heat batteries.

4.3 Sustainable solutions

In Chapter 3, the research methods for the sustainability subjects are elaborated. Below, the results of the sustainability questions are presented.

4.3.1 Lifetime system

The chiller and ice water cooling systems are used in practice and will not fail within critical time. This means that both cooling systems will last at least a year while being used at all times. Since this frequency of usage is much higher than realistic for the implementation of the High-Energy Laser, the lifetime of these systems will not negatively influence the choice of these systems. However, the magnetic refrigeration cooling system is unknown and not been used yet. Therefore, it is not possible to give a lifetime of the whole system. The known systems within the magnetic refrigeration system will not break down within a critical time. However, it is unknown if the magnets, for example, will degrade over time. Finally, the lifetime of the phase change material could be critical. Some materials do degrade and would therefore have a lower latent heat over time or even a different melt point. However, the material used in this research has little to no differences in melting temperature and latent heat after 1000 to 10000 cycles[4]. If, for a year-long, the HEL would be used every hour, which is very unlikely, there would be about 8500 cycles. Therefore, the lifetime of the phase change material is also long enough to endure a full year of missions at least.

---

[4] V. V. Tyagi et al.: A comprehensive review on phase change materials for heat storage applications: Development, characterization, thermal and chemical stability, in: Solar Energy Materials and Solar Cells 234 (Jan. 2022).

4.3.2 Energy neutrality

As mentioned in Chapter 3, using the waste heat of the HEL is a good way to achieve, or at least come close to, energy neutrality. Using the waste heat has two scenarios. The first one is that when cooling the HEL with the chiller, ice bank cooler, or magnetic refrigeration, there is a short time, 10 minutes, in which water of 26 °C is available. The second scenario is that while cooling the heat battery, water is available at about 18 °C for a more extended period, 50 minutes. Using the waste heat for only 10 minutes is less convenient than having a more stable energy source. However, it is possible in both cases that the waste heat is used for, for example, air conditioning[5]. However, it should be researched to see if integrating such a system is energy and cost-efficient, especially for the first scenario. Also, it should be remembered that the HEL will not operate constantly, maybe not every day, and therefore the amount of waste heat is not guaranteed. However, it will be more efficient if this system will not only run on the waste heat of the HEL but also on, for example, the generators and other waste heat producers onboard.

4.3.3 Seawater usage

A different way to have a more efficient cooling system is to use seawater when the temperature is below 26 °C. If the seawater is used through a heat exchanger in the loop of the standard cooling system, as shown in Figure 4.6, every moment of seawater colder than 26 °C can be used. This is done by cooling down the cooling water at least a little before it goes into the cooling system. This way of using seawater is already integrated into the standard cooling structure. Therefore, with the heat battery connected to the standard cooling structure, the extra heat exchanger is not needed anymore.

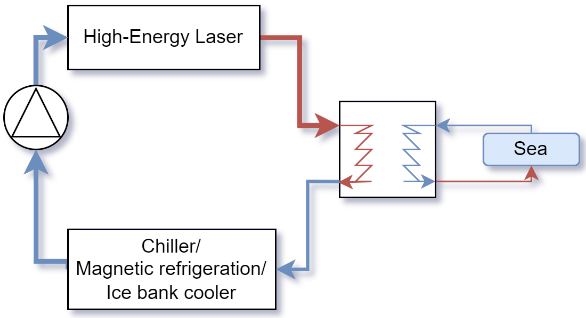


Figure 4.6: A concept of implementation of the use of seawater.

4.3.4 Universality

Some requirements should be met to use a universal cooling system for High-Energy Lasers on different vessels. First, the vessel should have the capacity below the deck to store the cooling system. The volume and weight should be added to the vessel according to the chosen cooling system. Also, the vessel should have enough energy for the High-Energy Laser itself and the cooling system connected to it.

Another requirement is essential if the heat battery of phase change material is chosen as the universal cooling system. The cooling structure of the vessel should have enough capacity to cool the heat battery in the given time. If this is not possible, there is also the option to have a small extra chiller onboard. However, this will be less efficient considering weight, volume and power demand.

---

[5] Mohamed Hamdy et al.: An overview on adsorption cooling systems powered by waste heat from internal combustion engine, in: Renewable and Sustainable Energy Reviews 51 (July 2015), pp. 1223–1234.

5 Discussion

The results shown in Chapter 4 are based on several assumptions. First, there are some assumptions related directly to the High-Energy Laser. Next, some assumptions regarding the simulations are presented. Finally, the assumptions looking at producibility and testing are given.
In Chapter 1, the efficiency of the High-Energy Laser is presented, indicating that 67% of the total input energy of the complete system is converted into waste heat. While this efficiency is based on a trustworthy source, it could be that the efficiency is different with future designs of HEL or that with the size of this HEL, a different efficiency is realistic. Also, the assumption is made that the cooling water takes the whole amount of waste heat, whereas it is also possible that the air around the HEL will also carry away parts of the heat. Nevertheless, the cooling methods will scale linearly relative to each other, and therefore, with changing efficiency or having less waste heat to cool, the research is still applicable. Finally, a demand of how long the HEL should be used and cooled is made. However, in practice, these times can differ. Therefore, more scenarios of turning the HEL off and on at different times should be simulated in the future.

Regarding the simulation, several simplifications are already mentioned in Chapter 3. These simplifications use a repeating unit and 2D simulation of the blocks tank. Additionally, the inlet is disregarded, and hexagons are used instead of circular shapes for a tube design. The influence of these simplifications is assessed and discussed. Nevertheless, the exact influences should be researched by comparing the simulations to real-life tests. Besides, the simulation does not make use of turbulence. Using the Reynolds number, there should not be turbulence in the system. However, turbulence does influence heat transfer and could therefore be interesting to implement by adjusting the PCM shapes a bit, for example. Next, in the simulations, the outside walls of the tank are disregarded. The repeating unit is seen as how it is throughout the whole tank. Therefore, no heat exchange takes place to the outside of the tank. However, if the amount of repeating units on the edge of the tank is compared to the ones inside the tank, and it is such a small number, it will not affect the result much. The same counts for disregarding the shell of the phase change material shapes. The shell is made of a thin layer of plastic to ensure the PCM stays in shape. However, the simulation disregards these shells to reduce the computational load. Finally, the starting point of the simulation differs from reality. The simulation starts with a prolonged increase in temperature at the inlet. However, since the first minute is not counted in the saturation time, this start does not badly influence the result.

Next, the simulation should be validated completely. An important phenomenon that should be checked is the temperature drop at certain spots. It could be possible that the material creates these temperature drops because it takes up too much heat. Another reason can be that the time step and mesh of the simulation give an uncertainty in the system. To test if this is the case, a simulation with a very small time step and mesh should be done to see if it gives the same result. To test the real heat battery and compare it with the simulation, a smaller version of the heat battery can be used to decrease the costs, but the properties of the phase change material and their shapes should be tested. Still, the results that are given by the simulation can be trusted since this kind of PCM blocks and cylinders are already used by other companies[1] and show the same properties as the simulation does. The difference is the time in which the heat should be taken from the water. Another difference between the simulation and real life is that the pipes between the High-Energy Laser and heat battery, and between the heat battery and the chiller, will probably influence the cooling water temperature. Since these influences are small, they can be disregarded compared to the total waste heat. Finally, using phase change material should be tested in real life. On the one hand, the producibility of the PCM blocks and cylinders, in size taken from the simulations, should be researched. On the other hand, the effects of the expansion of the phase change material should be tested. In the case of the shell-in-tube concept, the tubes have to be vertical to be sure that the expansion will not deform the tubes. In the case of the blocks and cylinders, the tank should have space for the shapes to expand. Also, the pressure should be held constant by using an expansion tank. Other effects of the expansion are unknown and should therefore be researched by testing with the PCM.

In the above text, some recommendations for future research are already made. Such as simulating different scenarios of how long the HEL is turned on, implementing turbulence in the model, validating the model, and finding the effects of the expansion of phase change material. Likewise, the tank can be optimized even further if a material with better properties is found or made. Therefore, research on the ideal phase change material can bring extra advantages. Also, the cooling system's efficiency could be increased if a different system is included, which uses

---

[1] Plus-ICE TM Phase Change Material (PCM) Theraml energy storage (TES) design guide, tech. rep., URL: `www.pcmproducts.net`.

the waste heat as explained in the energy neutrality section in Chapter 4. However, the exact advantages should be further investigated.

Although the heat battery of phase change material seems promising, other cooling methods could be looked into further, too. Magnetic refrigeration comes out very well in the comparison but has to be left out in the final recommendation because of the market readiness. If more thorough research can be done on magnetic refrigeration's capabilities and market readiness, it could become clear that it is the better option. Also, a heat battery of thermal chemical energy storage seemed suitable in Chapter 2. However, because no reaction could be found at the right temperature, this option is neglected throughout the rest of the research. The capabilities of chemical heat storage are expanding quickly since it is a good way of storing and even transporting energy without losses. Future research on the possibilities of doing this with lower temperatures could make chemical heat storage also an option for the cooling of the High-Energy Laser.

6 Conclusion

To conclude the research, the sub-questions and the main research question will be answered here. In Chapter 1, the research structure is visualized with a figure which indicates that the first three sub-questions represent the requirements of the product, the other sub-questions represent the preferences of the product, and all the questions have to fulfill the constraints. Together, the conclusion of the requirements, and the separate conclusions of the preferences, will give the final recommendation on the research question: “What are the implications of cooling a High-Energy Laser weapon system on a naval surface combatant?”

The first sub-question answered in this research is about which cooling methods are suited to cool the High-Energy Laser. The conclusion was that seven cooling methods may be feasible within the context of this project. All are considered and compared to the RPCs mentioned in Section 1.2.1. From there, only four passed: the chiller, the ice water cooling system, magnetic refrigeration, and a heat battery made from phase change material.
Next, the question is answered about which of these four cooling methods would have the lowest implications on the naval surface combatant. Chapter 4 gives all the results of the research on implications. Looking at the weight implication, the most optimal cooling method would be magnetic refrigeration. However, since this weight is very uncertain, the second place is also important: the heat battery of phase change material, specifically the blocks configuration. The heat battery is, in all configurations, the best choice regarding the volume demand, followed by the ice-water cooling system. The blocks configuration has the smallest volume demand of the three heat battery configurations, followed by the cylinders tank. Finally, the power demand of the different cooling methods is investigated. The best option is again magnetic refrigeration. The second best option is the heat battery, where the blocks and cylinders tank have the same power demand, and the shell-in-tube demands more.
The third sub-question was about the additional requirements and constraints of building this cooling system on a naval surface combatant. Section 2.2 mentions the requirements of integrating a system on a naval surface combatant. All cooling methods comply with these requirements, for example, being able to work between specific temperature gradients or having redundancy in the system. However, to endure shocks, all systems must be built on specific springs.

After the first three requirement sub-questions, the four preferences sub-questions are researched. First, the lifetime of the system is investigated. It is unknown what the lifetime will be for magnetic refrigeration, so no conclusion can be made on that. However, the other three cooling methods will all be able to run for a year at least. Therefore, no negative consequences are linked to the lifetime of the cooling systems besides not knowing of magnetic refrigeration.
The second sustainable solution is looking at energy neutrality. The advantage of a heat battery, in combination with an energy neutrality system besides it, is that there will be a constant flow of heated water, whereas, with the other cooling systems, this flow only lasts for ten minutes. Besides that, there are no differences between the systems and therefore does not influence the choice of the cooling system regarding energy neutrality.
The third preference sub-question is about using seawater for cooling. It is possible with all the cooling systems; however, if the heat battery is used, seawater usage is already integrated into the existing cooling structure. Therefore, no extra system, and therefore the volume, has to be integrated.
Finally, the requirements around universality are investigated. The most important requirement is that the vessel should have the weight and volume available needed to include the cooling system. For the heat battery, the existing cooling structure should have enough capacity to include the cooling of the heat battery itself.

In conclusion, the heat battery, with configuration block-shaped phase change material, is the most optimal to use when cooling the High-Energy Laser on a naval surface combatant. The weight, volume and power demand are the lowest of the now-ready systems. Also, using seawater to cool whenever possible is already integrated, and the system’s lifetime is proven to be long enough. Placing the heat battery on a naval surface combatant is possible as long as the springs for shock resistance are used, and making this system universal is also possible. Universality is even more possible because the shape of the heat battery can be adapted to a certain point. To answer the research question, the implications of cooling a High-Energy Laser on a naval surface vessel are an added weight of 2806 kg, a volume demand of 3 m^3, and a power demand of 57.4 MJ per cooling cycle. The lifetime will be at least a full year of using the system constantly; energy neutrality can be incorporated with a different system which needs more research, seawater will be used whenever the temperature is low enough, and the system can be made universal for different vessels.

Bibliography

AECTP-200 - 3 Environmental Conditions. URL: http://everyspec.com/NATO/NATO-AECTP/AECTP-200-3_3976/.

Alva, Guruprasad, Yaxue Lin, and Guiyin Fang: An overview of thermal energy storage systems, in: Energy 144 (Feb. 2018), pp. 341–378.

Andrews, David: Recent developments in the Safety Regime for Naval Ship design, in: Quality and Reliability Engineering International, vol. 22, Feb. 2006, pp. 21–30.

Aydin, Devrim, Sean P. Casey, and Saffa Riffat: The latest advancements on thermochemical heat storage systems, in: Renewable and Sustainable Energy Reviews 41 (2015), pp. 356–367.

Blinov, Andrei, Dmitri Vinnikov, and Tõnu Lehtla: Cooling Methods for High-Power Electronic Systems, in: Scientific Journal of Riga Technical University. Power and Electrical Engineering 29.1 (Oct. 2011), pp. 79–86.

CO2 as a Refrigerant — Properties of R744 - Climate Conversations, URL: https://emersonclimateconversations.com/2015/05/14/co2-as-a-refrigerant-properties-of-r744/.

Cook, Joung R. and John R. Albertine: The Navy's high-energy laser weapon system, in: Patrick G. O'Shea and Harold E. Bennett (eds.), May 1997, p. 264.

Cooling Plant - Heinen & Hopman, URL: https://www.heinenhopman.com/knowledge/cooling-plant/#overview.

Dawe, T and MEng CEng MIMechE: The potential of Thermal Storage Tanks to assist in managing Peak Heat Loads on Naval Ships, in: URL: https://doi.org/10.24868/issn.2515-818X.2020.037.

Dermitzakis, Konstantinos, Juan Pablo Carbajal, and James H. Marden: Scaling laws in robotics, in: Procedia Computer Science 7 (2011), pp. 250–252.

Dilshad, Saad et al.: Review of carbon dioxide (CO 2) based heating and cooling technologies: Past, present, and future outlook, in: Int J Energy Res 44 (2020), pp. 1408–1463.

Dincer, Ibrahim, Sadik Dost, and Xianguo Li: Perforemance analyses of sensible heat storage systems for thermal applications, tech. rep., 1997, pp. 1157–1171.

Egolf, P. W. and R.E. Rosensweig: Bulletin 2007-5 Magnetic Refrigeration at Room Temperature, tech. rep., 2007.

Hafften, Michael and Robert Stratton: High-Energy Laser Weapon Integration with Ground Vehicles, in.

Hamdy, Mohamed et al.: An overview on adsorption cooling systems powered by waste heat from internal combustion engine, in: Renewable and Sustainable Energy Reviews 51 (July 2015), pp. 1223–1234.

Heat Transfer: Conservation of Energy, URL: https://www.comsol.com/multiphysics/heat-transfer-conservation-of-energy?parent=fluid-flow-heat-transfer-and-mass-transport-0402-442.

Hopman, Heinen: Ventilation Air Conditioning Refrigeration Heating provided by 22 ° C, tech. rep.

How a Chilled Water System Works | HVAC Training Shop, URL: https://hvactrainingshop.com/how-a-chilled-water-system-works/.

IJsaccumulator PIB 25-160, tech. rep., URL: www.packocooling.com.

J., Roy: Multiphase Spray Cooling Technology in Industry, in: Advanced Technologies, Oct. 2009.

Jacobs, S. et al.: The performance of a large-scale rotary magnetic refrigerator, in: International Journal of Refrigeration 37.1 (Jan. 2014), pp. 84–91.

Kitanovski, Andrej and Peter W. Egolf: Application of magnetic refrigeration and its assessment, in: Journal of Magnetism and Magnetic Materials 321.7 (Apr. 2009), pp. 777–781.

Kitanovski, Andrej et al.: Present and future caloric refrigeration and heat-pump technologies, in: International Journal of Refrigeration 57 (Oct. 2015), pp. 288–298.

Koleser, Jeffrey A and Jeffrey Kline: Determining surface combatant characteristic requirements through a mission effectiveness analysis framework, in: 2007.

Kunze, Jay F: Magnetic Refrigeration Feasibility in Aircraft 7-24-1987, in: 2013, URL: https://www.researchgate.net/publication/236586376.

Mahmoudi, Amirhoushang et al.: A thorough investigation of thermochemical heat storage system from particle to bed scale, in: Chemical Engineering Science 246 (Dec. 2021).

Mohapatra, S S, S Chakraborty, and S K Pal: Experimental Studies on Different Cooling Processes to Achieve Ultra-Fast Cooling Rate for Hot Steel Plate, in: Experimental Heat Transfer 25.2 (2012), pp. 111–126, URL: https://www.tandfonline.com/action/journalInformation?journalCode=ueht20.

Mohapatra, Soumya S. et al.: Ultra fast cooling of a hot steel plate by using high mass flux air atomized spray, in: Steel Research International 84.3 (Mar. 2013), pp. 229–236.

Name, Chemical: Positively Innovative R513B Product information RefRIgeRantS, in.

Nayak, Santosh Kumar, Purna Chandra Mishra, and Sujay Kumar Singh Parashar: Influence of spray characteristics on heat flux in dual phase spray impingement cooling of hot surface, in: Alexandria Engineering Journal 55.3 (Sept. 2016), pp. 1995–2004.

Plus-ICE TM Phase Change Material (PCM) Theraml energy storage (TES) design guide, tech. rep., URL: `www.pcmproducts.net`.

R1234yf Refrigerant | ARC Industry Site, URL: `https://www.arctick.org/information/autogas/r1234yf-refrigerant/`.

Scheers, ir. L.C.W., ir. P.J. van den Berg, and dr. A.S. Stodolna: Beam combining techiniques for high energy lasers, tech. rep., Den haag: TNO, 2020.

Shrestha, G, H Polinder, and J A Ferreira: Scaling laws for direct drive generators in wind turbines; Scaling laws for direct drive generators in wind turbines, in: 2009.

Shu, Shili et al.: Heat dissipation in high-power semiconductor lasers with heat pipe cooling system, in: Journal of Mechanical Science and Technology 31.6 (June 2017), pp. 2607–2612.

Sonar, Deepesh: Renewable energy based trigeneration systems—technologies, challenges and opportunities, in: Renewable-Energy-Driven Future 2021, pp. 125–168.

Thompson, J, D Vaitekunas, and B Brooking: Signature management- The persuit of stealth lowering warship signatures: Electromagnetic and infrared, tech. rep., 2000, URL: `www.davis-eng.on.ca`.

Tyagi, V. V. et al.: A comprehensive review on phase change materials for heat storage applications: Development, characterization, thermal and chemical stability, in: Solar Energy Materials and Solar Cells 234 (Jan. 2022).

Wu, S.: Heat energy storage and cooling in buildings, in: Materials for Energy Efficiency and Thermal Comfort in Buildings 2010, pp. 101–126.

Xu, H. et al.: Towards higher energy efficiency in future waste-to-energy plants with novel latent heat storage-based thermal buffer system, in: Renewable and Sustainable Energy Reviews 112 (Sept. 2019), pp. 324–337.

Yan, T., R. Z. Wang, and T. X. Li: Experimental investigation on thermochemical heat storage using manganese chloride/ammonia, in: Energy 143 (Jan. 2018), pp. 562–574.

Yan, T. et al.: A review of promising candidate reactions for chemical heat storage, in: Renewable and Sustainable Energy Reviews 43 (2015), pp. 13–31.

Yilgor, Ilyas and Shanbin Shi: Scaling laws for two-phase flow and heat transfer in high-temperature heat pipes, in: International Journal of Heat and Mass Transfer 189 (June 2022).

Yu, B. F. et al.: Review on research of room temperature magnetic refrigeration, in: International Journal of Refrigeration 26.6 (Sept. 2003), pp. 622–636.

Yu, Bingfeng et al.: A review of magnetic refrigerator and heat pump prototypes built before the year 2010, 2010.

Appendices

A Refrigerant

Varying the refrigerant from the current standard is an option to increase sustainability. 134B (a synthetic refrigerant, or syn-ref) is the current refrigerant. A more environment-friendly version could be 513B or 515B (both a syn-ref). Other alternatives are CO_2 (an example of a natural refrigerant: nat-ref), or 1234YF (syn-ref), which has a CO_2 equivalent of 1. Table A.1 gives more details about these specific refrigerants. The table presents that as a result of CO_2 as refrigerant, the system needs to be adapted to work at such high pressures. On the contrary, 1234YF does not need many adaptions. However, there is a higher risk with a more flammable product. Therefore, refrigerant 515B is the best option since it is non-flammable, has a usual pressure point, and has a relatively low global warming potential.

Properties	134B	513B	515B	1234YF	CO_2
Global warming potential [-]	1430	540	299	<1	<1
Flammability and toxicity rating [-]	A1 Non flammable	A1 Non flammable	A1 Non flammable	A2L Mildly flammable	A1 Non flammable
Critical temperature [°C]	102	96	109	95	31
Saturation pressure at 20 °C [kPa gauge]	567	530	497	580	5620

Table A.1: Properties of considered refrigerants to implement in the chiller systems [1].

---

[1] R1234yf Refrigerant | ARC Industry Site, URL: `https://www.arctick.org/information/autogas/r1234yf-refrigerant/`; CO2 as a Refrigerant — Properties of R744 - Climate Conversations, URL: `https://emersonclimateconversations.com/2015/05/14/co2-as-a-refrigerant-properties-of-r744/`; Chemical Name: Positively Innovative R513B Product information RefRIgeRantS, in.

B PCM and TCES material overview

height	Method	Latent heat [kJ/kg]	Melting point [°C]	Thermal conductivity[W/mK]	Change in density [-]	Chemical stability[-]	non-toxic[-]	Flammability[-]	non-explosive[-]	Density [kg/m^3]
General numbers	Paraffin wax	200 - 280	-20 - 100	Low	-	Stable	-	No	-	Medium
	Non-Paraffin organics	90 - 250	5 - 120	Low	-	Unstable at high temperature	-	High	-	Medium
	Hydrated salts	60 - 300	80 - 100	High	-	Unstable over repeated cycles	-	-	-	Light
Paraffin wax	n-heptadecane	213	22	0.145	760-779	Yes	-	-	-	779
	n-Octadecane	236	28	0.358	774-814	Yes	-	-	-	814
	Paraffin C16-C18	152	20-22	0.15	-	Yes	-	-	-	880
	Paraffin C23-C24	189	22-24	0.21	760-900	Yes	-	-	-	900
	RT 11 HC	200	11	0.2	770-880	Yes	Long term	No	Yes	880
	RT 12	165	12	0.2	770-880	Yes	Long term	No	Yes	880
	RT 15	155	15	0.2	770-880	Yes	Long term	No	Yes	880
	RT 18 HC	260	18	0.2	770-880	Yes	Long term	No	Yes	880
	RT 21 HC	190	21	0.2	770-880	Yes	Long term	No	Yes	880
	RT 25 HC	230	22-26	0.2	770-880	Yes	Long term	No	Yes	880
	RT 28 HC	250	27-29	0.2	770-880	Yes	Long term	No	Yes	880

Table B.1: Overview of several Phase Change materials compared on the constraints.

Method	Density [kg/m^3]	Molar energy [kJ/mol]	Reaction temperature [°C]	Heat capacity [kJ/kg]	Change in volume [m^3]	Need of katalysator[-]	Chemical stability[-]	Degradation[-]	non-toxic[-]	non-flammable[-]	non-explosive[-]
$CaCl_2 \cdot 4\,NH_3 + NH_3 \leftrightarrow CaCL_2 \cdot 8NH_3$	11030	43.8	140	177	Big	Ti	Yes	No	Yes	Yes	NH_3 when exposed to high temperatures
$2BaO + O_2 \leftrightarrow 2BaO_2$	7555	163.1	434	965	Small	-	-	Yes	No	Yes	Yes
$NaBr + 5NH_3 \leftrightarrow NaBr \cdot 5NH_3$	8389	30.5	140	162	Big	-	-	-	Yes	Yes	NH_3 when exposed to high temperatures
$MnCl \cdot 2NH_3 + 2NH_3 \leftrightarrow MnCl \cdot 4NH_3$	7072	47.3	140	298	Medium	Graphite	-	-	Yes	Yes	NH_3 when exposed to high temperatures
$K_2CO_3 + (1 \cdot 5)H_2O_{(s)} + \Delta\, H \leftrightarrow K_2CO_{3(s)} + (1 \cdot 5)H_2O_{(g)}$	2148	-	45	826	-	No	Yes	No	Yes	Yes	Yes

Table B.2: Overview of several reaction that can be used for TCES compared on the constraints.

C Shape calculation PCM

Here, the calculation on the sizes and amounts of the phase change material shapes that are needed are shown. First, to calculate the volume of PCM needed, if only the latent heat range is used, the following equation is used:

$$V = \frac{Q_{HEL}}{L_{1\to 2}\rho_{pcm}}, \tag{C.1}$$

where Q_{HEL} is the heat dissipated by the High-Energy Laser [J], $L_{1\to 2}$ is the latent heat of the PCM [J/kg], and ρ_{pcm} is the density of the PCM [kg/m^3]. This results in a needed volume of

$$V = 1.166m^3, \tag{C.2}$$

where only the heat capacity of the material is considered. Unlike the high latent heat of the material, the conductivity is quite low. Consequently, the heat transfer surface should be calculated too. The following equation can do this:

$$A_{heattransfer} = \frac{Q_{HEL}\Delta x}{k\Delta T}. \tag{C.3}$$

Here, Q_{HEL} is the heat dissipated by the HEL [W], Δx is the thickness of the material considered [m], k is the conductivity [W/mK], and ΔT is the temperature difference between the fluid and the PCM [K]. The shapes' minimal heat transfer surface and the outside surface are needed for further calculation. The outside surface of the pipes (per meter), building blocks (only top and bottom), cylinders, and balls can be found, respectively, as follows:

$$A_{pipe} = \pi D, A_{block} = 2hw, A_{cylinder} = \pi DL, A_{ball} = 4\pi r^2. \tag{C.4}$$

In these equations, D is the diameter [m], h is the height [m], w the width [m] and r the radius [m]. Dividing $A_{heattransfer}$ by the surface of one of the shapes results in the number of shapes needed to comply with the heat transfer surface. Only the stacking of the shapes influences how much space will be between the shapes for the fluid, in the case of the three PCM containing shapes, building blocks, cylinders, and balls. The building blocks will have an in-between space of 8 mm. With this information, the total volume used with building blocks can be calculated as follows:

$$V_{total} = \text{amount of blocks} \cdot hwd_{block}d_{fluid}. \tag{C.5}$$

Since blocks can be stacked easily, this calculation is straightforward. However, for cylinders and balls, it is different. For the cylinders, the packing density can be used. The packing density of hexagonal packing is 0.91. Therefore, the total volume needed for cylinders can be calculated by

$$V_{total} = \frac{\text{amount of cylinders} \cdot \pi r^2 L}{0.91}. \tag{C.6}$$

The same way can be used for balls, except that it has a packing density of 0.74. Therefore, the volume can be calculated as follows:

$$V_{total} = \frac{\text{amount of balls} \cdot \frac{4}{3}\pi r^3}{0.74}. \tag{C.7}$$

Finally, the shell-in-tube's total volume can be calculated the same way as the cylinders, except that the Δx has to be added to the radius of the pipe in order to stack with enough PCM between the pipes. This results in the following equation:

$$V_{total} = \frac{\text{meters of pipe} \cdot \pi(r + \Delta x)^2}{0.91} \tag{C.8}$$

To calculate the volume of PCM inside the tanks, the following is used:

$$V_{PCM} = \text{amount of shape} \cdot V_{shape}, \tag{C.9}$$

where V_{shape} is calculated with $r = r - 1$ and $d_{block} = d_{block} - 1$ since the blocks will be surrounded by a layer of 1 mm thick plastic. With this volume, the weight can be calculated too by multiplying the volume by the density. On the contrary, for the shell-in-tube concept, the weight of the pipes is calculated too, which adds up to 42 kg of copper.

With iteration of these equations, the best option for Δx and D, d is chosen per shape. This results in the numbers in Table 3.1.

D Inlet

A full tank with phase change material is a huge simulation. Consequently, some simplifications are introduced to decrease the size of the simulation. However, these simplifications should not affect the result of the simulation. Therefore, the inlet's influence on the fluid's velocity between the blocks is simulated here. If there is an influence, it would be noticeable in the velocity difference between the middle of the tank and the top or bottom since those "pipes" are the furthest away from the inlet.
Theoretically, the velocity should not vary between the tubes. Bernoulli's principle is a theoretical way of finding pressure and velocity values throughout a system where the energy per unit of liquid mass is uniform throughout the reservoir. Therefore, the equation and constant can be used to evaluate the tanks. Bernoulli's equation is:

$$\frac{1}{2}\rho u^2 + \rho g z + p = \text{constant}. \tag{D.1}$$

The z is the point's elevation above a reference plane. However, when calculating the constant in the pipes, there is no elevation, which makes the second term equal to zero. When calculating the constant in the beginning part of the tank, there is an elevation before it enters the pipes. Therefore, the velocity will decrease towards the bottom of the tank. However, this does not influence the velocity inside the pipes.

Similarly, the simulation shows that the velocity will be constant over all the pipes. The only velocity difference will be in the inlet part, which does not matter for the accuracy of the rest of the simulations.

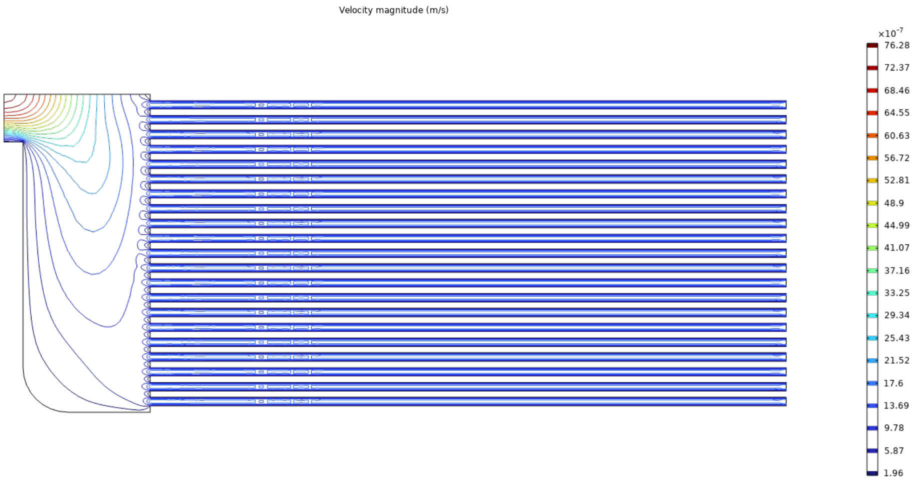


Figure D.1: Simulation of the velocity from the inlet into the pipes.

E Mesh

Another simplification of the model is related to the mesh. COMSOL has trouble meshing round shapes since the meshing shapes are all triangular or squared. Therefore, the shape of the hexagon will be more straightforward for the model to compile. However, first, the comparison between a circle and a hexagon should be made. Looking at the perimeter of a circle, the following formula is used:

$$P = 2\pi r. \tag{E.1}$$

In this formula, r is the radius of the circle. The perimeter of a hexagon is calculated by

$$P = 6r. \tag{E.2}$$

Likewise, the area of the circle and hexagon should be the same too. The area of the circle is calculated by

$$A = \pi r^2, \tag{E.3}$$

and the area of the hexagon is calculated by

$$A = \frac{3\sqrt{3}r^2}{2}. \tag{E.4}$$

Table E.1 presents the differences in radius needed for the same perimeter and area. It also indicates that having the same perimeter and area at the same time is impossible. Due to the low conductivity, the perimeter is the most important to have the same, whereas the volume of the phase change material will not be used completely.

		Radius hexagon	
		Same P	Same A
Radius	15 mm	15.7 mm	16.5 mm
circle	20 mm	20.9 mm	22 mm

Table E.1: Comparison of the radius differences between the circle and hexagon to have the same perimeter and area of the shape.

F Magnetic refrigeration prototypes

Design	Cooling capacity	Dimension	Weight	Design type
Halbach type [1]	2.3 T	0.16 x 0.20 x 0.19m	83kg	Reciprocation
Xi'an Jiaotong University [1]	18.7 W	0.14 x 0.08 x 0.04m		AMR
Tokyo institute of Technology [1]	560 W	0.41 x 0.40 x 0.39m		Rotary
Chelyabinsk state university [1]	40 W	0.15 x 0.20 x 0.20m		Rotary
University of Genoa [1]	1.55 T	0.10 x 0.50 x 0.13m	30 kg	Reciprocating
Jacobs et al. [2]	2kW	1.02 x 0.81 x 0.91m		Rotary
Rife et al. [3]	48kW	Size of vapor-compression system	165 kg	Rotary

Table F.1: Existing prototypes with the known information. The cooling capacity is presented in Watt and in cases the cooling capacity is not known in Watt, the magnetic force is shown, in Tesla [T].

Looking at Table F.1, the last row presents a design that can be scaled with less than 10 to reach the desired cooling capacity. Also, volume is scalable with the size of a chiller, and the weight is known per compartment. Therefore, this design is the most realistic to scale; however, since it is only one concept that will be scaled, the weight and volume resulting from this are uncertain. To estimate the weight increase with scaling to the desired cooling capacity, every part will be checked to determine if linear scaling is possible or if some other scaling law should be used. The overview of the weight estimate can be seen in Table F.2. The cooling capacity has to be increased by a factor of 8.5.

Part	Current weight	Scaling law	Future weight
Electric motor	11.8 kg	$\tau_{max} \propto m^{1.00}$ [4]	100.3 kg
Generator	25.0 kg	$\frac{m_1}{m_2} = \frac{P_1}{P_2}$ [5]	212.5 kg
Heat exchangers	9.0 kg	Linear [6]	76.5 kg
Gadolinium	12.7 kg	Working medium, so linear [3]	108 kg
Wheel housing	5 kg	Direct link to gadolinium [3]	42.5 kg
Controls, valves	22.7 kg	Stays about the same	25 kg
Installation	13.6 kg	Usually 22% of total weight (without generator) [3]	
Regenerator fluid	4.5 kg	In HEL cyclus	0 kg
Superconducting magnet	24.8 kg	Working material, so linear [3]	208.3 kg
Magnet can	11.2 kg	Direct link to magnets [3]	95.2 kg
Cryostat	11.3 kg	Direct link to magnet can [3]	96.1 kg
Refrigerator	11.3 kg	Efficiency the same, so linear	96.1 kg
He reliquifier	2.3 kg	Liquid hydrogen fuel is available so eliminated [3] (since heat can then be rejected at much lower temperature)	0 kg
Total weight	165.1 kg		1060.5 kg

Table F.2: Scaling of the weight in the article to the desired cooling capacity of the system.

---

[1] Bingfeng Yu et al.: A review of magnetic refrigerator and heat pump prototypes built before the year 2010, 2010

[2] S. Jacobs et al.: The performance of a large-scale rotary magnetic refrigerator, in: International Journal of Refrigeration 37.1 (Jan. 2014), pp. 84–91

[3] Jay F Kunze: Magnetic Refrigeration Feasibility in Aircraft 7-24-1987, in: 2013, URL: `https://www.researchgate.net/publication/236586376`

[4] Konstantinos Dermitzakis/Juan Pablo Carbajal/James H. Marden: Scaling laws in robotics, in: Procedia Computer Science 7 (2011), pp. 250–252.

[5] G Shrestha/H Polinder/J A Ferreira: Scaling laws for direct drive generators in wind turbines; Scaling laws for direct drive generators in wind turbines, in: 2009.

[6] Ilyas Yilgor/Shanbin Shi: Scaling laws for two-phase flow and heat transfer in high-temperature heat pipes, in: International Journal of Heat and Mass Transfer 189 (June 2022).

G Test plans

Several steps determine the optimization process of the PCM heat storage. First, the best material is chosen based on different latent heat and melt points. Next, the thickness/radius of the PCM shape is determined based on the capability of taking up heat from the water and when the material is fully saturated. Then, the shape of the tank is decided based on when the tank is saturated and gives high-temperature water at the end of the tank. Preceding, the amount of tanks is chosen based on the practical use of the tanks and heating and cooling capabilities. Finally, the flow rate for cooling is determined.

Test plan 1: Material choice:

1. Use the shape with realistic thickness/radius and calculate the flow rate based on the amount of PCM shapes.
2. Change the latent heat and melt point in the phase change material section of the COMSOL model.
3. Run the first study on the model for 20 minutes (or longer if needed) and write down at which point the outgoing water has an average temperature of 293 K or higher.
4. Run the second study on the model with a flow rate of 0.5 kg/s and an initial temperature of 299 K. The cooling water has a temperature of 299 K. Write down at which point in time 90% of the PCM is solid.
5. Change the latent heat and melt point to the following material to test and return to step 3.

Test plan 2: Thickness/radius PCM shape:

1. Implement the chosen material of the above test plan.
2. Use an appropriate length for the model and keep this the same throughout the whole test.
3. Calculate the number of blocks needed, dependent on the material's heat capacity and the blocks' thickness.
4. Determine the tank's dimensions with the set length and a width and height of the same range.
5. Calculate the flow rate between 2 layers by dividing the total flow rate: 5.974 kg/s by the number of fluid layers between blocks.
6. Run study 1 on the COMSOL model and write down at which point the outgoing water has an average temperature of 293 K or higher.
7. Take the next thickness/radius and continue with step 3.

Test plan 3: Shape tank:

1. Implement the chosen material and the PCM shape thickness/radius of the above test plans.
2. Determine which lengths of the tank should be tested.
3. Determine the amount of PCM shapes needed based on the latent heat and thickness/radius of the PCM shape.
4. Calculate the needed width and height for the chosen length.
5. Calculate the flow rate for the chosen dimension
6. Run study 1, and write down at which point the outgoing water has an average temperature of 293 K or higher.
7. Take the next length and continue with step 4.

Test plan 4: Amount of tanks:

1. Implement the chosen material, thickness/radius of the PCM shape, and tank length of the above test plans. Also, use the flow rate that goes with the earlier determined tank length.

2. Calculate the length of a single tank if several tanks are used. Also, calculate the time the tank can be cooled earlier if it is saturated using several tanks.
3. Implement the right length of the tank in the model.
4. Run study 1 in the COMSOL model and write down at which point the outgoing water has an average temperature of 293 K or higher.
5. Multiply the measured time by the number of tanks. This presents the total time the system can cool.
6. Take the next amount of tanks and continue with step 2.

Test plan 5: Flow rate cooling:

1. Implement the material, thickness/radius, size tank, flow rate, and number of tanks in the model in COMSOL.
2. Run study 1 10 minutes. (If there are several tanks, fill up each tank till the point the outgoing water has an average temperature of 293 K, and continue with the other minutes in the next tank)
3. Calculate the flow rate based on the heat capacity of water and the amount of time that cooling is possible (50 min + extra cooling time of multiple tanks). Use this flow rate as a starting point.
4. Run study 2 with water of temperature 283 K and write down at which point 80% of the PCM is solid, 90% of the PCM is solid, and how many % is solid at 60 minutes of cooling.
5. Repeat steps 3-4 in the case of multiple tanks.
6. Take the next flow rate and continue with step 2.

H Results test plans

H.1 Test results blocks

Material	Melting point [°C]	Latent heat [kJ/kg]	t @T≥ 293	t @ solid = 90%
RT12	12	165	13.7 min	25.9 min
RT15	15	155	14.5 min	11.2 min
RT18HC	18	260	23.9 min	12.0 min
RT21HC	21	190	21.5 min	7.8 min

Table H.1: Test plan 1 blocks: Determining material.

Thickness [mm]	Amount blocks	Dimensions tank[m]	Volume [m^3]	Flow rate [kg/s]	t @T≥ 293
6	1500	3x1.00x0.74	2.21	0.190	12.2 min
8	1500	3x1.00x0.86	2.59	0.190	12.7 min
12	1500	3x1.00x1.11	3.33	0.190	11.9 min
16	1500	3x1.00x1.36	4.07	0.190	14.0 min
20	1500	3x1.00x1.61	4.82	0.190	14.2 min

Table H.2: Test plan 2 blocks: Determining thickness blocks.

Length of tank [m]	Width x height [m]	Flow rate [kg/s]	t @T≥ 293
2	1.00x1.31	0.127	13.3 min
3	1.00x0.86	0.190	12.7 min
4	1.00x0.65	0.254	14.6 min
5	0.75x0.70	0.239	14.3 min
6	0.75x0.58	0.285	13.0 min

Table H.3: Test plan 3 blocks: Determining shape of the tank.

Amount of tanks	Length single tank [m]	Extra cooling time	t @T≥ 293	Total t @T≥ 293
1	4	0 min	14.6 min	14.6 min
2	2	5 min	7.0 min	14.0 min
4	1	8 min	2.7 min	10.8 min

Table H.4: Test plan 4 blocks: Determining amount of tanks.

Flowrate tank [kg/s]	Flowrate model [kg/s]	t @ solid = 80%		t @ solid = 90%		solid % @ t=60min	
		Tank 1	Tank 2	Tank 1	Tank 2	Tank 1	Tank 2
1.88	0.04	22.4 min	22.4 min	28.9 min	28.9 min	100%	100%
2.39	0.051	17.9 min	17.9 min	23.3 min	23.3 min	100%	100%
2.82	0.06	15.8 min	15.8 min	20.0 min	20.0 min	100%	100%

Table H.5: Test plan 5.2 blocks: Determining cooling flow rate double tank.

H.2 Test results cylinders

Material	Melting point[°C]	Latent heat [kJ/kg]	t @T≥ 293	t @ solid = 90%
RT12	12	165	35.4 min	> 60 min
RT15	15	155	35.6 min	39.5 min
RT18HC	18	260	54.2 min	41.2 min
RT21HC	21	190	43.5 min	25.0 min

Table H.6: Test plan 1 cylinders: Determining material

Radius [mm]	Amount cylinders	Dimensions tank [m]	Volume [m^3]	Flow rate [kg/s]	t @T≥ 293
8	19894	3x0.90x0.90	2.2	0.00180	2.1 min
12	13263	3x1.04x1.04	3.3	0.00270	18.0 min
16	9947	3x1.21x1.21	4.4	0.00360	23.2 min
20	7958	3x1.35x1.35	5.5	0.00450	21.9 min

Table H.7: Test plan 2 cylinders: Determining radius cylinders.

Length of tank [m]	Width x height [m]	Flow rate [kg/s]	t @T≥ 293
2	1.28x1.28	0.00180	16.9 min
3	1.04x1.04	0.00270	18.0 min
4	0.91x0.91	0.00360	18.8 min
5	0.81x0.81	0.00451	19.2 min
6	0.74x0.74	0.00541	19.8 min

Table H.8: Test plan 3 cylinders: Determining shape of the tank.

Amount of tanks	Length single tank [m]	Extra cooling time	t @T≥ 293	Total t @T≥ 293
1	6	0 min	19.8 min	19.8 min
2	3	5 min	7.7 min	15.4 min
3	2	7.5 min	4.6 min	13.8 min

Table H.9: Test plan 4 cylinders: Determining amount of tanks.

Flowrate Tank [kg/s]	Flowrate model [kg/s]	t @ solid = 80%		t @ solid = 90%		solid % @ t=30min	
		Tank 1	Tank 2	Tank 1	Tank 2	Tank 1	Tank 2
1.11	0.0005	18.8 min	18.8 min	> 30 min	> 30 min	85%	85%
2.40	0.0011	9.6 min	9.6 min	19.8 min	19.8 min	96%	96%
3.32	0.0015	7.6 min	7.6 min	14.9 min	14.9 min	100%	100%

Table H.10: Test plan 5 cylinders: Determining cooling flow rate double tank.

H.3 Test results shell-in-tube

Material	Melting point [°C]	Latent heat [kJ/kg]	t @T≥ 293	t @ solid = 90%
RT12	12	165	10.7 min	> 60 min
RT15	15	155	9.9 min	26.5 min
RT18HC	18	260	13.3 min	27.5 min
RT21HC	21	190	8.8 min	17.3 min

Table H.11: Test plan 1 shell-in-tube: Determining material.

Radius tube [mm]	Amount tubes	Dimensions tank [m]	Δx [mm]	Volume [m^3]	Flow rate [kg/s]	t @T≥ 293
5	3979	3x0.8x0.8	1.5	2.0	0.000751	7.9 min
7.5	3536	3x1.1x1.1	2.0	3.4	0.000845	13.4 min
10	3315	3x1.4x1.4	2.5	6.2	0.000901	23.2 min
12.5	2653	3x1.5x1.5	2.5	7.1	0.001126	22.7 min

Table H.12: Test plan 2 shell-in-tube: Determining radius tubes using material RT18HC.

Length of tank [m]	Width x height [m]	Flow rate [kg/s]	t @T≥ 293
2	1.24x1.38	0.000563	13.3 min
3	1.01x1.13	0.000845	13.4 min
4	0.88x0.98	0.001126	13.3 min
5	0.78x0.88	0.001408	13.4 min
6	0.71x0.80	0.001689	13.4 min

Table H.13: Test plan 3 shell-in-tube: Determining shape of the tank with material RT18HC and a radius of the tubes of 7.5 mm.

Amount of tanks	Length single tank [m]	Extra cooling time	t @T≥ 293	Total t @T≥ 293
1	4	0 min	13.4 min	13.4 min
2	2	5 min	5.0 min	10.0 min
4	1	7.5 min	2.1 min	8.4 min

Table H.14: Test plan 4 shell-in-tube: Determining amount of tanks with material RT18HC, tube radius of 7.5 mm, and total length of the tanks of 4 m.

Flowrate tank [kg/s]	Flowrate model [kg/s]	t @ solid= 80%	t @ solid= 90%	solid % @t=60min
1.06	0.0001	> 60 min	>60 min	65%
2.39	0.0002	43.0 min	60 min	90%
3.18	0.0003	32.9 min	42.3 min	100%
5.31	0.0005	18.8 min	24.4 min	100%
11.95	0.00113	8.6 min	11.4 min	100%

Table H.15: Test plan 5 shell-in-tube: Determining cooling flow rate of a single tank of 4 m, with material RT18HC, and a tube radius of 7.5 mm.

H.4 Test results cooling down PCM

In Table H.16, the result is shown of a test to find out how much of the PCM should change back to solid before starting the cycle again. At first, the thought was to change all the PCM to solid before starting the cycle again. However, as presented in previous tests, Table H.5, for example, reaching the point of 100% solid, takes relatively much time. However, going up to 80% or 90% is a lot faster. Therefore, the test below is done. When starting with 80%, the heating heats the storage too much, giving out too hot water before the cycle ends. Hence, 80% at the start is not possible. However, starting with 90% and following the usual cycle also ends with 90% or less, which is a perfect and natural cycle to follow. Figure H.1 shows that starting at 100% or 90% both gives almost the same result. Therefore, it is not necessaty to cool all the way back to 100% solid.

Solid % @ start	solid % @ heating t=10	solid % @ cooling t=60min
100%	44%	90%
90%	43%	91%
80%	35%	84%

Table H.16: Test plan cooling to phase change material percentage.

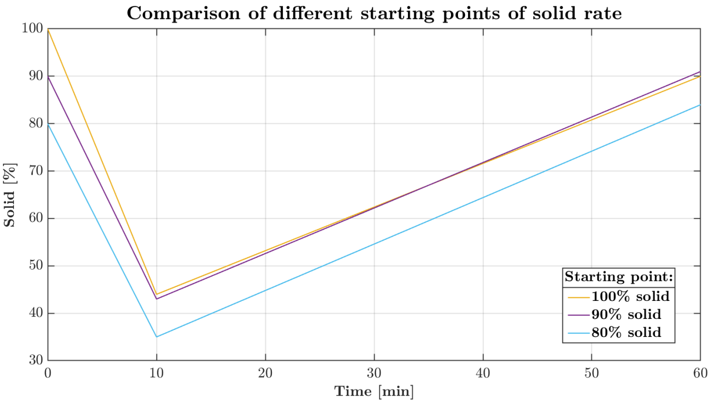


Figure H.1: Comparing the different starting points of the rate of solid.

I Power demand

For the cooling of the High-Energy Laser towards the direct cooler or towards the heat battery, a flow rate of 15.93 kg/s is needed. A pump with pump curves shown in Figure I.3 uses 1.31 kW. However, some extra waste heat is generated since a frequency regulator is needed to efficiently get the pump to the working point. Therefore, the needed power for this pump is defined by the following:

$$1.31 \cdot 1.02 = 1.336kW. \tag{I.1}$$

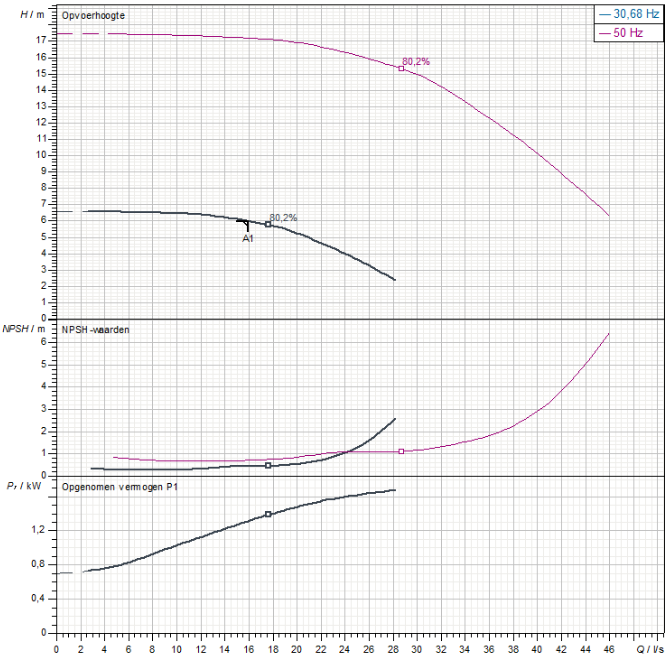


Figure I.1: Pump curve of a centrifugal pump with working point A1 for the correct flow rate from the HEL to the direct cooler or heat battery.

For cooling the heat battery with block-shaped PCM, a flow rate of 2.39 kg/s is needed. For cooling the heat battery with a cylindrical-shaped PCM, a flow rate of 2.41 kg/s is needed. The same pump can be used for both. A pump with pump curves shown in Figure I.2 uses 261 W at the working point.

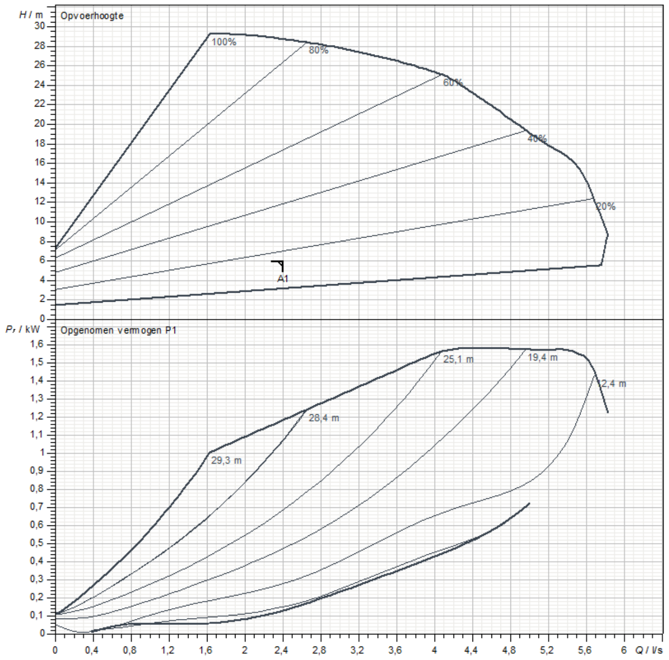


Figure I.2: Pump curve of a centrifugal pump with working point A1.

For cooling the heat battery with shell-in-tube-shaped PCM, a flow rate of 3.18 kg/s is needed. A pump with pump curves shown in Figure I.3 uses 360 W. However, some extra waste heat is generated since a frequency regulator is needed to efficiently get the pump to the working point. Therefore, the needed power for this pump is defined by the following:

$$360 \cdot 1.02 = 367W. \tag{I.2}$$

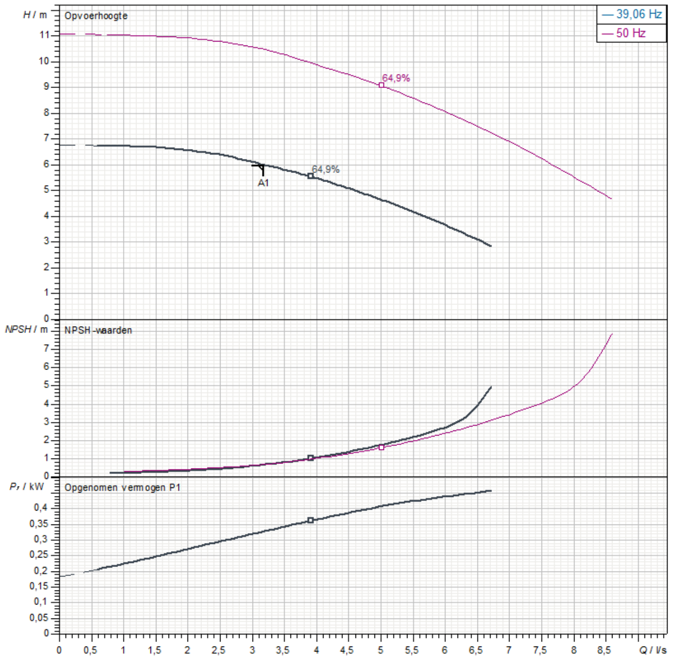


Figure I.3: Pump curve of a centrifugal pump with working point A1 for the correct flow rate in the shell-in-tube situation.

Technische Universiteit
Eindhoven
University of Technology

The implications of cooling a High-Enery Laser on a naval surface combatant are investigated. Different cooling methods are reviewed by literature research, and the best options are further explored. The implications of using a chiller, ice water cooling system, and magnetic refrigeration are gathered from the information of manufacturers and literature research. The implications of using a heat battery made from phase change material are researched by a computational fluid dynamics simulation in COMSOL. Using magnetic refrigeration gives the best results considering the implications; weight, volume and power demand. However, there are no working systems of the required size. Therefore, using a heat battery combined with the existing chillers is the most feasible option, considering it has to be implemented with the midlife update of the vessel.