CHALMERS

Concept development of cooling systems for electronic speed controller’s onboard hydro-foiling vessels

Bachelor thesis for Marine Engineering Program

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CONCEPT DEVELOPMENT OF COOLING SYSTEMS FOR ELECTRONIC SPEED CONTROLLER'S ONBOARD HYDRO-FOILING VESSELS

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Cover:
An illustration from the Swedish Sea Rescue Society of their perspective hydrofoil boat.

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PREFACE

This bachelor's thesis is written as a part of the Marine Engineering program at Chalmers technical university. It represents the final task of the marine engineer program and contributes to 15 higher education credits towards the total requirement of 180 credits. The thesis work has been a collaboration with SIGMA Energy and Marine on behalf of the Swedish Sea Rescue Society (SSRS).

We would like to express our sincere gratitude to Fredrik Borg at SIGMA Energy and Marine for his invaluable support and engagement throughout our work. We also extend our appreciation to our coworkers at SIGMA for their warm reception and all the assistance they provided. It was truly a pleasure collaborating with such a dedicated and helpful team.

We would also like to extend our gratitude to Fredrik Falkman at the Swedish Sea Rescue Society for his valuable support and insightful discussions, which have greatly contributed to our work.

Finally, we would like to sincerely thank Peter Hartzell, our supervisor at Chalmers University of Technology.

Konceptutveckling av kylsystem för elektroniska hastighetsregulatorer ombord på bärplansbåtar

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SAMMANDRAG

Denna kandituppsats är skriven som en avslutande uppgift av studierna på Chalmers Tekniska Högskola på Sjöingenjörsprogrammet. Arbetet har varit på uppdrag av Svenska Sjöräddningssällskapet och i samarbete med SIGMA Energy and Marine.

Svenska sjöräddningssällskapet har i ett samarbetsprojekt, med hjälp av flera olika företag, utvecklat en ny räddningsbåt med bärplanskonstruktion och elektrisk drivlina. Anledning till bärplanskonstruktionen är för att minska motståndet mellan båtskrov och vattnet, vilket resulterar i lägre energiförbrukning och ökad räckvidd. För att styra varvtalet på elmotorerna och på så sätt hastigheten på båten används elektroniska hastighetsregulatorer. När hastighetsregulatorerna arbetar förbrukas energi, vilket resulterar i en värmeutveckling hos de elektroniska hastighetsregulatorerna.

Sjöräddningen vill säkerställa att inga kritiska temperaturer uppnås, för att åstadkomma detta krävs ett kylsystem som leder bort värmen från hastighetsregulatorerna. Problemet ifall höga temperaturer uppnås är att det reducerar verkningsgraden, sänker prestandan och förkortar livslängden hos elektroniska hastighetsregulatorer. Till slut kommer kritiska temperaturer leda till att regulatorerna stängs av.

Arbetet syftar till att utveckla ett kylsystem till hastighetsregulatorer som kan implementeras ombord på sjöräddningens båt av bärplanskonstruktion. Utvecklingen av kylsystemen är baserade på sjöräddningens behov och designat efter deras fartygskonstruktion. Utveckling av ett komplett kylsystem med fullständig kringutrustning undersöks inte i detta arbete.

Nyckelord: Bärplan, Fartyg, Båt, Kylsystem, Elektroniska hastighetsregulator, kylsystem, värmeväxlare.

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ABSTRACT

This bachelor thesis is written as a final part of the studies at Chalmers University of Technology in the marine engineering program. The work has been conducted on behalf of the Swedish Sea Rescue Society and in collaboration with SIGMA Energy and Marine.

The Swedish Sea Rescue Society has developed a new rescue boat with hydrofoil construction and an electric drivetrain through a cooperative project, with assistance from several companies. The reason for the hydrofoil design is to reduce resistance between the hull and the water, which leads to lower energy consumption and increased range. Electronic speed controllers are used to control the speed of the electric motors and in this application the speed of the boat. When the speed controllers are in operation, energy is consumed, resulting in heat generation in the electronic speed controllers.

SSRS wants to ensure the reliable function of their vessel and that no critical temperatures are reached. A cooling system that conducts heat away from the electronic speed controllers is required to accomplish this. The problem with high temperatures is that it reduces efficiency, reduces performance, and shorten the life of the controllers. In the end, critical temperatures will cause the controllers to shut down.

The work aims to develop a cooling system for speed controllers that can be implemented onboard SSRS's rescue boat which is of hydrofoil construction. The development of cooling systems is based on the needs of the sea rescue and designed according to their ship structure. This report does not include the development of a whole cooling system with external components.

Keywords: Hydrofoil, Ship, Vessel, Boat, Electronic speed controllers, Cooling systems, Heat exchanges.

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ACRONYMS AND TERMINOLOGY

Alternative current	AC
Characteristic length of engine case	l_e
Circle area of coolant pipe	A_p
Computational Fluid Dynamics	CFD
Delta temperature of air	ΔT_a
Delta temperature of coolant	ΔT_w
Demand	D
Density of air	ρ_a
Density of aluminum	ρ_{Au}
Density of coolant	ρ_w
Diameter of coolant pipe	D_p
Direct current	DC
Electronic Speed Controller	ESC
Heat exchange value for radiator	Q_r
Heat transfer coefficient aluminum	k_{Au}
Heat transfer coefficient of engine case	h_e
Heat transfer surface area inside radiator	A_r
Inlet temperature of air to radiator	T_{incold}
Inlet temperature of coolant to radiator	T_{inhot}
Kesselring criterium grade	v
Logarithmic mean temperature difference	ΔT_{ln}
Main function	MF
Nusselt number	Nu
Outlet temperature of air to radiator	$T_{outcold}$
Outlet temperature of coolant to radiator	T_{outhot}
Overall heat transfer coefficient of radiator	U_r
Plane area of engine case	A_e
Prandtl number	Pr
Reynolds number	Re
Specific heat capacity of air	Cp_a
Specific heat capacity of aluminum	Cp_{Au}
Specific heat capacity of coolant	Cp_w
Swedish Sea Rescue Society	SSRS
Thermal conductivity coolant	k_w
Thermal resistance of engine case	R_e
Thickness of material engine case	L_e
Unwanted function	U
Velocity of coolant	ν_w
Viscosity of coolant	μ_w
Volume flow of air	F_a
Volume flow of coolant	F_w
Weight factor multiplied with	t
Wish	W

1. INTRODUCTION

Electrification is happening at an accelerated pace, and the demand for electrically driven boats and vessels is growing. An electrical powertrain can contribute to decreasing emissions and the environmental footprint of boats. The energy density of lithium-ion batteries, which are commonly used in electric vehicles and other applications, ranges from about 100 to 265 watt-hours per kilogram (Wh/kg) (Lithium-Ion Battery - Clean Energy Institute, n.d). In contrast, the energy density of diesel fuel is between 37 – 39 MJ/l which is equal to about 10,000 watt-hours per kilogram (Khan, 2011). Since batteries weigh so much more per usable energy output than diesel the construction of an electrically driven vessel needs to be different.

The amount of energy needed to move a boat depends on the resistance. Hydrofoils lift the hull out of the water and nearly neutralize the resistance of the water. The hydrofoil will lift the hull up from the water because they include wings which gives a lifting force when the boat is making speed. Since water causes around 90% of the resistance, the required energy to propel the boat will dramatically be reduced by hydrofoils (Giraldo-Pérez, E., Betancur, E., & Osorio-Gómez, G., 2022).

The most common cause of electrical system damage is overheating. Each electronic component in a device requires electrical energy to work. The excess energy is converted to heat when the element has fulfilled its actions. (Ozbalci, O., Dogan, A., & Asilturk, M., 2022). Swedish sea rescue society (SSRS) wants to make sure that their electronic speed controllers (ESC) can operate without failure that may occur due to overheating. For this reason, SSRS wants us to develop a cooling system for their ESCs that may be integrated into their new hydro foiling recuse vessel.

Most vessels today use seawater for cooling, but on hydro-foiling boats, the hull of the vessel is above the water level when cruising, making it more difficult to use seawater for the cooling system. This report consists of a case study of how a cooling system can be developed for electronic speed controllers onboard a hydrofoil vessel. The cooling system will be 3D modeled and hydrodynamically calculated in partnership with Sigma Energy and Marine. The study will be based on the SSRS new development of a 9-meter-long electric-driven hydrofoil lifeboat. By having a more effective sea rescue, SSRS's upcoming building project will support a more active engagement in the environment and enable it to save more lives.

1.1 Background

SSRS is a voluntary rescue organization that focuses on saving lives and preventing accidents at sea. SSRS as a rescue society, wants to be able to operate in all different kinds of weather conditions, and therefore high demands are placed on their equipment. In particular, the proper functioning of electrical motors is crucial for their operations. The Electronic Speed Controller (ESC) plays a vital role in ensuring the efficient performance of these motors under various conditions while maintaining their optimal operating temperature.

However, the utilization of electrical-driven hydro foiling vessels is still under development, leading to a knowledge gap regarding the design of a suitable cooling system for the ESC. This gap needs to be addressed to ensure the ESC's effective functioning and temperature regulation, especially during the warmest days of summer when temperatures can reach up to 35 degrees. Cooling systems will be evaluated to ensure proper function during this weather conditions. The work and the development of cooling systems will be in collaboration with SIGMA Energy and Marine, a consult which focus on technology development within the marine sector.

Note: The temperature of 35 degrees Celsius represents the extreme operating conditions where it is essential for the cooling capacity to remain sufficient, ensuring optimal operation as required by SSRS.

The function of an ESC is like a switch, sending incredibly quick pulses of electricity to the motor that control the speed. Heat will be generated from the controllers and it’s important to keep them at their operating temperature due to manufacturers recommendation for proper function. Ensuring sufficient temperature on the cooling water will minimize failure and increase efficiency. (Everything You Need to Know About Electronic Speed Controllers (ESC), n.d).

1.2 Aim of the study

The aim of this thesis is to develop a cooling system for the electronic speed controllers onboard the Swedish sea rescue's electrical-powered hydrofoil vessel.

1.3 Research questions

This report will answer the following questions:

- How can a cooling system for electronic speed controllers onboard a hydro foiling boat be designed and integrated?
- What cooling system is most efficient to conceive and develop for the SSRS's hydrofoil boat?

1.4 Delimitations

The delimitations in this report are the following:

- This research examines the cooling system for electronic speed controllers on SSRS's project to build a new electric-driven hydrofoil boat. The specifications for cooling systems on different vessels may differ, thus this aims to only focus on the specific vessel.
- There will be no prototypes for testing, only cooling system calculations, and simulations.
- Economic factors will not be a part of the report.

2. THEORY

This chapter contain theory which the method, result and discussion is partly based on.

2.1 Electronic speed controllers (ESC)

An ESC draws current from a source that delivers constant voltage and frequency. The task of the ESC is to deliver the voltage and frequency that the motors need to provide a specific speed. Almost all ESC employ with some form of closed-loop (feedback) control system and the basic arrangement of a speed control system has a speed reference and feedback from the actual speed at the motor. If the speed reference and the actual speed feedback do not correspond the ESC could adjust with some sort of regulator. The ability to be turned ON and OFF on demand is essential in any inverter which feeds an active load such as an induction motor and there are several different types of switching devices. Switching device has a small power loss in comparison with the power throughput and therefore ESC has often a high efficiency. The heat from the power loss which is produced in the switching device is however released in the active region of the semiconductor which is sensitive to overheating and will break down unless it is adequately cooled. ESC is often cooled by either heat sinks and drawing air from a fan or by liquid cooling often in the form of water/glycol or oil. The ESC designer aims in both cases to minimize the thermal resistance between the hot devices in the ESC and the cooling device. The thermal resistance can be minimized by ensuring good thermal conduct between the cooling device and the semiconductor. (Hughes & Drury, 2019)

2.2 Heat exchanges

There are numerous types of innovative heat exchange designs to match the heat transfer hardware to the heat transfer requirements. Heat exchanges are commonly used in practice, and they operate for long periods of time with small changes in their operating conditions. An engineer is often able to select a heat exchanger that will achieve a specified temperature change in a fluid where the mass flow rate is known or to predict the outlet temperature in a specified heat exchanger. Heat exchanges can often be modeled as a steady-flow device because the mass flow rate of the fluids remains constant and the fluid properties such as temperature and velocity remain the same at the inlet and outlet. Also, the fluid streams only experience little change in their velocities and elevations and therefore the kinetic and potential energy changes are negligible. (Çengel et al., n.d.)

2.2.1 Heat sinks

A heat sink is a device to transfer heat energy to the surroundings using different types of surfaces such as fins and spines. Heat sinks are used in a wide range of applications where you often use the surrounding air for cooling. For example, heat engines, refrigeration, and electronic equipment often use heat sinks for the heat exchange to take place with the surrounding air. The performance of a heat sink depends on the thermal conductivity of the fins, the surface area of the fins, or the heat transfer coefficient. The convection to the heat sinks is in many applications forced with the use of fans. Heat sinks can also be optimized by maximizing the heat transfer rate of a fin with respect to the fin thickness, the profile length, and the spacing between the fins. (Lee, H. S,. 2010).

2.2.2 Plate heat exchanger

This type of heat exchanger consists of a series of plates with corrugated flat flow passages where there is one hot and one cold fluid on each side of the plates. The heat exchange is very effective thus the warm fluid is surrounded by a cold fluid on both sides. Plate heat exchanges can easily be modified with increasing cooling demand by mounting more plates. (Çengel et al., n.d.). There are several advantages to using plate heat exchanges for heat exchange purposes and they are widespread in the industry. Plate heat exchanges are compact with large heat exchange areas however there are some limitations due to the design requirement for corrugate heat exchange plates. The heat transfer directly depends on the geometry of the corrugations on the surfaces of the plates to minimize deposits and to create local flow tribulations. (Korobiichuk et al., 2022)

2.2.3 Tube heat exchanger

This type of heat exchanger might be the most common one in industrial applications. Tube heat exchanges contain a shell with many tubes (sometimes several hundred) packed inside the shell. There is one fluid flowing inside the tubes and another fluid flowing inside the shell which enables the heat transfer between the fluids. Inside the shell, there could be baffles to force the fluid to flow across the shell in a certain way and to connect the tubes with maintain uniform spacing to optimize the heat transfer. The limitation with a tube heat exchanger is their relatively large size and weight and they are therefore not as suitable for vehicles with these types of limitations. (Çengel et al., n.d.)

2.3 Cooling fluids

There are many requirements for liquid coolants for electronic applications and cooling has become a major challenge due to smaller and more advanced components. Liquid coolant has a higher heat transfer coefficient compared to air cooling which makes it attractive to use. There are several different requirements for a liquid coolant for electronics and they may vary dependent on the type of application. Some general requirements are good thermo-physical properties, low freezing point, non-corrosive to materials, economical and non-toxic. The selection of the best coolant for specific applications requires a proper understanding of the characteristics and thermos-physical properties of the fluid. (Satish C. Mohapatra, n.d.)

2.4 Heat transfer

Heat is a form of energy that can be transferred from one system to another where there is a heat difference. The energy always transfers from the warmer medium to the colder and the energy transfer between the mediums will stop when they have reached the same temperature. There are three basic mechanisms of heat transfer, which are conduction, radiation, and thermal conductivity. (Çengel et al., n.d.)

Conduction can take place in solids due to a combination of vibrations of the molecules in a lattice and energy transport by free electrons. Conduction can also take place in gases or liquids due to the collisions and diffusion of the molecules. The amount of heat energy that is conducted through a medium depends on its geometry, thickness, material, and temperature difference across the medium. (Çengel et al., n.d.)

Conductivity is a measure of the ability of a material to conduct heat. A high conductivity value indicates that the material is a good heat conductor, and a low value means that the material is a poor heat conductor, a poor heat conductor can also be seen as an insulator. Pure crystals and metals have the highest thermal conductivities and are therefore often used where there is a need for an effective heat transfer. (Çengel et al., n.d.)

Thermal radiation transfer heat through electromagnetic waves and the energy is emitted by matter. It is the fastest way to transfer heat energy and it does not suffer attenuation in a vacuum. All solids, liquids, and gases emit thermal radiation at a temperature above absolute zero and could all absorb or transmit to varying degrees. (Çengel et al., n.d.)

2.4.1 Thermal diffusivity

Thermal diffusivity is a material property that represents how long it takes for heat to diffuse through the material. It can be seen as the ratio of the heat conducted through the material to the heat stored per unit volume and the unit is measured in m^2/s. The thermal diffusivity of a material greatly influences how effective a cooling system will be. A large thermal diffusivity will give a fast propagation of heat into the medium and a small thermal diffusivity means that the heat is mostly absorbed by the material. (Çengel et al., n.d.)

2.4.2 Thermal resistance

The thermal resistance of heat transfer applies to conduction, radiation, and convection. The resistance of a medium depends on the geometry and thermal properties of the medium. Different thermal resistance can add up to the equivalent thermal resistance of a system and declare how long it takes for the heat to transfer through the system. (Çengel et al., n.d.)

2.4.3 Fouling factor

The heat transfer through a heat exchanger usually deteriorates with time because of fouling which is a result of accumulation of deposits on the surface of the heat exchanger. The heat transfer surface is usually caused by fouling in form of precipitation of solids in a fluid, for example there could be calcium-based deposits especially where there is hard water. Deposits from fouling can often be cleaned by scratching the surface or by chemical treatment. In a heat exchanger it is critical with fouling because it will affect both the heat transfer and the flow passage. Another form of fouling is corrosion and the growth of algae. To avoid fouling it is important to investigate the material, fluids, operating temperatures, and materials. For example, using coated pipes or choosing pipes made of plastic instead of metal could be beneficial in terms of fouling. In applications where there is a big risk of fouling, it is important to design a heat exchanger so that it meets the design requirements after fouling occurs or investigate how maintenance for avoiding fouling could be improved. (Çengel et al., n.d.)

2.5 Pumps

Cooling systems that have liquid fluid often involve pumps for the circulation of the fluid. The pump in a cooling system has different requirements depending on for example pressure drops in the system, necessary flow, and viscosity of the fluid.

A pump is usually used for increasing the pressure, velocity, and/or elevation of a fluid by supplying mechanical energy to the fluid. Pumps are often electrically driven and the effectiveness of the conversion from electrical energy to rotating mechanical energy is characterized by motor efficiency which can be higher than 97 percent. A pump is often packaged together with its motor and therefore the overall or combined efficiency is often more important to investigate in a system. (Çengel et al., n.d.)

All pumps may be divided into two major categories which are dynamic and displacement. Dynamic pumps are when energy is continuously added to increase the fluid velocities in the system to greater than the velocities at the discharge which results in a pressure increase. Displacement pumps are when energy is periodically added by the application of force in a specific fluid volume which results in a direct pressure increase up to the value required to move the fluid through the system. (Satish C. Mohapatra, n.d.)

3. METHODS

The project methodology is described in this chapter and is divided into several steps: *feasibility study, problem determination, problem solving, evaluation, assessment, and choice of concept.* Each representing a different stage of the product development process. Selection of methods is based on the purpose of the project and its research questions. Each part is described together with the project's executive decision and the implementation of the work.

3.1 Feasibility study

In a feasibility study, the purpose is to make an unbiased problem analysis for a potential new development. Its relevant to bring forward analyses and background material about the market, design, and technology. It’s important to uncritically review various possible technical solutions and other conditions so as not to start resource-intensive work on the wrong premises. A feasibility study should lead to an initial requirements specification where first all functional requirements, i.e. functions that the product must fulfill, are identified. During the sequential development of technical solutions and production concepts, decisions are made on how requirements will be fulfilled. Specifications are specified and further developed along the way of the project (Johannesson et al., 2013).

The project's feasibility study began with an analysis of the existing market for electrically driven hydrofoil vessels, and which designs and technologies exist and are used today in the cooling process of ESCs. Various technical solutions were discussed in an uncritical manner during the feasibility study. This project is a collaboration with SIGMA Energy and Marine and the work is for SSRS. Therefor a first requirement specification was generated after a discussion with the project’s supervisor at SIGMA Energy and Marine.

3.2 Problem determination

The purpose of problem determination is to clarify the problem and its nature. The result of a well-researched problem determination is an important basis for specifying “what” will be the result. The project has used two methods to characterize the problems, *the question method and situational determination.* The question method implies that the final problem description is formed by combining views and facts. This data is collected by formulating questions that are answered. Examples of questions can be, "what is the problem?”. “why does it exist?", "where is the problem?”, "when does the problem exist?”, “why does it exist at that time?" The problem determination can be improved by answering the relevant questions (Johannesson et al., 2013).

Situational determination can also be used to gain a deeper understanding of the problem. The method involves conducting site visits at the location where the problem exists or where the solution will be implemented. The method also includes the ability to acquire a better understanding of the problem through conversations as well as your own observations and documents of the place. One of the goals of this method is to gain an understanding of the problem by own experience and to understand the conditions surrounding it (Johannesson et al., 2013)

Further in the problem determination, a visit to SSRS head office together with the projects supervisor at SIGMA Energy and Marine was carried out where a greater understanding and product knowledge could be created. This was done through meetings where questions like those in the *question method* could be asked and answered. Furthermore, discussions about technical aspects, the boat's construction, and wishes from SSRS contributed to the continued work. Located at the headquarter of SSRS was the prototype developed on behalf of SSRS, which is in scale 0,6. By examining the prototype, greater product knowledge could be established, which contributed to a better understanding of how a cooling system for ESCs can be designed. Together, these factors contributed to the compilation of a requirement specification.

The requirements specification was created by categorizing the functions of the cooling system. *Main function* - The primary or general purpose for which the product is designed. *Secondary functions* - Features that interact to generate the main function.
Support function - The functions that support and facilitate the use of the product but are not critical to the product's main function. *Unwanted features* - unwelcome additions to the product.

Each established criterion in the requirement specification was then classed as a Main function (MF), Demand (D), Wish (W), or Unwanted features (U), with weight factors ranging from 1 to 5 (1-low, 5-high). The requirement specifications are in the result chapter, table 1.

3.3 Problem solving

The problem knowledge and information gathered thus far can now be used to develop product solutions in the concept generation phase. The work has chosen to support the creative process on two methods, the catalog method, and morphological matrix, to generate different concepts on product solutions that meet the product specification. The concept generation phase seeks to produce as many solution proposals as possible, from which to choose. This approach is implemented to ensure thorough consideration of all potential solutions and to prevent any valuable options from being overlooked or underestimated.

The catalog method is a straightforward way to encourage creative thinking. It is based on the fact that information is sought in literature, "catalogs," and the internet. This method can be used to investigate how others solved the problem at hand, or something similar. Searches also provide an opportunity for inspiration for new ideas (Johannesson et al., 2013).

The work used the catalog method to gather information from the internet, primarily about cooling systems and what similar systems for maritime use might look like.

The process of developing concepts follows a well-known method and began with the creation of a morphological matrix. The identified problems were divided into sub-problems. After that, solutions are sought separately for each of the subsystems. Total solutions are created by dragging polygons in the matrix, i.e. binding together different partial solution options into a total solution. After creating several different concepts that meet the product specification requirements, some could be sorted out through dialogue with the sea rescue organization.

3.4 Evaluation, assessment, and choice of concept

A known established method for the evaluation process was carried out to determine which of the work's various concepts best fulfills, wishes, design and technical specifications. The evaluation was carried out using the decision matrix method, also known as the Pugh's method. Pugh's method is used to assess various solutions in the most objective and systematic manner as possible (Ullman, 2010). The evaluation in Pugh's method is as follows. First, the chosen concepts are defined; second, a reference solution is selected against which the concepts should be initially compared. The reference solution can either be one of the generated concepts or an existing solution. Thirdly, the criteria against which the concepts should be set are designed. In the comparison, the concepts are assessed whether it meets the chosen criterion better than (+), as good (0) or worse (-) than the reference solution. A ranking is produced after compiling a summary assessment of how the concepts performed in comparison to the reference solution. The same evaluation is then repeated, but this time with the winning concept from the first round as a reference.

To determine the relative importance of criteria within Pugh's matrix, a weight determination matrix was developed. This matrix facilitates a comparison of the criteria listed in Pugh's matrix, assigning values that reflect their degree of relevance. When comparing two criteria, such as criterion A and criterion B, the evaluator determines their relative importance. If criterion A is significantly more important, a grade level of (1) is assigned to criterion A and (0) to criterion B. If both criteria are considered equally important, a grade level of (0.5) is assigned to each.

Once all the criteria have been evaluated, the total value of each criterion is calculated by adding together the grades assigned to it. These total values are then divided by the sum of all grades. This calculation results in a sum value for each criterion.

To convert the sum values into weight factors, scales ranging from 1-5 or 1-10 are used. This conversion allows for a standardized representation of the relative importance of each criterion. By utilizing the weight determination matrix in this way, the evaluator can assign appropriate weight factors to each criterion, providing a clearer understanding of their significance within the decision-making process.

Note that the scales mentioned (1-5 and 1-10) are just examples and can vary depending on the specific context or requirements of the evaluation.

The concepts are then evaluated using the criterion matrix (Kesselring), which assigns a grade to each concept based on how well it meets the various criteria. The grades are multiplied by the weight factor for each criterion, and the total merit value is calculated. The matrix also contains an ideal solution with the highest rating for each criterion. Additionally, the final merit value of each concept is divided by the ideal's merit value and ranked accordingly. After the criterion weight matrix (Kesselring) was carried out, a ranking was able to determine the best concept. To further evaluate the solution, a meeting was scheduled with the actor for whom the work is for (Johannesson et al., 2013).

The wining concepts are then designed using CAD and the material properties and the coolant properties are defined for further evolution regarding the cooling capacities. To strengthen the credibility of the evolution, there is a CFD simulation performed by a computational engineer at SIGMA Energy and Marine. Furthermore, calculations have been performed which has been verified by the project’s supervisor at Chalmers University of Technology.

4. RESULTS

The result in this chapter is presented through sections with respectively subsection included. it's divided into several main sections with respectively subsection included. First the the problem determination is explained in the section 4.1 with the included subsections, *problem formulation, product description,* and *Functional requirement specification.* Following from that the problem solving is explained in section 4.2 with included subsection *Catalog method and Concept generation.* Evaluation of concept is presented in section 4.3 and lastly detailed construction is presented in section 4.4.

4.1 Problem determination

This chapter will explain how the formulation of the problem was introduced and a description of the product that require cooling. It will also explain the specific requirements for the cooling system which is the basis for the concept's generation.

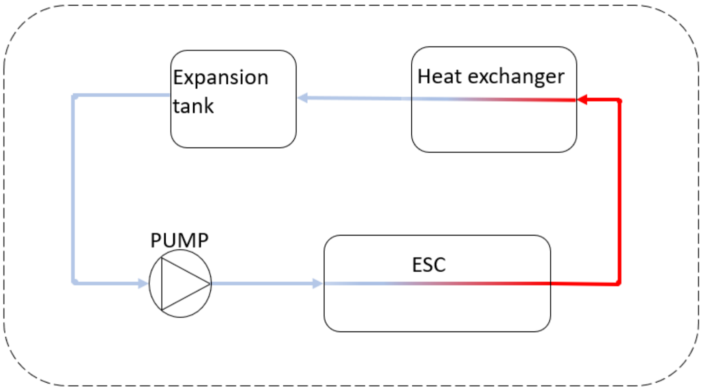
4.1.1 Problem formulation

The problem formulation was formed by a visit at SSRS office together with supervisor from SIGMA Energy and Marine where a discussion led to a gained product knowledge of the hydro-foil boat and its components. SSRS had a prototype of the hydro-foil boat at scale 0,6 where it was possible to investigate the components that required cooling, where the components were mounted and where it could be possible to mount cooling devices. During the meeting which led to the problem formulation there were also a discussion about the delimitation for this project which are reported in chapter 1.

SSRS hydro-foil boat will operate on two electric-driven propulsion motors and will need an ESC for each motor to control the revolution of the motors. The ESC for this boat has high efficiency but the remaining loss will turn to heat and will need cooling. SSRS needs a propulsion system that is reliable and therefore it is crucial that the ESC does not exceed its maximum operating temperature. One of the problems with a hydro-foil boat is that the hull of the boat does not have contact with the water when foiling which makes it more difficult to use the seawater as a conventional boat for cooling applications. Furthermore, the requirement for a reliable system makes it more difficult to use seawater onboard for a heat exchanger due to filters that might be clogged. To solve this problem, it will be necessary to design a cooling system for the ESC which is reliable and meets the cooling demand. At the same time, the cooling system must be lightweight and small enough to be fitted onboard where a heat exchange is possible to be implemented.

During the meeting with SSRS, it was established that this project will focus on different concepts of potential heat exchanges that might meet the cooling demands for the hydro-foil boat. The concepts should then be evaluated, and the winning concept will be designed in CAD and then be furthermore evaluated by calculations and by a CFD simulation. Figure 1 below shows the main components in a cooling system for the hydro-foil boat and the arrows symbolize the fluid lines in the system where red indicates warm and blue indicates cold. This project will only investigate the heat exchanger.

Figure 1
The main components in a cooling system.



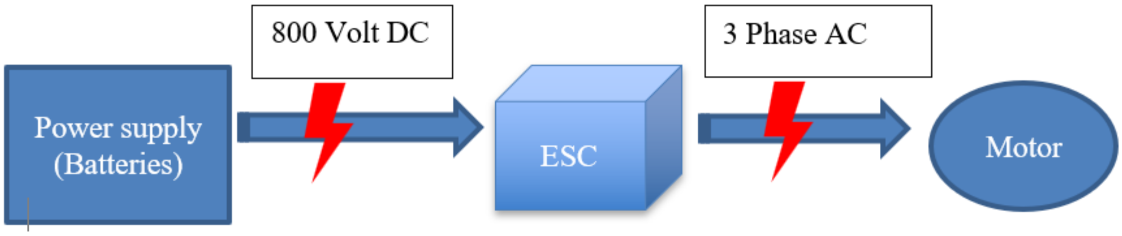
Note: The illustration is created by the authors.

4.1.2 Product description

This section describes the product for which the cooling system is designed. Electronic speed controllers are used to control the rotational speed of electric motors. ESCs make it possible to control the revolution of the electric motors, and thus the speed of the boat. The company that manufactures the ESCs offers models with varying power; the ESCs that are involved in the work and are delivered to the SSRS boat have a given power of 50kw each. The power of the ESCs is determined by what is being controlled; since two electric motors of 50 kw each are used for propulsion, two ESCs of the corresponding capacity are also used to deliver the intended power. The electronic speed controller's is fed from the battery by 800 volts of direct current (DC) as well as a control signal of 24 volts. Inside the ESC, direct current (DC) is then converted to alternative current (AC). The main components are shown in figure 2 below.

The ESCs have a minimum of 95% efficiency during normal operating according to the manufacturer when using a power of 50kw. Therefore, the total cooling requirement for two ESCs will maximum be 5kW, $(50 * 0{,}95 * 2 = 5)$. Thus, with a power of 50 kW and an efficiency of 95% distributing two ESC's 95kw becomes usable power rest becomes a loss in the form of heat.
The controllers optimum drive temperature is 45°C, with an allowable maximum temperature of 65°C. The ESC's have built-in cooling channels as well as coolant input and output. The manufacturer calculates the coolant flow rate to be 8 l/min and will be composed of equal parts water and glycol.

Figure 2
Main components in the electronic propulsion system.



Note: The illustration is created by the authors.

4.1.3 Functional requirement specification

The functional requirement specification has different ratings. Each function is rated with, MF for main function, D for demand, W for wish and U for unwanted function.

Requirements and functional specifications were designed in collaboration with SSRS and are presented in table 1 below.
Features that have been classified with W have also been given a weight factor depending on how strong the desire is. Ranging from 1 to 5 where 1 is low and 5 is high.

Table 1
Functional requirement specification.

Functional requirement specification		
Function	Class	Note
Main Function		
Cooling of the electronic speed controllers.	MF	Always required
Secondary function:		
Transportation of cooling fluid:	D	With hoses and pump
Transfer heat from one side to another:	D	
Support function		
Waste heat recovery	W -3	Heating of, for example, handles.
Energy efficient:	W -4	
Reliability:	W -5	
Life cycle concerns	W- 3	Maintainability Diagnosability Reparability
Ease of controlling and sensing state	W - 3	Monitoring equipment
Appearance	W - 2	
Unwanted features		
Increase in weight	U	
High cost	U	
Increased maintenance	U	
Design changes	U	

4.2 Problem solving

In this section the results from the catalog method and the concept generation where morphological matrix where used will be present. The results will then be evaluated in the next chapter.

4.2.1 Catalog method

There are different types of heat exchanges on the market in different designs and configurations. This section research existent cooling systems for boats to encourage a creative thinking. Volvo Penta delivers a wide range of diesel engines for conventional boats. Below follows a fundamental explanation of one of their cooling systems.

Volvo Penta uses a freshwater system for their D4-175 3.4-liter diesel engine with a power output on the crankshaft of 129kW. The heat exchanger is mounted directly on the engine itself and exchanges heat from seawater to freshwater by a tubular heat exchanger. The seawater is delivered with an impeller pump mounted on the engine which runs from the drive belt on the engine. There is also a seawater filter mounted on the engine which must be regularly checked otherwise there is a risk that the filter gets clogged, resulting in the engine overheating. (*Manuals & Handbooks | Volvo Penta*, n.d.)

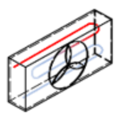
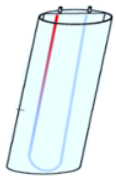
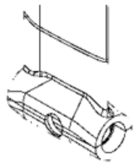
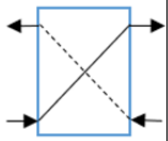
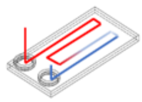
There are some different electric-driven boats on the market that have been compared and analyzed with each other. Candela is a hydrofoil boat with similar propulsion engines to SSRS's new building boat. X-shore and RAND are other brands that deliver electric boats, but they are not of hydro-foil type. During this process pictures of these boats and the designs have been studied to get a better understanding of how cooling systems might be implemented. Due to the limited number of companies delivering electric-driven hydrofoil boats the research during this process has been bounded.

Note: Other diesel driven engines then the Volvo Penta has not been more thoroughly investigated because they usually involve seawater and are rather similar to each other. Furthermore, diesel driven engines demands different cooling capacities and operating temperatures then the ESC for this project.

4.2.2 Concept generation

The different concept was generated by using a morphological matrix where different subfunctions added up to one concept. There are six different concepts in six different colors shown in table 2. The concepts were generated by first deciding one general cooling design of the heat exchanger and then deciding where it could be mounted, how to mount it, and what material it should be manufactured in. The subfunctions were made by identifying different problems and opportunities for the cooling system of the SSRS hydro-foil boat.

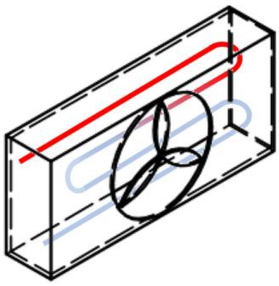
Table 2
Morphological matrix.

Subfunction	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Cooler design	Air to water	Water to water block	Coil with water filed mast	Integrated cooling channels in the engine casing.	Plate heat exchanger	Keel cooling
						
Location of cooler	Deck	Foil mast	Engine casing	Integrated	Hull underside	
Connection	Bolt/Screw	Welding	Gluing			
Material	Copper	Aluminum	Mix			

Concept “Blue”

This concept is based on a heat exchange between air to water where an electric driven fan is drawing air across a radiator with cooling liquid circulating in it using a pump. See figure 3 below. The heat exchanger will be mounted on the deck either close to the ESC or somewhere else where it could be protected. The air takes up heat from the cooling fluid and afterward, it can be used for defrosting the windscreen on the boat or for other heating purposes. If there is no need for waste heat recovery the warm air could just be ventilated to the outside. The heat exchanger will be manufactured in aluminum to make it light weight.

Figure 3
Concept ”Blue”.

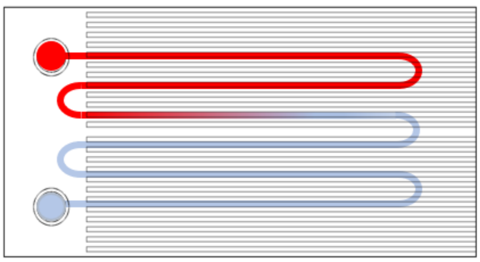


Note: figure created by the author.

Concept “Green”

This concept will use the area inside the engine casing between the two electric-driven motors and the propellers to exchange the heat from the ESC. The engine casing is always under the seawater, and it will be a flow of seawater through the engine casing when the vessel is making speed. This makes is possible to design a heat exchanger in this area and use the seawater for cooling purposes. This area is small and already complicated with different important parts such as three-phase cables to the electric motors, and a strut for adjusting the angle of the foil wings and the propeller shaft. The cooling system for the heat exchange must therefore be efficient and small. In this concept, there will be a block heat exchanger at the bottom of the engine casing. Figure 4 below is a layout of a block heat exchanger.

Figure 4
Concept “Green”.

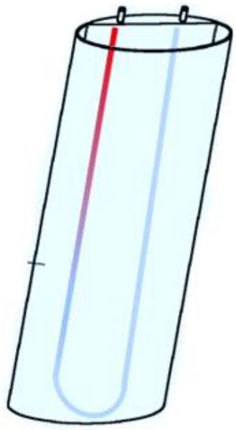


Note: figure created by the author.

Concept "Red"

SSPA, a maritime engineering consultancy, is a project partner of SSRS and has played a crucial role in providing design and solution for the hydrodynamics of the vessel. Throughout the project, SSPA has provides essential information and expertise regarding the hydrofoil design. During a conversation with SSRS and SSPA there were an idea of designing the hydro-foil mast to achieve a seawater flow inside the mast. The contact with SSPA during this project has been throughout email and a meeting at SSPA's head office. SSPA designs the foil mast and the engine casing for this boat. If there is a seawater flow inside the mast, there is an opportunity to use the area inside the mast for a heat exchanger. In this concept, the heat exchanger consists of a circular pipe in an eclipse coil pattern to match the inside area of the mast. By using the design of a coil there will still be possible to run the cables to the propulsion engines and a strut for adjusting the angle of the foil wings in the mast as well. The piping will be connected to the inside of the carbon fiber mast by fasteners that are glued to the mast. Figure 5 illustrates a simplified sketch of the mast to which the hydrofoil wings are connected.

Figure 5
Concept "Red".

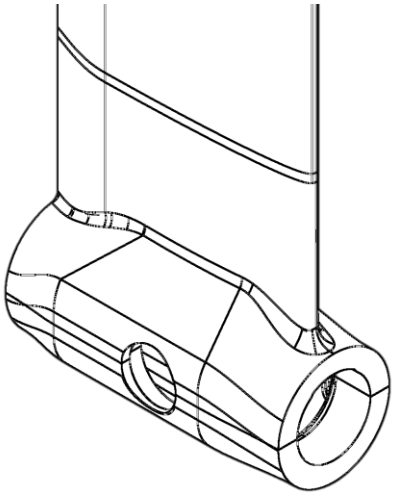


Note: figure created by the author.

Concept "Orange"

In this concept the engine casing between the two electrical motors will be the heat exchanger and will have integrated channels in the construction. The engine casing connects to the two electrical motors together with two propellers and the aft hydrofoil wing, figure 6 below illustrates the engine casing. The engine casing is manufactured in aluminum which has a thermal conductivity of 237 W/m·K, (Çengel et al., n.d.). The engine casing is always surrounded by seawater and will also have a flow of seawater through itself when the vessel is making speed. The engine casing is already complex and the area where integrated channels could possibly be implemented is limited. However, the integrated channels in the engine casing are an opportunity to achieve a heat exchange without using a separate heat exchanger and therefore this solution will be advantageous in several aspects. One of the challenges with this solution is to design the integrated channels in a way where it is possible to manufacture them without getting too expensive. The channels in this concept must therefore be drilled and milled out in the aluminum casing and not molded.

Figure 6
Concept "Orange".

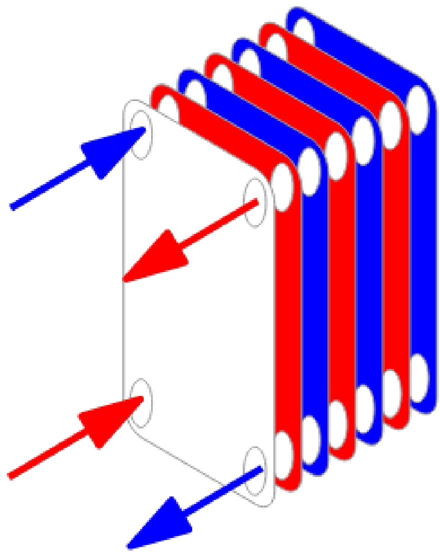


Note: figure created by the author.

Concept "Grey"

Concept "Grey" refers to a plate heat exchanger that is commonly used on conventional vessels to cool fluids. In this concept, seawater is pumped onboard through a pipe that passes through the mast for the hydrofoil at the aft and is then pumped overboard. The plate heat exchanger is mounted on the aft deck and is protected by a housing. It is bolted down to the deck to ensure stability.

Figure 7
Concept "Grey".

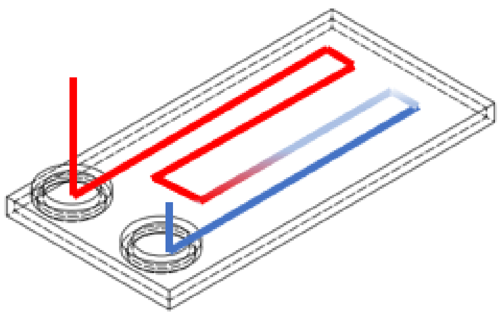


Note: CC-licensed (*File:Plate Frame 1.Svg - Wikimedia Commons*, n.d.).

Concept "Purple"

The idea of this concept comes from an existing cooling solution for vessels which is called keel cooling. Keel cooling is when the heat exchanger is mounted under the boat and therefore has direct contact with the seawater. Keel cooling systems is often simpler and cheaper than plate heat exchange systems because of cost of pumps and piping is saved. (Aijjou et al., 2018). Onboard a hydro-foil vessel the hull will not have contact with the water when foiling and neither will a keel cooling heat exchanger. This means that the heat exchanger in this concept must be designed to achieve the necessary heat exchange when it has contact with the seawater and when foiling with the air from making speed. The heat exchanger will be bolted under the hull of the boat, and it will be mounted to minimize the air and water resistance. Below follows figure 8 which is a concept design of a possible heat exchanger which could be mounted under the keel.

Figure 8
Concept "Purple".



Note: figure created by the author.

4.3 Evaluation of concept generation

This section presents the results of the completed concept generation work. First, the relative decision matrix is presented, which outlines the key factors and criteria used to evaluate each concept. Next, the weight determination matrix is shown, which assigns weights to each criterion based on their relative importance. Finally, the criteria weight matrix is presented, which combines the results of the previous two matrices to provide a comprehensive evaluation of each concept.

4.3.1 Relative decision matrix – Pughs

To be able to compare the different concepts against each other multiple Pugh matrixes with different reference concepts were done and are in this section presented.

The choice of criteria used in the Pugh matrix was determined by a combination of what was considered most important in the requirements and functional specifications. The criteria were then reduced to create a relevant and effective evaluation. The Pugh matrix is a tool used to evaluate and compare multiple concepts against a reference concept, based on a set of predetermined criteria. After the initial evaluation using the Pugh matrix, the results show that concepts "Blue", "Red", and "Orange" are preferable to the first reference concept. These concepts will be further evaluated and compared to one another, as shown in Table 3.

Table 3
Pugh matrix 1.

Criteria	Reference concept	Concepts				
	Plate heat exchanger	Blue	Green	Red	Orange	Purple
Effective heat transfer A		-	-	-	-	-
Minimize of design changes B		0	-	0	-	-
Low weight C		0	0	0	+	0
Minimize maintenance D		+	+	+	+	-
∑ +		1	1	2	2	0
∑ 0		2	1	2	0	1
∑ -		1	2	1	2	3
Net		0	-1	0	0	-3
Ranking		1	3	1	1	4

Concept "Blue" was chosen as the reference concept in the following evaluation, and the results are shown in table 4 below. Concepts "Green", "Red", and "Orange" come out on top, and "Purple" being considered worse than concept "Blue". Although indications of which concepts could be the best are now being given, evaluation continues.

Table 4
Pugh matrix 2.

Criteria	Reference concept	Concepts			
	Blue	Green	Orange	Red	Purple
Effective heat transfer A		+	+	+	-
Minimize of design changes B		-	-	-	-
Low weight C		+	+	+	-
Minimize maintenance D		0	0	0	-
∑ +		2	2	2	0
∑ 0		1	1	1	0
∑ -		1	1	1	4
Net		1	1	1	-4
Ranking		1	1	1	2

In the final pugh matrix concept "Green" is the reference concept. The net result for concept "Red" and "Orange" is 1, indicating that it outperforms concept "Green". The net result for concepts "Blue" is -1 indicating it assumed to be worse than the reference concept "Green". Concept "Purple" receives a net result of -3. The concept's ranking is shown in table 5 below.

Table 5
Pugh matrix 3.

Criteria	Reference concept	Concepts			
	Green	Blue	Orange	Red	Purple
Effective heat transfer A		-	0	0	-
Minimize of design changes B		+	-	+	0
Low weight C		-	+	0	-
Minimize maintenance D		0	+	0	-
∑ +		1	2	1	0
∑ 0		1	1	3	1
∑ -		2	1	0	3
Net		-1	1	1	-3
Ranking		2	1	1	4

4.3.2 Weight determination matrix

The result from the weight determination matrix is presented in this section. Here, the importance of each criterion has been determined.

To determine the importance of each criterion, their priorities for SSRS are considered. Table 6 below shows that criterion A (Effective heat transfer) and criterion B (Minimize design changes B) are the most important.

Table 6
Weight determination matrix.

Criterium	A	B	C	D	Sum	Sum/Tot
Effective heat transfer A	-	0,5	1	1	2,5	0,417
Minimize of design changes B	0,5	-	1	1	2,5	0,417
Low weight C	0	0	-	1	1	0,167
Minimize maintenance D	0	0	0	-	0	0,000
				Tot	6	1,000

Note: The weight determination matrix is an essential component of Pugh's matrix, providing a systematic way to assign relative importance to the evaluation criteria. It aids in comparing design alternatives and plays a key role in the decision-making process.

Scale weight factors are used to facilitate evaluation in the criterion weight matrix. As shown in table 7.

Table 7
Scale weight factor.

Criterium	Sum/Tot	Scale 1-5 weight factor (WI)	Scale 1-10 weight factor (wi)
Heat transfer A	0,417	5	10
Minimize design changes B	0,417	5	10
Weight C	0,167	4	8
Minimize maintenance D	0,000	3	6

4.3.3 Criteria weight matrix

After the evaluation with the criteria weight matrix, the selection of concept can be done. Each concept received a value "v" for how well it is considered to meet the criterium. 10 is considered high and that the concept meets the criterion in the best way. 0 is the opposite. The value "t" is then obtained by multiplying "v" by the weight factor.

The Kesselring matrix in table 8 below shows the following ranking: 1^{st} place concept “Blue”. 2^{nd} place concept “Orange”, 3^{rd} place concept “Red”, 4^{th} place concept “Green” and 5^{th} place concept “Purple”.

Concept “Blue” stands as the winner as shown in the matrix and the next step is to determine how the concept can be implemented. However, the project will also choose to make a further analysis of how concept “Orange” could be implemented. This is due to the great variation between the two concepts “Blue” and “Orange”. Also, concept “Orange” provides the best cooling capacity in relation to weight if design changes are disregarded.

Table 8
Kesselring.

Criterium		Ideal		Blue		Green		Red		Orange		Purple	
	weight factor	v	t	v	t	v	t	v	t	v	t	v	t
Effective heat transfer A	10	10	100	7	70	9	90	9	90	9	90	8	80
Minimize of design changes B	10	10	100	10	100	3	30	5	50	2	20	4	40
Low weight C	8	10	80	5	40	5	40	6	48	10	80	6	48
Minimize maintenance D	6	10	60	6	36	7	42	7	42	8	48	7	42
T=∑t			320		246		202		230		238		210
T/Tmax			1.0		0,76875		0,63125		0,71875		0,74375		0,65625
Ranking					1		4		3		2		5

4.4 Detailed construction

Concept “Blue” and “Orange” will in the following sections be more accurately defined and designed using CAD drawings and figures. The concepts material properties and the coolant properties will be selected to evaluate the concepts cooling capacities in section 4.4.1.

Properties of coolant:

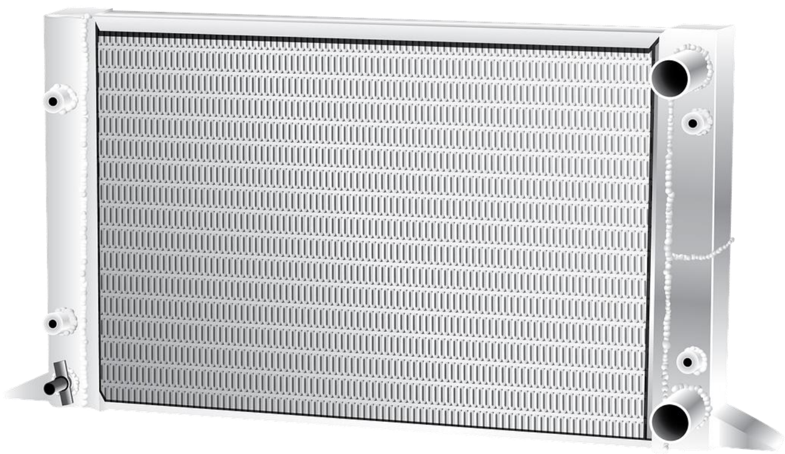
The cooling fluid has been determined by the manufacturer of the ESCs and will be a blend of 50 % water and 50 % ethylene glycol which has a specific heat capacity of cp=3.534 kJ/kg°C, density of 1067 kg/m3 and a viscosity of 0,0065 kg/ms at 40°C (*Ethylene Glycol Heat-Transfer Fluid Properties*, n.d.). The volume flow of the coolant will be 16 l/min through the heat exchanger and coolant line will split before the two ESCs to deliver 8 l/min to each. The velocity of the coolant will be added with help of a dynamic electric driven pump. The cooling system will include an expansion tank to manage the heat expansion of the coolant. It may also be some sort of temperature sensor to monitor the temperature and control the water pump to save energy. The control of the pump may be implemented by using a temperature on and off switch which allows the pump to run only when there is a cooling demand.

Properties of concept "Blue":

There are lots of air-to-water heat exchangers on the market in different configurations to meet different needs. For SSRS it is important to keep the weight and size down of the radiator to be able to implement it onboard the lifeboat, therefor the radiator will be manufactured in aluminum. Furthermore, a lot of high-performance radiators for vehicles on the market are made of aluminum which often is inexpensive compared to manufacturing a custom radiator. Aluminum weighs 30 percent lighter than copper but the thermal conductivity is 60 percent less than copper (*Copper vs. Aluminum Heatsinks: What You Need to Know*, n.d.). The radiator will have an efficient heat sink design to get a larger heat transfer area which makes the radiator more efficient (Lee, 2010). The convection of air will be forced with an electrically driven high-performance fan. Here follows some example data from a high-performance radiator fan; the fan delivers a volume of max 3320 m^3/h, weighs 2,57 kg, and has a power consumption of 260 Watts (*Spal Kylfläkt 385mm Tryckande - Värsting*, n.d.). The electric fan may be controlled by a temperature switch to save energy which allows the fan to run only when there is a cooling demand. The overall heat transfer coefficient in an air-to-water heat exchanger is approximately somewhere between 600 and 750 $W/(m^2/K)$ (*Heat Exchangers - Heat Transfer Coefficients*, n.d.). The calculation will assume an overall heat transfer coefficient of 600 $W/(m^2/K)$ to rather oversize the required heat transfer area than dimension a radiator that does not fulfill the cooling demand. Figure 9 shows an illustrated picture of a typical aluminum air-to-water radiator.

Figure 9

Aluminum air-to-water radiator.



Note: CC-licensed (Radiator Kyla Mellanliggande - Gratis Bilder På Pixabay, n.d).

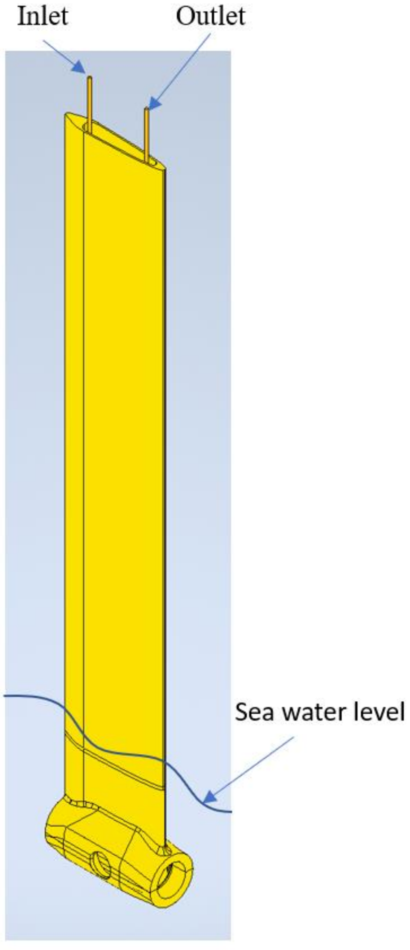
Properties concept "Orange":

The engine case is fully made of aluminum, and it is manufactured in two pieces that will be bolted together, see figure 10 and 11. These two pieces will be CNC-milled and aluminum pipes alternative some sort of hoses for coolant will be connected to the upper piece of the engine case. There will be coolant channels in the engine case that will be drilled and milled out, see figure 12 and 13. Due to the coolant channels that will be drilled out it might be some holes in the upper section of the engine case that must be plugged when manufacture it. The cooling channels in the engine case will have a minimum gods material thickness of 1 mm to keep the engine case as strong as possible, therefor the cooling channels are limited to a diameter of 7 mm. The two engine case pieces will have a thin layer of gasket silicone in between before they are bolted together to avoid leakage from coolant fluid or sea water from escaping into the cooling system.

Below follows some figures of the design of the engine case and its cooling channels with a circuit diagram of the fluid. The engine case is a bit simplified in the figures to be able to see the cooling channels and the flow path more easily.

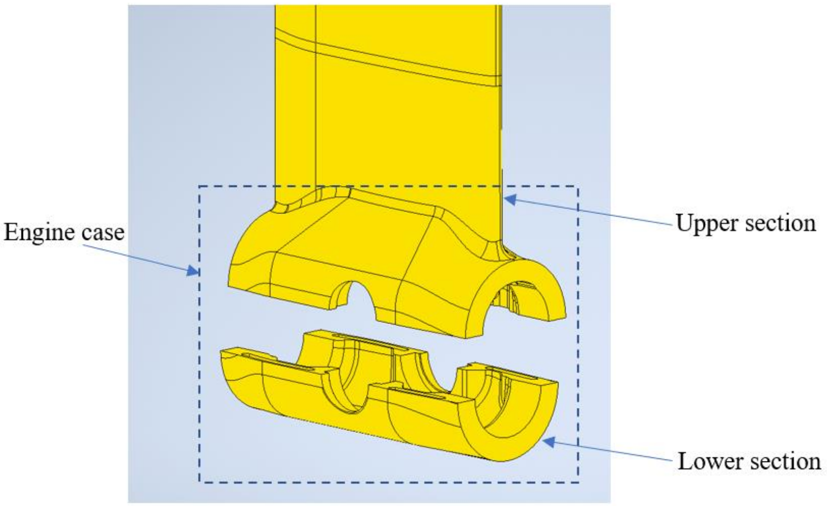
Figure 10

Overall design of the foil mast and the engine case.



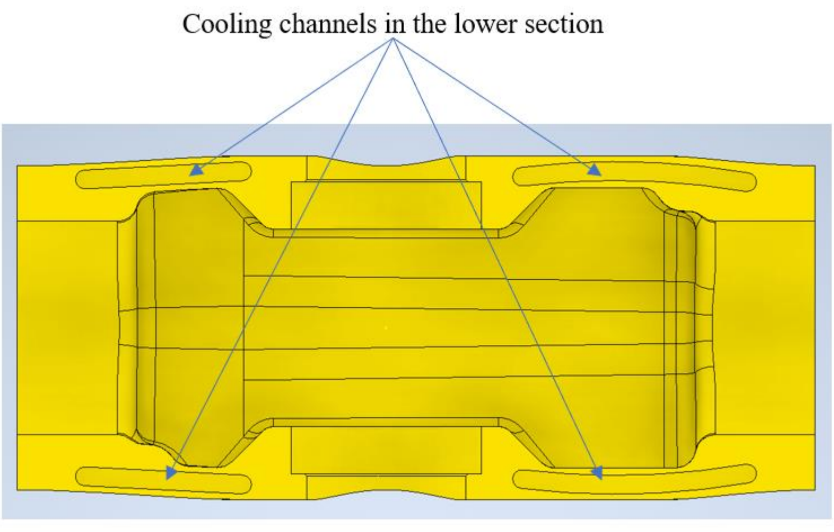
Note: CAD drawing provided by SSRS and edited by the authors.

Figure 11
Engine case, upper and lower section.



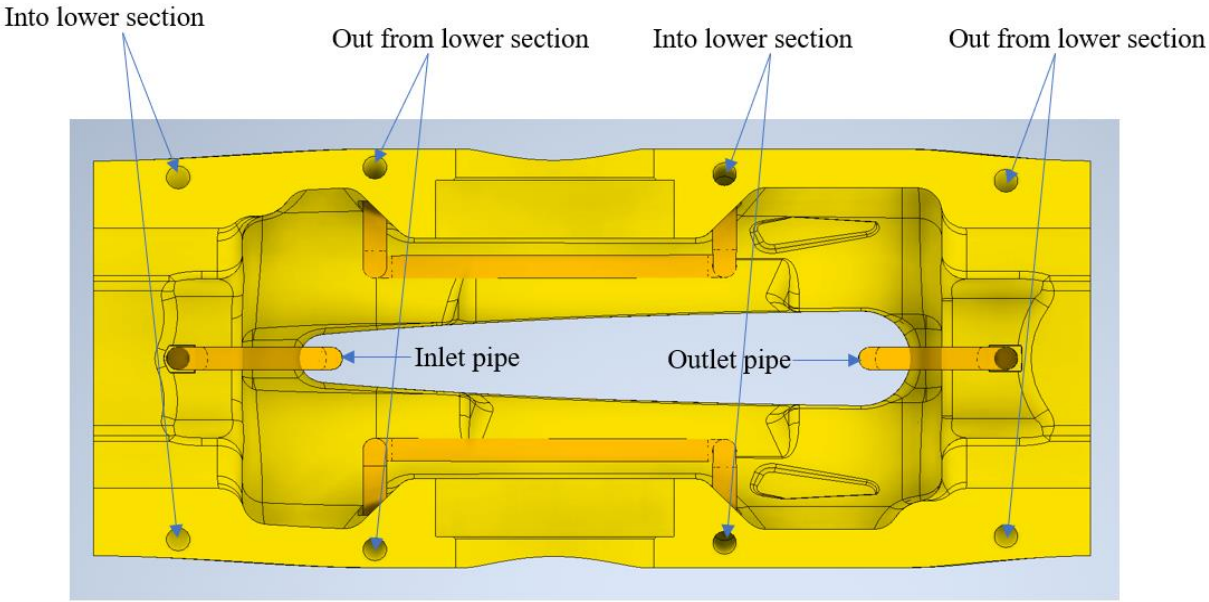
Note: CAD drawing provided by SSRS and edited by the authors.

Figure 12
Lower section of engine case.



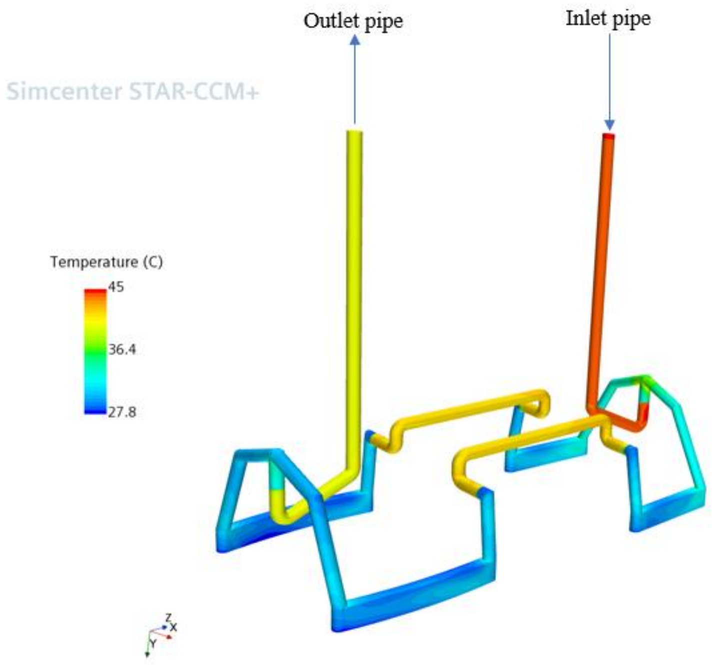
Note: The figure is provided by SSRS and edited by the authors

Figure 13
Upper section of engine case.



Note: CAD drawing provided by SSRS and edited by the authors.

Figure 14
Coolant fluid simulation diagram, the colors represent the surface temperature of the coolant.



Note: The figure is from a CFD simulation in STAR CCM+ done in collaboration with SIGMA Energy and Marine.

Material properties of aluminum:

Table 9
Properties of aluminum.

ρ_{Au}, kg/m3	Cp_{Au}, J/kg·K	k_{Au}, W/m·K
2702	903	237

(Çengel et al., n.d.)

4.4.1 Evolution of detailed construction

Concept “Blue” and “Orange” will in this section be evaluated using thermodynamic calculations and with a CFD simulations.

Heat loads determine of the ESC.

Equation 1:

To determine the difference in inlet and outlet temperature of the coolant the ΔT_w *is calculated.*

$$\Delta T_w = \frac{Q_r}{F_w * \rho_w * Cp_w} \qquad (1)$$

(Çengel et al., n.d.)

Table 10
Known figures for equation 1.

Q_r, kW	F_w, l/s	ρ_w, kg/dm3	Cp_w, J/kg·K
5	≈ 0,267	1,067	3,534

Calculation 1

$$\Delta T_w = \frac{5}{0{,}267 * 1{,}067 * 3{,}534} \approx 4{,}97℃$$

Comments:

The ESC operation temperature is 45℃ and therefore the inlet temperature to the ESC should be 40℃ with a ΔTv ≈ 4,97℃. Furthermore, this means that the inlet temperature to the heat exchanger is 44,97℃ and the outlet temperature from the heat exchanger must be maximum 40℃.

Evolution of concept "Blue"

Equation 2:

To determine the difference in inlet and outlet temperature of the cooling air the ΔT_a is calculated.

$$\Delta T_a = \frac{Q_r}{F_a * \rho_a * Cp_a} \tag{2}$$

(Çengel et al., n.d.)

Table 11

Known figures for equation 2.

Q_r, kW	F_a, l/s	ρ_a, kg/dm3	Cp_a, J/kg·K
5	≈ 922	0,00128*	1,006*

*These values come from this source (Çengel et al., n.d.)

Calculation 2

$$\Delta T_a = \frac{5}{922 * 0{,}00129 * 1} \approx 4{,}2℃$$

Equation 3:

To determine the logarithmic mean temperature difference between the coolant and the cooling air.

$$\Delta T_{ln} = \frac{(T_{inhot} - T_{outcold}) - (T_{outhot} - T_{incold})}{ln\,[\frac{T_{inhot} - T_{outcold}}{T_{outhot} - T_{incold}}]} \tag{3}$$

(Çengel et al., n.d.)

Table 12

Known figures for equation 3.

T_{incold}, ℃	$T_{outcold}$, ℃	T_{inhot}, ℃	T_{outhot}, ℃
35*	39,2	44,97	40

Note*: *This figure is the air temperature outside a hot summer day in Sweden.*

Calculation 3

$$\Delta T_{ln} = \frac{(44{,}97 - 39{,}2) - (40 - 35)}{ln\,[\frac{44{,}97 - 39{,}2}{40 - 35}]} \approx 5{,}38℃$$

Equation 4:

To determine the heat transfer surface area required.

$$A_r = \frac{Q_r}{U_r * \Delta T_{ln}} \quad (4)$$

(Çengel et al., n.d.)

Table 13

Known figures for equation 4.

Q_r, W	U_r, W/(m^2 / K)	ΔT_{ln}, °C
5000	600*	5,38

Calculation 4

$$A_r = \frac{5000}{600 * 5{,}38} \approx 1{,}55 \text{ m^2}$$

Comments: The result from calculation 4 signifies that the two ESC:s need one air-to-water radiator with a heat transfer surface area of ≈1,55 m^2 to manage the cooling demand when the outside air temperature is 35°C. This result is based on the decided parameters for cooling airflow, coolant flow, and the total heat transfer coefficient for the radiator; if any of these parameters is changed the heat transfer surface area will also change. In addition, there is an alternative solution that is worth considering to minimize the heat transfer area. The alternative solution involves using a more effective cooling medium than air, which can significantly reduce the heat transfer surface area.

Evolution of concept "Orange"

The concept "Orange" was evaluated using a CFD simulation performed by a professional CFD computational engineer at SIGMA Energy and Marine. A surface mesh of the 3d model of concept "Orange" was done in the computer program ANSA pre-processor before the simulation was done in the computer program STAR CCM+. The coolant's boundary conditions were added, and the initial condition for the solids was set to 25°C. A volume mesh of the model was created, and calculations for the heat transfer coefficient were added to the solid parts and the coolant. The simulation was done to simulate the outlet temperature of the coolant when the sea temperature is 25°C. The seawater was simulated to have a velocity of 15,43m/s corresponding to the rescue boat making the speed 29,16 knots. The simulation was done in a steady state, meaning there is no value of time in the simulation. Instead, several iterations were performed until the simulated value stabilized.

Calculations of heat transfer coefficient

The following equation below (equation 5-10) was made to provide the thermal resistance of the engine casing to provide the value for the CFD simulation. The calculation was done by a computational engineer at SIGMA Energy and Marine.

Equation 5:

To determine the velocity of the coolant.

$$\nu_w = \frac{F_w}{A_p} \quad (5)$$

(Çengel et al., n.d.)

Equation 6:

Reynolds number, Re.

$$Re = \frac{\rho_w * \nu_w * D_p}{\mu_w} \quad (6)$$

(Çengel et al., n.d.)

Equation 7:

Prandtl number, Pr.

$$Pr = \frac{\mu_w * Cp_w}{k_w} \quad (7)$$

(Çengel et al., n.d.)

Equation 8:

Nusselt number, Nu.

$$Nu = 0{,}664 Re^{1/2} * Pr^{1/3} \quad (8)$$

(Çengel et al., n.d.)

Equation 9:

Heat transfer coefficient, h_e.

$$h_e = \frac{Nu * k_{Au}}{l_e} \quad (9)$$

(Çengel et al., n.d.)

Calculations of thermal resistance

Equation 10:

Thermal resistance, R_e.

$$R_e = \frac{L_e}{h_e * A_e} \quad (10)$$

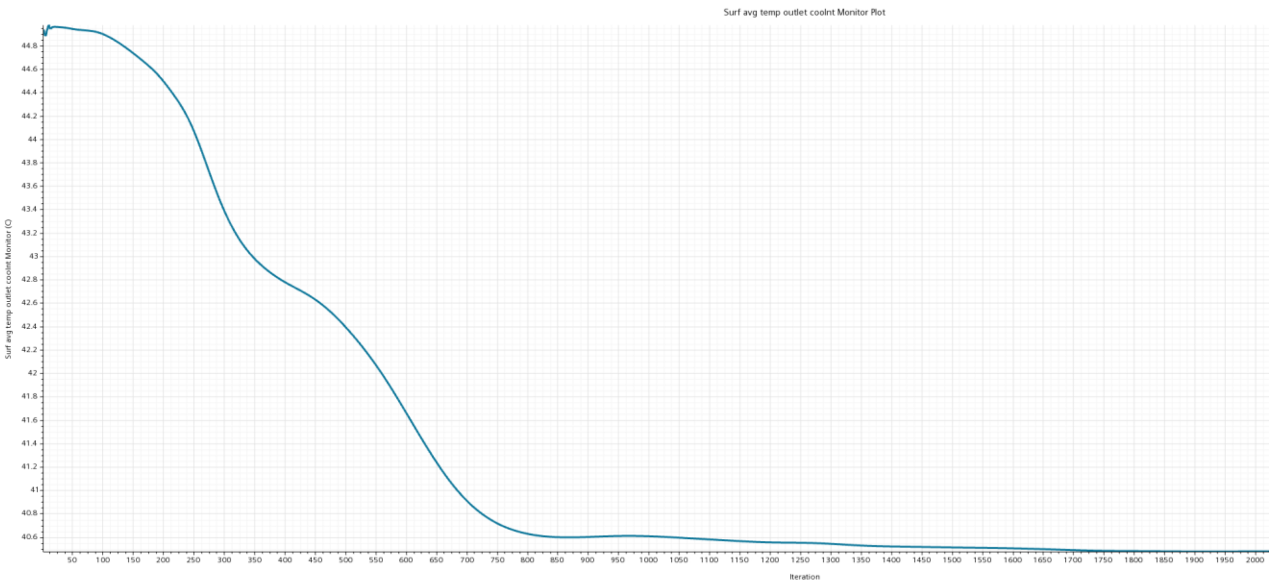
(Çengel et al., n.d.)

Figures from the simulation

Figure 15 shows the coolant outlet temperature for the simulation, the coolant temperature was set to 45°C at the start of the simulation. The diagram shows the surface average temperature of the outlet on the y-axle and the number of iterations on the x-axles. The coolant flow was set to 16 l/min. The simulation iteration was done until the result had stabilized, giving the result of a surface average temperature at the outlet at 40,2°C. Figure 15 and 16 indicates the surface temperature of the engine casing and the hoses for the coolant from the CFD simulation. The inlet temperature to the ESC should be 40°C known from equation 1 and the outlet temperature from the engine casing cooling channels is 40,2°C, which is 0,2°C higher. However, the simulation only investigated the heat exchange inside the engine case but, there will probably be some exchange of heat inside the mast as well. The hoses for the coolant had in this simulation a high thermal resistance to simulate that they were made of rubber. The result would be better if they were manufactured in aluminum pipes with lower thermal resistance to achieve a more beneficial heat exchange.

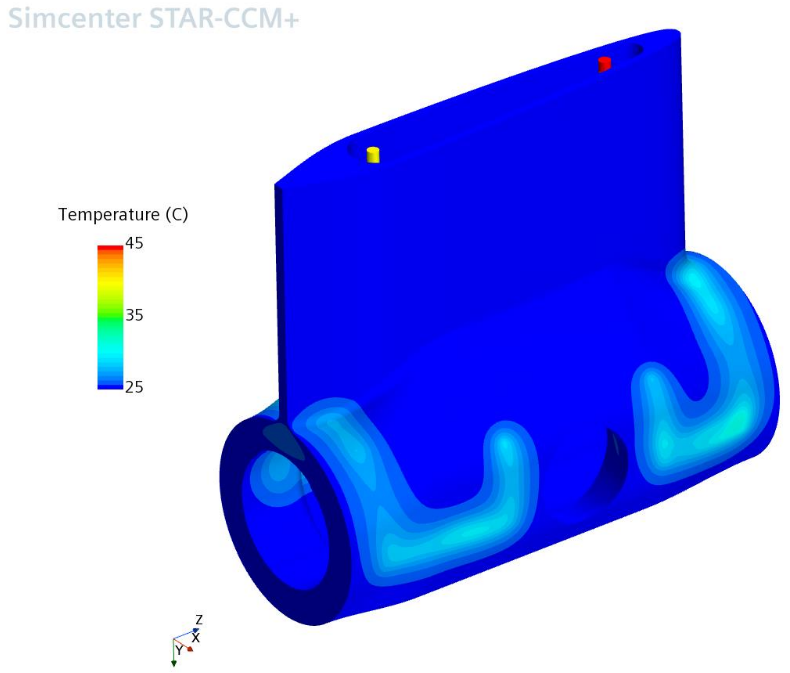
Figure 15

The surface average temperature at the outlet



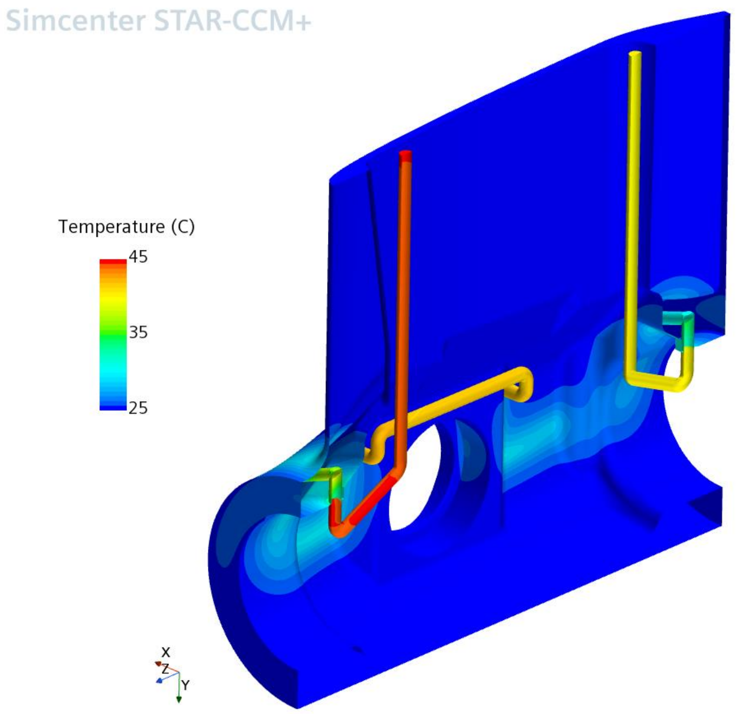
Note: The figure is from a CFD simulation in STAR CCM+ done in collaboration with SIGMA Energy and Marine.

Figure 16
Surface temperature indication



Note: The figure is from a CFD simulation in STAR CCM+ done in collaboration with SIGMA Energy and Marine.

Figure 1
Surface temperature indication



Note: The figure is from a CFD simulation in STAR CCM+ done in collaboration with SIGMA Energy and Marine.

5. DISCUSSION

This chapter discusses the results of the study and how they connect to the research questions. A discussion about the method used in this study and how it was applied to the research question is also included.

5.1 Discussion of the outcome.

This study aimed to develop a solution for how a cooling system for ESC’s can be designed and implemented on board a hydrofoil boat. The work has resulted in two proposed solutions regarding the implementation of cooling systems for ESC’s. The concept development has been carried out regarding the requirements that SSRS imposes on design and cooling needs for their ESC’s. The cooling equipment has been carefully dimensioned to ensure reliable operation, even during the most extreme weather conditions, such as the warmest days of summer. As mentioned in the background it is crucial for SSRS to operate under diverse weather conditions. In the calculations and analysis presented in the results section, we specifically accounted for a reference air temperature of 35 degrees Celsius. This temperature selection allows us to assess the performance and capabilities of the cooling equipment under challenging operating conditions.

The work has generated two winning concepts that can be implemented to ensure the cooling needs onboard in accordance with the first point of the research question.

The reason why two concepts have been chosen to highlight is related to the second point. The second point of the research question aims to answer which cooling system is most effective and best to implement onboard SSRS’s new foil rescue boat. Since both concepts “Blue” and “Orange” will be able to ensure the cooling needs, it will be the factors of low weight and minimization of design changes that will be decisive. It is interesting that these factors seem to have a negative correlation with each other. The concept “Blue”, which includes an air-to-water radiator, provides the lowest degree of design changes but will negatively affect weight and take up a lot of space relative to the size of the boat. The concept “Orange”, where major design changes need to be made, also provides the lowest weight.

The models in the result regarding the concept “Orange” have been developed through construction work in the CAD program inventor and have been thermodynamically analyzed in the CFD program Star CCM+. Since neither CAD construction nor CFD analysis has been included in the marine engineering program, this knowledge has been provided through help from SIGMA Marine and Energy.

5.2 Solutions to exclude.

This work has chosen not to investigate any possible solutions when involving taking onboard seawater for cooling purposes as most conventional boats do. This is to see if alternative solutions that do not include seawater onboard can be used to avoid filters, multiple water pumps, maintenance, and the risk of the seawater filter becoming clogged. The exclusion of seawater was also made due to the system's sensitivity to corrosion and fouling for minimizing the required maintenance of the system. However, as mentioned in the results section, the use of seawater as a cooling medium can be an alternative solution to consider.

Seawater can be a promising approach to minimize the heat transfer area since it provides excellent cooling capacity and can significantly reduce the size of the heat exchanger. Although we acknowledge the potential of seawater as a cooling medium, we decided to focus on other alternatives for this particular project due to limitations in time and resources.

5.3 Discussion of method

The choice to use different methods in the product development process is a common approach. This is because the development process is divided into several stages, each with its own characteristics and needs to be addressed accordingly. The use of recognized and proven methods for the different stages of product development argues for the validity of the study. A negative aspect that concerns the chosen methods is the limited availability of scientific sources within the subject. Another disadvantage of product development is the limitation of similar existing solutions for cooling ESC onboard hydrofoil boats. In the marine industry, boats with electric propulsion and hydrofoil construction are unusual and there are few manufacturers. The technology is relatively unexplored and there are no standardized solutions in the same way as for traditional boats. The sources of the work were assessed for credibility and relevance.

A positive aspect that has contributed to broader insight and facilitated the reliability of the results is that continuous dialogue has been conducted with SSRS, supervisors, and engineers at SIGMA Marine and Energy. These dialogues have also provided support in the developing process and have been able to prove that the developed concepts have relevance.

5.4 Sources of error

During concept development, there is a risk that various sources of error will affect the results of the work. One possible source of error that should be considered is the outdoor temperature, which can significantly impact the cooling capacity. It is important to note that the temperature interval extends up to 35 degrees Celsius, as this represents the extreme conditions that may challenge the cooling system's effectiveness. In concept “Blue”, a temperature on the cold side has been assumed to be 35 degrees, which is a high temperature for air in Swedish conditions. The high temperature contributes to the fact that the area of the radiator must be increased. This could lead to the radiator being oversized and unnecessarily large.

The overall heat transfer coefficient assumed for air-to-water radiators is taken from a table with generally estimated values and has thus not been fully verified. It is also important to note that CAD constructions are exemplary solutions, and a final design may look different. The work has assumed that the cooling water absorbs all produced heat in both ESCs, but the heat will also be emitted through radiation. This can in turn lead to over-dimensioned heat exchangers.

6. CONCLUSION

This research aimed to develop and identify the best possible cooling system for electronic speed controllers onboard a hydrofoil rescue vessel. Based on the project’s methodology to develop a cooling system, it can be concluded that weight and size are important factors to consider when designing a cooling system for a hydrofoil boat. One of the most significant findings from this study is that sufficient cooling capacity can be achieved by using the engine casing and the foil mast like in the concept “Orange”. According to the study's findings, weight and design changes are negatively correlated. In SSRS's case, weight plays a major role and the space for an air cooler is limited. Therefore, the concept “Orange” would be the most effective system for SSRS according to this research. However, the concept of using a water-to-air radiator like in the concept “Blue” has some advantages even then it will probably be hard to fit on SSRS rescue boat. A water-to-air radiator is readily available on the market which makes it easier to implement and it is an affordable choice.

To enhance the validity of this study, a comprehensive feasibility study was conducted during the initial stages. This involved conducting an accurate analysis of the existing market for electrically driven hydrofoil vessels and thoroughly examining the designs and technologies used in cooling systems for ESC’s. By gathering relevant background material and critically reviewing technical solutions, a solid foundation was established for problem analysis and solution development.

In the problem determination phase, various methods were employed to characterize the problem and gain a deeper understanding of its nature. The question method was utilized to systematically explore the problem through well-formulated questions, enabling a comprehensive examination of its different aspects. Additionally, situational determination involved conducting site visits and engaging in conversations to gather firsthand information and observations. These approaches contributed to a comprehensive problem description and a more accurate problem-solving process.

During the problem-solving phase, two methods were employed to generate a wide range of concepts for the cooling system. The catalog method involved seeking inspiration and information from relevant literature, catalogs, and the internet, ensuring that existing solutions and approaches were considered. Additionally, the morphological matrix technique was used to systematically combine partial solutions, resulting in the creation of multiple concept options. By employing these methods, a diverse set of potential solutions was explored, reducing the risk of overlooking innovative or effective approaches.

In the evaluation, assessment, and choice of concept phase, the decision matrix method, specifically Pugh's method, was utilized. This provided an objective and systematic approach to compare the concepts against a reference solution and evaluate their performance based on predetermined criteria. The weight determination matrix was developed to assign appropriate weight factors to each criterion, ensuring a fair and accurate evaluation of their relative importance.

It is important to note that throughout the study, close collaboration was maintained with our supervisor from SIGMA Energy and Marine, who provided valuable guidance and insights. Additionally, ongoing discussions were held with the SSRS, allowing for the incorporation of their perspectives and practical considerations into the research process.

In summary, by conducting a comprehensive feasibility study, employing rigorous problem determination and solution development methods, and actively involving our supervisor from SIGMA Energy and Marine, this study aimed to enhance its validity and reliability. The critical analysis of existing designs and technologies, the systematic exploration of potential solutions, and the collaboration with stakeholders contribute to the overall robustness and credibility of the research process.

6.1 Recommendations for further research

Future research should concentrate on investigating different heat exchange concepts from a manufacturing and economical perspective. Furthermore, concepts should be tested for more detailed evaluations. Different kinds of concepts could also be designed and evaluated for different cooling demands where seawater is avoided.

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