



HØGSKOLEN
I ÅLESUND

Aalesund University College

Master's degree thesis

IP501909 Msc thesis, discipline oriented master

Ballast Water Treatment using Waste Heat
from propulsion Engines-System simulation
and experimental study

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Number of pages including this page: 99

Aalesund, 29,05,2015

TITLE:

**Ballast Water Treatment using Waste Heat from propulsion Engines-
System simulation and experimental study**

CANDIDATE NAME:

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DATE:

29.05.2015

COURSE CODE:

IP501909

COURSE TITLE:

Master Thesis

RESTRICTION:

STUDY PROGRAM:

Product and System Design

PAGES/APPENDIX:

78/20

LIBRARY NO.:

SUPERVISOR(S):

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ABSTRACT:

The master thesis aims to test and simulate a new efficient ballast water treatment system. The simulation part will combined with ship machinery system and ballast water treatment system. The experiment part will focus on the analysis of heat transfer with different volume flow. Finally to acquire the optimized temperature, which not only effectively kill the bacteria but also save the energy. On the other hand, the machinery system models were tested with vessel behavior models to improve the accuracy.

- Heating transfer analysis combined simulation
- Experiment test result analysis
- BWT and propulsion system simulation
- Vessel behavior simulation combined with machinery system

From the simulation result based on heat transfer experiment. The whole process will be simulated in the 20sim to define the key heat transfer parameters. Then the whole WHR system will combined propulsion system for overall simulation.

This thesis is submitted for evaluation at Ålesund University College.

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ASSIGNMENT

MASTER THESIS 2015 FOR STUD.TECHN. QIN LIANG

Ballast Water Treatment using Waste Heat from propulsion Engines-System simulation and experimental study

Background

The guidelines and regulations for ballast water treatment is becoming more serious with the time passing. The ballast water contains a variety of organisms including bacteria, viruses and the adult and larval stages of the marine and coastal plants and animals. The problem increased as trade and traffic volume expanded over the last few decades, and in particular with the introduction of steel hulls, allowing vessels to use water instead of solid materials as ballast. This paper aims to develop and test a new efficient method to treat the ballast water. The whole research is composed of lab experiment and process simulation. From the experiment result, the effective and efficiency of the system could be analysed. From the process simulation, the heat transfer efficiency and heat transfer coefficient relationship with volume flow could be investigated. The heating process temperature could be checked and investigated more accurately in the simulation model.

Objective

Research Study

- Heat transfer coefficient relationship
- Experimental theory
- Ballast water principles and regulations
- Thermal dynamics
- 20SIM Modeling and programming skills

Work

- Ballast water treatment experiment in the lab.
- Lab experiment simulation in 20sim
- Machinery components modelling and simulation
- Thermal transfer theory and parameters investigation
- Waste heat recovery system simulation
- Machinery system load simulation combined with vessel model

The thesis should be written as a research report with summary, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is needed. Discussion of research method, validation and generalization of results is also appreciated.

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- Literature and sources to be studied

- A list of work tasks to be performed
- An A3 sheet illustrating the work to be handed in.

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The thesis shall be submitted as two paper versions. One electronic version is also requested on a CD or a DVD, preferably as a pdf-file.

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Delivery: 29-05-2015

PREFACE

The master thesis project is submitted following the requirements for a Master's Degree in Product and System design at Aalesund University College. The supervisor for this master thesis is Professor Vilmar Æsøy, Faculty of Maritime Technology and Operations (AMO). Most of the projects has been done by the author, however, without the contributions of previous works of others, this thesis will not be finished. The related reference has been made thoroughly in the reference list.

The Author of this thesis obtained his bachelor degree in Dalian Maritime University with major marine engineering. The main research focus is on the machinery system specified in propulsion and hydraulic system. After graduation from China, the author come to Norway for master degree.

This project is part of the ongoing research in the Machinery Lab at Aalesund University College under the Ballast Water Project. The whole project aims to develop and test a new efficient ballast water treatment system using waste heat recovery systems on ship. This master thesis consists of two main parts, first is the experimental test in the lab, the second is the simulation part.

In the experiment part, the setup of the equipment, experiment design, variable control, data collection and analysis will be introduced. In the simulation part, the main components of the machinery is modelled based on appropriate simplification. For the experiment part, the temperature could only be obtained in several limited points. Hence, the experiment setup will be simulated to cater the requirements of temperature during the heating process. The machinery system will be connected to the vessel model which contains the hydrodynamic force and wave condition to simulate the load on the machinery system.

I would like to thank Professor Vilmar Æsøy for his teaching, advice and assistance on the process of thesis. Without his advice and knowledge I could not finish this thesis.

On the other hand, I also appreciate the help of Yanran Cao on the biological analysis. The biological analysis is a mandatory part of the whole project which will feed back the research work on the parts.

Finally, I really appreciate the 2 years spend in Aalesund University College, which lets me know more about the foreign culture and learn the advanced marine knowledge here.

Aalesund University College

May. 2015

Qin Liang

ABSTRACT

The master thesis aims to test and simulate a new efficient ballast water treatment system. The simulation part will be combined with ship machinery and ballast water treatment system. The experiment part will focus on the analysis of heat transfer with different volume flow. Finally to acquire the optimized temperature, which not only effectively kill the bacteria but also save the energy. On the other hand, the machinery system models were tested with vessel behavior models to improve the accuracy.

- Heating transfer analysis combined simulation
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From the simulation result based on heat transfer experiment. The whole process will be simulated in the 20sim to define the key heat transfer parameters. Then the whole WHR system will be combined propulsion system for overall simulation.

KEYWORDS

Ballast water treatment, waste heat recovery, machinery system, simulation, 20sim

Table of contents

ASSIGNMENT	2
LIST OF FIGURES	8
1 INTRODUCTION	10
1.1 PROJECT BACKGROUND	10
1.2 MOTIVATION AND OBJECTIVES	11
1.3 METHODOLOGY	12
2 BACKGROUND AND THEORETICAL BASIS	12
2.1 BALLAST TREATMENT METHOD INVESTIGATION	13
2.2 MACHINERY SYSTEM WASTE HEAT RECOVERY	16
3 METHODS.....	17
3.1 MODELLING OF DYNAMIC SYSTEMS	17
3.2 BASIC ELEMENTS	18
3.3 HEAT TRANSFER AND THERMODYNAMIC	19
3.3.1 Heat transfer overview.....	19
3.3.2 Heat transfer mechanisms.....	20
3.3.3 Thermodynamics.....	20
3.4 EXPERIMENTAL METHODS	20
4 BALLAST WATER EXPERIMENT AND SIMULATION	21
4.1 EXPERIMENT DESIGN	21
4.2 EXPERIMENT EQUIPMENT	22
4.3 EXPERIMENTAL PARAMETERS CALIBRATION AND SETUP	24
4.3.1 Pump volume flow.....	24
4.3.2 Water Bath temperature.....	25
4.3.3 Pre-experiment and heat transfer coefficient.....	25
4.4 EXPERIMENT MODELLING	29
4.4.1 Heating Process.....	29
4.4.2 Heat Holding Process.....	31
4.4.3 Cooling Process.....	32
4.5 EXPERIMENT SIMULATION	32
4.5.1 Simulation controls	32
4.6 SIMULATION RESULTS AND ANALYSIS	33
4.6.1 Heating Process.....	33
4.6.2 Heat Holding Process.....	34
4.6.3 Cooling Process.....	35
4.6.4 Whole process Analysis.....	36
4.7 EXPERIMENT RESULTS AND ANALYSIS	38
5 MACHINERY SYSTEM SIMULATION	40
5.1 MACHINERY SYSTEM INTRODUCTION.....	40
5.1.1 Diesel Engine.....	40
5.1.2 Governor.....	42
5.1.3 Generator.....	43
5.1.4 Electric motor	44
5.1.5 Central Cooling system.....	45
5.2 MACHINERY COMPONENTS MODELLING	48
5.2.1 Diesel engine modelling.....	50
5.2.2 Gear Box and Flexible Coupling	52
5.2.3 Propeller model	52
5.3 WASTE HEAT RECOVERY MODELLING.....	54
5.3.1 Heating unit 1	55
5.3.2 Heating Unit 2	56
5.3.3 Economizer	57
5.3.4 Central Cooler	57
5.3.5 Heat holding unit	58

5.3.6	<i>Machinery components</i>	59
5.4	WASTE HEAT RECOVERY SIMULATION	59
5.4.1	<i>Simulation parameters</i>	59
5.4.2	<i>Simulation Result analysis</i>	62
5.5	VESSEL BEHAVIOR MODEL CONNECTION	69
5.5.1	<i>Thrust force application</i>	69
5.5.2	<i>Propeller direction variation</i>	70
5.5.3	<i>Thrust force apply on center of gravity</i>	71
5.6	VESSEL BEHAVIOR SIMULATION	72
5.6.1	<i>Simulation parameters</i>	72
5.6.2	<i>Simulation result analysis</i>	74
6	CONCLUSIONS	76
7	FURTHER WORK	77
	REFERENCES	78
	APPENDIX A MODEL PARAMETERS	79
	EXPERIMENT SIMULATION MODEL	79
	WASTE HEAT RECOVERY MODEL	84
	APPENDIX B EXPERIMENT DATA	91
	APPENDIX C SIMULATION DATA	95
	APPENDIX D MATLAB EQUATIONS	98

LIST OF FIGURES

Figure 1-1 Ballast water usage	10
Figure 2-1 Product received Basic Approval from IMO	14
Figure 2-2 Product received Final Approval from IMO	14
Figure 2-3 Waste heat recovery system configuration	16
Figure 3-1 Bond graph elements	18
Figure 4-1 BWT system illustration	21
Figure 4-2 Lab experiment	22
Figure 4-3 heat transfer theory	28
Figure 4-4 Experiment simulation model	29
Figure 4-5 Heating process model	30
Figure 4-6 Heat holding process model	31
Figure 4-7 Cooling process model	32
Figure 4-8 Simulation result-heating process	33
Figure 4-9 Simulation result-holding process	34
Figure 4-10 Simulation result-holding process zoom	34
Figure 4-11 Simulation result-cooling process	35
Figure 4-12 Simulation result-cooling process zoom	35
Figure 4-13 Simulation result curve with element unit scaling	36
Figure 4-14 Simulation result curve with time scaling	37
Figure 4-15 February 2 experiment result	38
Figure 4-16 February 5 experiment result	39
Figure 5-1 Ship machinery system	40
Figure 5-2 Diesel engine energy flow	41
Figure 5-3 Governor control theory	42
Figure 5-4 Generator energy flow	43
Figure 5-5 Motor energy flow	44
Figure 5-6 Central cooling system energy flow	45
Figure 5-7 Diesel Engine directly propulsion system	48
Figure 5-8 Diesel-electric propulsion system	48
Figure 5-9 Waste heat recovery system	49
Figure 5-10 Vessel behaviour simulation model (Control Real time simulation)	49
Figure 5-11 Vessel behaviour simulation model	49
Figure 5-12 Diesel Engine model	50
Figure 5-13 Gear box model	52
Figure 5-14 Propeller model	52
Figure 5-15 Waste heat recovery model	54
Figure 5-16 Heating unit 1 model	55
Figure 5-17 Heating unit 2 model	56
Figure 5-18 Economizer model	57
Figure 5-19 Heat holding unit model	58
Figure 5-20 Engine and propeller working RPM	62
Figure 5-21 Engine ratio	62
Figure 5-22 Engine cooling	63
Figure 5-23 Engine and cooling zoom	63
Figure 5-24 Engine and exhaust temperature	63
Figure 5-25 Engine and Propeller Power	64
Figure 5-27 Vessel Speed	64
Figure 5-28 Heating Unit 1 temperature	65
Figure 5-29 Heating Unit 1 temperature zoom	65
Figure 5-30 Heating Unit 2 temperature zoom2	66
Figure 5-31 Heating Unit 2 temperature	66
Figure 5-32 Heating Unit 2 temperature zoom 1	66
Figure 5-33 Heat holding temperature	67
Figure 5-34 Heat holding temperature zoom 2	67

Figure 5-35 Heat holding temperature zoom 1	67
Figure 5-36 BWT volume flow	68
Figure 5-37 BWT volume flow zoom	68
Figure 5-38 Vessel model	69
Figure 5-39 Vessel coordinate system	69
Figure 5-40 Vessel coordinate system	69
Figure 5-41 Propeller coordinate system 1	70
Figure 5-42 Propeller coordinate system 2	70
Figure 5-43 Vessel coordinate system	71
Figure 5-44 Propulsion resistance curve	73
Figure 5-45 Engine working condition	74
Figure 5-46 Vessel Speed	74
Figure 5-47 Engine working temperature	75
Figure 5-48 Movement of the vessel	75

1 INTRODUCTION

1.1 Project background

The ballast water is used to stabilize vessels at sea, which could increase the stability and propulsion efficiency. The ballast water will be pumped into vessel from the origin, then the ballast water will be pumped out at destination. Before the pump out process, the ballast water should be treated with ballast water treatment equipment.

A number of Ballast Water Treatment technology options are currently available including one or more of the processes. With the exception of a small number of systems, all use a 2-stage approach involving mechanical separation (1st stage) followed by physical/chemical treatment (2nd stage). It is noted that some of the available systems use a combination or two or more physical and/or chemical treatment processes. While most of the BWT equipment need to be powered from the ship, with the strict rules and large amount of ballast water, the BWT system will consume a great deal of energy.

On the other hand, the machinery system on the vessels will continuously produce waste heat which need to be cooling down by the cooling system. The purpose of this project is to develop and verify a new method for ballast water treatment with the heat source from machinery system. The experiment is carried out in Machinery lab in Aalesund University College. Our research is all based on the International Maritime Organization (IMO) Ballast Water Management Convention 2004.

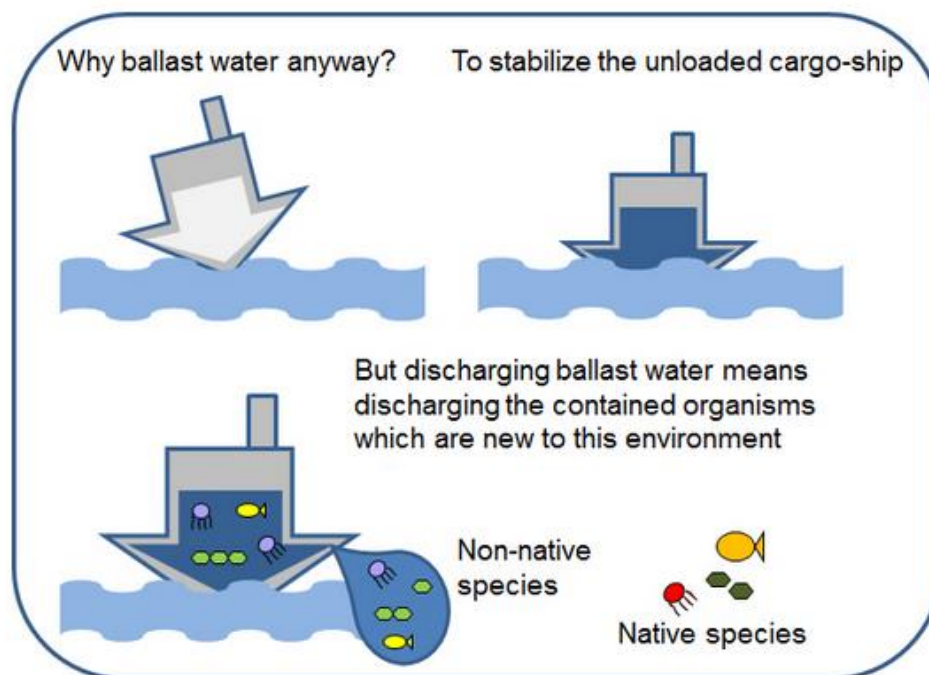


Figure 1-1 Ballast water usage

- **The threat of ballast water**

The ballast water inside a ship can be seen as an onboard aquarium full of microscopic life forms. That's because small organisms living in the sea water are pumped into ballast tanks along with the water. Moreover, coastal sediments and any associated organisms may be pumped into ballast tanks. The ballast water is taken from coastal port areas and transported inside the ship to the next port of call where the water may be discharged, along with all the surviving organisms. This way, ballast water may introduce organisms

into the port of discharge that do not naturally belong there. These introduced species are also called exotic species. Populations of exotic species may grow very quickly in the absence of natural predators. In that case they are called 'invasive'. Only few species are successful invaders, because most species are not able to survive in new surroundings, because temperature, food, and salinity are less than optimal. However, the species that do survive and establish a population are very hardy species that have the potential to cause major harm (to ecology, economy or human health).

- **What can we do about this problem?**

The invasive exotic species can be treated in two ways: prevent them from invading in the first place, or eliminate the exotic species that have invaded. Getting rid of established exotic species is practically impossible and very expensive. Preventing invasions to occur is the more practical and economical solution. In order to prevent possible invasions, organisms should not be discharged from ballast tanks. This can be achieved by treating the ballast water, for instance by killing organisms that are travelling in the ballast water. Several treatment methods are on the market, for instance using damaging properties of light (UV radiation). Unfortunately, most of the ballast water treatment method consume a lot of energy, on the other hand, could not completely eliminate the risk of introducing exotic species. So in this thesis a new kind of efficient ballast water treatment method will be investigated.

1.2 Motivation and objectives

Ballast water is essential to improve the stability and maneuverability. On the other hand, Ballast water contains a variety of organisms including bacteria, viruses and the adult and larval stages of the many marine and coastal plants and animals. As such, it poses serious ecological, economic and health problems and has serious negative effects on the global environment.

The machinery system will continuously produce waste heat during the operation. The heat will be dismissed from the high temperature (HT) cooling water, low temperature (LT) cooling water and exhaust gas. This part of energy will occupy almost 25 percent of the total energy. If this amount of energy can be efficiently utilized, the efficiency of the whole vessel will be enhanced.

The purpose of the whole Ballast water Project in Aalesund University College is to develop methods for verification of heat treatment methods to be used in designing new ballast water treatment system.

However, from the lab experiment only limited data and parameters could be measured and obtained. While, in order to analysis the heating process and heating temperature required, the detailed parameters need to be investigated. Therefore, the simulation process could be combined with the experiment to acquire the detailed parameters.

In this thesis, the whole project consists of the lab experiment part and simulation part. In the experiment part, the procedures and experiment design follows the experiment variable control method, in which the results are compared. In the simulation part, a generic modelling of thermal dynamic system by using bond graph technique in simulation software 20-sim. Some of the thermal parameters are calculated in the programme designed in Matlab.

The parameters of thermal dynamic simulation model should be modified according to the users' requirements. The machinery system will be composed of a machinery simulation

modelled library, different configuration of the machinery system could be obtained. Then the machinery model will be connected to the Dr.Jiafeng's vessel dynamic model to simulate the load affection on the machinery system

1.3 Methodology

The main method used in this thesis is lab experiment and dynamic simulation. The primary target of this thesis is to test the heat treatment affection the ballast water. To define the appropriate heating temperature which could not only treat the ballast water but also save the energy.

As for economic and safety reasons, a full size experiment of ballast water treatment not is practically impossible for the industry. A pre-experiment in the lab and corresponding simulation work in the computer shall thusly be developed which allows researchers to interact with. Physical objects and equipment in the lab are being represented as components with different functionality in the simulation system. The parameters in the system can be modified by the user (e.g., volume flow, heat transfer coefficient, average heat exchange temperature, machinery system related parameters and so on).

Due to the limitation of experiment, only the input temperature and output temperature of the system could be measured. Based on the limited data and thermal theory, the heat transfer coefficient could be calculated. Then the heat transfer coefficient could be taken into the simulation model for further simulation analysis.

2 BACKGROUND AND THEORETICAL BASIS

Under the Ballast Water Management Convention, adopted in 2004, all ships in international traffic are required to manage their ballast water and sediments to a certain standard, according to a ship-specific ballast water management plan. All ships will also have to carry a ballast water record book and an international ballast water management certificate. The ballast water management standards will be phased in over a period of time. With the time processing, the standards will become stricter. As an intermediate solution, ships should exchange ballast water mid-ocean. However, eventually most ships will need to install an on-board ballast water treatment system.

IMO G8 is a political compromise including biological matters. G8 provide the technical specifications and the approval and certification procedures to be used by Administration when granting Type Approval.

Regulation D-1 Ballast Water Exchange Standard - Ships performing Ballast Water exchange shall do so with an efficiency of 95 per cent volumetric exchange of Ballast Water. For ships exchanging ballast water by the pumping-through method, pumping through three times the volume of each ballast water tank shall be considered to meet the standard described. Pumping through less than three times the volume may be accepted provided the ship can demonstrate that at least 95 percent volumetric exchange is met.

Regulation D-2 Ballast Water Performance Standard - Ships conducting ballast water management shall discharge less than 10 viable organisms per cubic meter greater than or equal to 50 micrometers in minimum dimension and less than 10 viable organisms per milliliter less than 50 micrometers in minimum dimension and greater than or equal to 10 micrometers in minimum dimension; and discharge of the indicator microbes shall not exceed the specified concentrations.

Regulation D-3 Approval requirements for Ballast Water Management systems provides that Ballast Water Management systems must be approved by the Administration in accordance with IMO Guidelines (G8 Guidelines for the approval of Ballast Water Management Systems). These include systems which make use of chemicals or biocides; make use of organisms or biological mechanisms; or which alter the chemical or physical characteristics of the Ballast Water.

2.1 Ballast treatment method investigation

A number of Ballast Water Treatment technology options are currently available including one or more of the processes. With the exception of a small number of systems, all use a 2-stage approach involving mechanical separation (1ststage) followed by physical/chemical treatment (2nd-stage). It is noted that some of the available systems use a combination or two or more physical and/or chemical treatment processes.

Table 2-1 Existing BWT method

Mechanical	Physical	Chemical
Cyclonic Separation	Ultra Sound	Electro chlorination
Filtration	Cavitation	Ozonation
	Ultra Violet	Chlorination
	Heat	Chlorine Dioxide
	De oxygenation	Advanced Oxidation
	Coagulation	

Ballast Water Treatment system selection is very much dictated by ship owner/operator. There are a number of factors including but not limited to

- Capital cost and operation cost
- Ship operating profile and associated ballast activities
- Ballast water pump size/rate and Ballast Water Treatment capacity requirements
- Ship integration constraints, for space and power requirements
- System durability and maintenance requirements
- Ease/cost of installation
- Supplier credibility

According to the data from IMO, among availability of ballast water management systems, 50 have been granted IMO Basic Approval, 36 have been granted IMO Final Approval. 51 systems have been granted Type Approval by their Administration.

For Ballast Water Treatment system, some factors/operating conditions, sailing patterns etc. are challenging to the design.

The low quality of dirty water will make the filters with more possibilities to be clogged. For some special configuration of filters which aims to improve the filtration, the filter makers have done plenty of testing for such conditions.

On the other hand, UV systems are always challenged with dirty water conditions as the high turbidity reduce the efficiency of the UV light.

The BWT system using an electrochemical process are challenged by the level of salinity. The effect is influenced by salinity which is related to the construction of the electrochemical cells they use. On a general basis: Low salinity means higher power consumption. If the vessel is operated in fresh water, Ozone will act as a corrosive oxidant and can be a corrosion risk.

Temperature is generally an issue for most electrochemical systems with a direct flow. For heat treatment system it will consume more energy and processing time. Systems using Ozone get an extended reaction time at low temperatures.

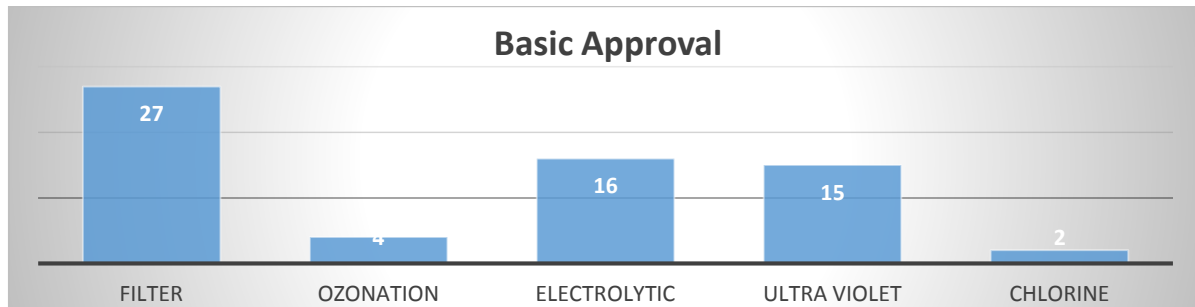


Figure 2-1 Product received Basic Approval from IMO

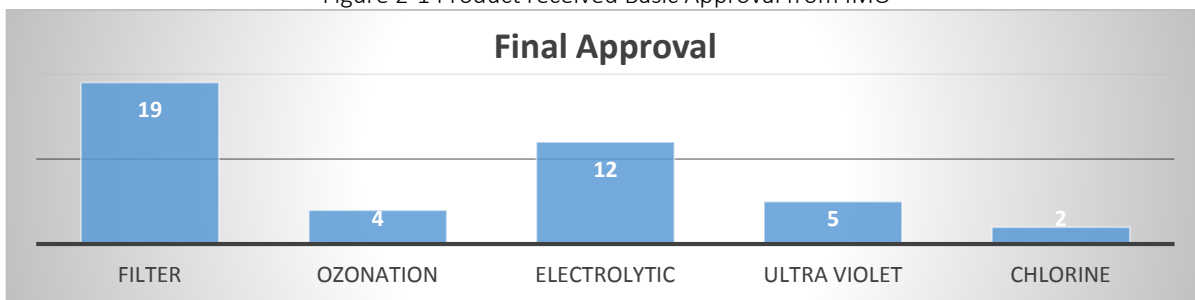


Figure 2-2 Product received Final Approval from IMO

From the previous two forms, it could be clearly found that most of the ballast water treatment system are combined with two stages of processing. The first stage will adapt filters, it's very convenient to install and maintain. While the filters will cause flow reduction and pressure drop. The advantages and disadvantage of different technology are presented in the following form.

Table 2-2 BWT system method comparison

Technology	Advantages	Disadvantages
Filters	1. Self cleaning 2. Convenient installation 3. Easy maintenance	1. Efficiency in high sediments water 2. Flow rate reduction 3. Pressure drop
UV	1. Efficient 2. Easy installation 3. Minimal safety issues 4. Independent of salinity	Power consumption
Electrolysis	1. Onboard disinfection 2. Efficient 3. 1-way treatment	1. Salinity 2. Power consumption 3. Hydrogen 4. Corrosion
Chemical	1. Low cost 2. 1-way treatment 3. Convenient installation	1. Safety 2. Storage 3. Corrosion
Ozonation	1. Efficient 2. Independent of salinity 3. 1-way treatment	1. Corrosion 2. Safety

As mentioned in the previous test, there are three main categories of treatment: mechanical, physical, chemical. From the previous form, different technologies have disadvantages and advantages. Different size of ship need to have different configuration of BWT system. Most of the BWT system adapt the filter plus UV/ Electrolysis, due to large amount of ballast water the UV/ Electrolysis will consume large amount of energy. The ship

machinery system will create heat when constantly launching. On the other hand, heat can be used for ballast water treatment, but among the existing products, the heat treatment technology is still not being utilized. Such as the main engine of the ship, approximately 50 percent of the energy is dismissed during the working process. Exhaust gas, cooling water, air cooler, heat radiation are the sources of waste heat, if these part of energy can be used for ballast water treatment, not only the efficiency and energy saving but also the low maintenance work and long life cycle.

While if the volume of ballast water is huge, the heat treatment will consume more energy than the machinery waste heat cannot provide. Additionally, the waste heat recovery technology plays an important role in this process. To capture and reuse the waste heat onboard is a potential way to improve efficiency. For the future BWT system design, the heat treatment can be one of the stages of the system. The corresponding calculation and efficiency test need to be applied before the design to define the possibilities.

2.2 Machinery system waste heat recovery

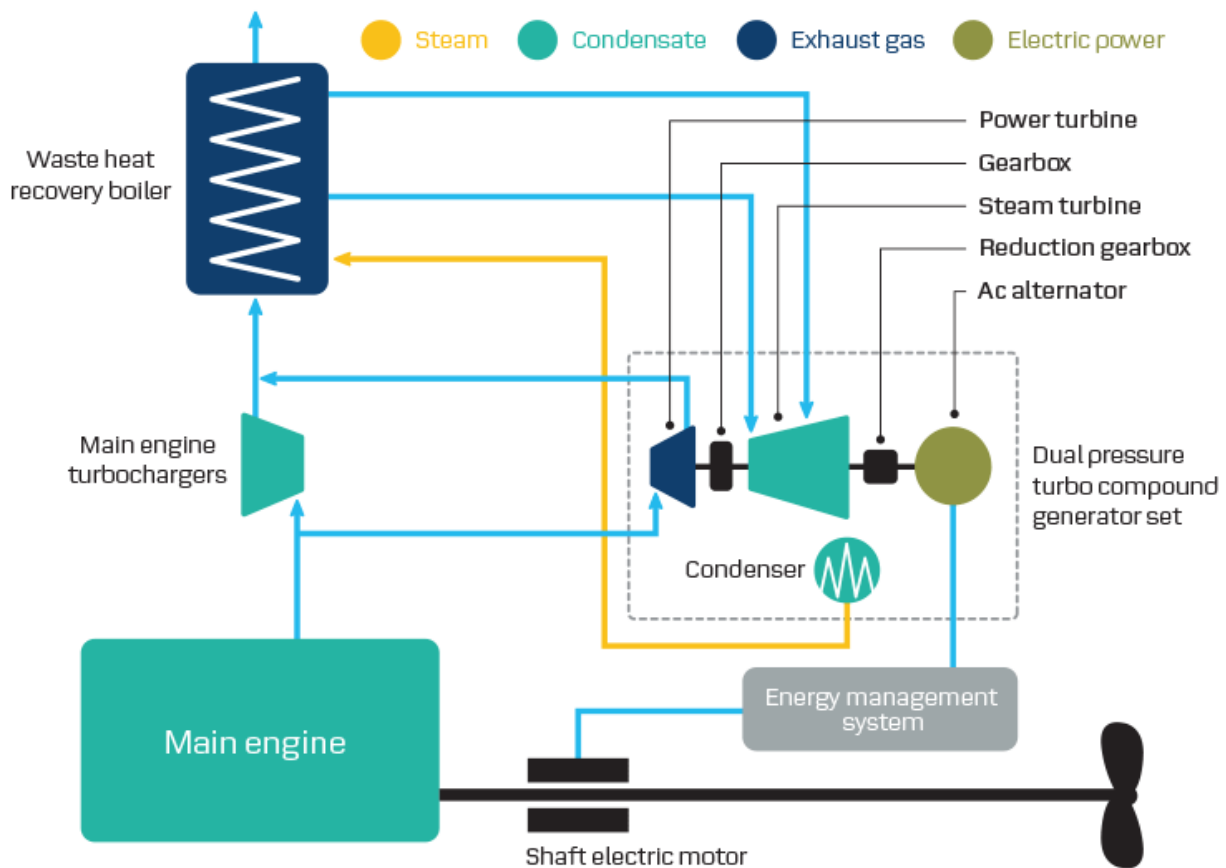


Figure 2-3 Waste heat recovery system configuration

The waste-heat recovery system for a main marine propulsion engine as a solution for strengthened environmental restrictions and increasing demand for improved fuel oil consumption. The waste heat means the energy that is generated in operation processes without being put to practical use. A waste heat recovery unit (WHRU) is an energy recovery heat exchanger that recovers heat from hot streams with potential high energy content, such as hot flue gases from a diesel generator or steam from cooling towers or even waste water from different cooling processes such as in steel cooling.

Sources of waste heat include hot combustion gases discharged to the atmosphere, heated products exiting working processes, and heat transfer from hot equipment surfaces. The exact quantity of industrial waste heat is poorly quantified, but various studies have estimated that as much as 20 to 50% of energy consumption is ultimately discharged as waste heat. There are several different commercial recovery units for the transferring of energy from hot medium space to lower one:

- **Recuperators:** This name is given to different types of heat exchanger that the exhaust gases are passed through, consisting of metal tubes that carry the inlet gas and thus preheating the gas before entering the process. The heat wheel is an example which operates on the same principle as a solar air conditioning unit.
- **Regenerators:** This is an industrial unit that reuses the same stream after processing. In this type of heat recovery, the heat is regenerated and reused in the process.
- **Heat pipe exchanger:** Heat pipes are one of the best thermal conductors. They have the ability to transfer heat hundred times more than copper. Heat pipes are mainly

known in renewable energy technology as being used in evacuated tube collectors. The heat pipe is mainly used in space, process or air heating, in waste heat from a process is being transferred to the surrounding due to its transfer mechanism.

- Thermal Wheel or rotary heat exchanger: consists of a circular honeycomb matrix of heat absorbing material, which is slowly rotated within the supply and exhaust air streams of an air handling system.
- Economizer: In case of process boilers, waste heat in the exhaust gas is passed along a recuperator that carries the inlet fluid for the boiler and thus decreases thermal energy intake of the inlet fluid.
- Heat pumps: Using an organic fluid that boils at a low temperature means that energy could be regenerated from waste fluids.
- Run around coil: comprises two or more multi-row finned tube coils connected to each other by a pumped pipework circuit.

Additionally, newly designed waste heat recovery system, in which the exhaust gas from a main diesel propulsion engine is utilized in an exhaust gas economizer and a steam turbine generation system, all of the exhaust gas from the diesel engine passes through a turbocharger. On the other hand, the High temperature (HT) and Low temperature (LT) cooling water can also be used for the other recovery uses. The newly developed super waste-heat recovery system consists of a conventional combined system and a power turbine (gas turbine) that utilizes a portion of the exhaust gas with an automatic overrunning clutch between the power turbine and the steam turbine. In this system, the turbines are used to drive a generator. The steam and the power turbines have control systems to share the load according to the electricity requirements of the ship. This system increases the electric generation capability and the marine engine plant efficiency (relative value of 8%–10%) while reducing carbon dioxide emissions.

3 METHODS

3.1 *Modelling of dynamic systems*

The dynamic system modelled in the following chapters are based on the bond graph theory. Bond graph is an explicit graphical tool for capturing the common energy structure of systems. Bond graph can increase engineers' insight into systems behavior. Complex systems can be described concisely by bond graph in vector form, and the notations of causality provides a tool not only for formulation of system equations, but also for intuition based discussion of system behaviors, such as controllability, observability, fault diagnosis, etc.

- Power variables of Bond Graphs

The language of bond graphs aspires to express general class physical systems through power interactions. The factors of power, **Effort** and **Flow**, have different interpretations in different physical domains. Yet, power can always be used as a generalized co-ordinate to model coupled systems residing in several energy domains. One such system may be an electrical motor driving a hydraulic pump or a thermal engine connected with a muffler; where the form of energy varies within the system. Power variables of bond graph may

not be always realizable (viz. in bond graphs for economic systems); such factual power is encountered mostly in non-physical domains and pseudo bond graphs.

In the following table, effort and flow variables in some physical domains are listed.

Table 3-1 Bond graph in different domain

Systems	Effort (e)	Flow (f)
Mechanical	Force (F)	Velocity (v)
	Torque (t)	Angular velocity (w)
Electrical	Voltage (V)	Current (i)
Hydraulic	Pressure (P)	Volume flow rate (dQ/dt)
Thermal	Temperature (T)	Entropy change rate (ds/dt)
	Pressure (P)	Volume change rate (dV/dt)
Chemical	Chemical potential (m)	Mole flow rate (dN/dt)
	Enthalpy (h)	Mass flow rate (dm/dt)
Magnetic	Magneto-motive force (em)	Magnetic flux (f)

In this project, the bond graph will be used in mechanical, electrical and thermal domain. The detailed modelling process will be illustrated in the later chapters.

3.2 Basic elements

Bond graph is a graphical representation of physical dynamic system. It is a graphical approach to modeling in which component energy ports are connected by bonds that specify the transfer of energy between system components. Power is the universal currency of physical systems. Designing and analyzing the structure of a system. The method of modeling focuses on interconnecting ideal basic elements where the interconnected elements will be able to predict the behavior of actual devices and systems within acceptable limits of accuracy

A power bond is considered to transmit power instantaneously and without loss of power from one port to another. The power direction is interpreted as power flowing in the direction of the half-arrow whenever the power is positive.

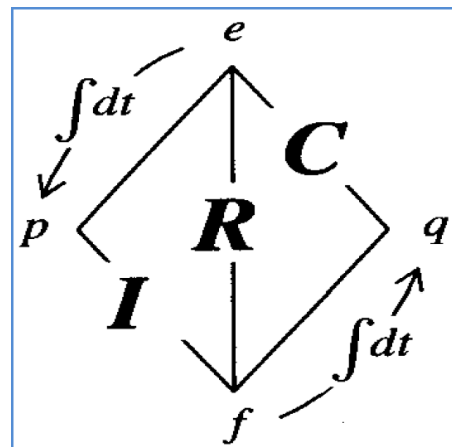


Figure 3-1 Bond graph elements

The signal bond indicates a signal flow at very low power. The notation for a signal bond is identical to that for a signal in a block diagram.

In bond graph, the variables effort denoted by "e", and flow denoted by "f". There are three quantities associated with a power bond, effort, flow, and power. The power flowing into or out of a port is the effort multiplied by flow. Momentum is defined as the time integral of an effort and displacement is the time integral of a flow.

Capacitor

Capacitor element are used to store energy, and most systems can store energy in two forms, for example in mechanical systems they are potential and kinetic energy. Consider

the 1-port device in which a single valued static constitutive relationship exists between an effort and a displacement variable. It is called C-element.

Inertia Element

The other energy storage element come into being when a single valued static constitutive relationship between a momentum p and a flow f . It is called I-element. In linear case I is a constant parameter. The inertia element is an idealization of physical objects such as a mass, inertia effects in hydraulic systems or inductance in electrical systems. The positive power direction is into the element as shown:

Resistor Element

Another 1-port element is a single valued static relationship between an effort e and a flow f , and is called R-element. It handles power dissipation. The R-element is used to model all kinds of energy dissipation such as mechanical and hydraulic friction and electrical resistors.

3.3 Heat transfer and thermodynamic

3.3.1 Heat transfer overview

Heat transfer describes the exchange of thermal energy, between physical systems depending on the temperature and pressure, by dissipating heat. The three fundamental modes of heat transfer are conduction or diffusion, convection and radiation.

The exchange of kinetic energy of particles through the boundary between two systems which are at different temperatures from each other or from their surroundings. Heat transfer always occurs from a region of high temperature to another region of lower temperature. Heat transfer changes the internal energy of both systems involved according to the First Law of Thermodynamics. The Second Law of Thermodynamics defines the concept of thermodynamic entropy, by measurable heat transfer.

Thermal equilibrium is reached when all involved bodies and the surroundings reach the same temperature. Thermal expansion is the tendency of matter to change in volume in response to a change in temperature.

Enthalpy is a thermodynamic potential, designated by the letter "H", that is the sum of the internal energy of the system (U) plus the product of pressure (P) and volume (V). Joule is a unit to quantify energy, work, or the amount of heat.

Heat transfer is a process function (or path function), as opposed to functions of state; therefore, the amount of heat transferred in a thermodynamic process that changes the state of a system depends on how that process occurs, not only the net difference between the initial and final states of the process.

Thermodynamic and mechanical heat transfer is calculated with the heat transfer coefficient, the proportionality between the heat flux and the thermodynamic driving force for the flow of heat.

Thermal engineering concerns the generation, use, conversion, and exchange of heat transfer. As such, heat transfer is involved in almost every sector of the economy.[7] Heat transfer is classified into various mechanisms, such as thermal conduction, thermal convection, thermal radiation, and transfer of energy by phase changes.

3.3.2 Heat transfer mechanisms

- Advection

Advection is the transport mechanism of a fluid substance or conserved property from one location to another, depending on motion and momentum.

- Conduction or diffusion

The transfer of energy between objects that are in physical contact. Thermal conductivity is the property of a material to conduct heat and evaluated primarily in terms of Fourier's Law for heat conduction.

- Convection

The transfer of energy between an object and its environment, due to fluid motion. The average temperature, is a reference for evaluating properties related to convective heat transfer.

- Radiation

The transfer of energy from the movement of charged particles within atoms is converted to electromagnetic radiation.

3.3.3 Thermodynamics

Thermodynamics arose from the study of two distinct kinds of transfer of energy, as heat and as work, and the relation of those to the system's macroscopic variables of volume, pressure and temperature. Transfers of matter are also studied in thermodynamics.

Thermodynamic equilibrium is one of the most important concepts for thermodynamics. The temperature of a thermodynamic system is well defined, and is perhaps the most characteristic quantity of thermodynamics. As the systems and processes of interest are taken further from thermodynamic equilibrium, their exact thermodynamic study becomes more difficult. Relatively simple approximate calculations, however, using the variables of equilibrium thermodynamics, are of much practical value. In many important practical cases, as in heat engines or refrigerators, the systems consist of many subsystems at different temperatures and pressures. In engineering practice, thermodynamic calculations deal effectively with such systems provided the equilibrium thermodynamic variables are nearly enough well-defined.

3.4 Experimental methods

Experimental design is the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. However, in statistics, these terms are usually used for controlled experiments. Formal planned experimentation is often used in evaluating physical objects, chemical formulations, structures, components, and materials.

In the design of experiments, the experimenter is often interested in the effect of some process or intervention (the "treatment") on some objects (the "experimental units"), which may be people, parts of people, groups of people, plants, animals, etc. Design of experiments is thus a discipline that has very broad application across all the natural and social sciences and engineering.

- Controlled experiments

In this project, mostly the controlled experiments is carried. There are many forms of controlled experiments. A relatively simple one separates research subjects or biological specimens into two groups: an experimental group and a control group. No treatment is given to the control group, while the experimental group is changed according to some key variable of interest, and the two groups are otherwise kept under the same conditions.

Controls eliminate alternate explanations of experimental results, especially experimental errors and experimenter bias. The selection and use of proper controls to ensure that experimental results are valid (for example, absent of confounding variables) can be very difficult.

For this project, the heating time, heating temperature, volume flow, heat holding time, samples and so on will be controlled under the experiment. Then the result from different controlled groups will be analyzed.

4 BALLAST WATER EXPERIMENT AND SIMULATION

4.1 Experiment design

The heat treatment of ballast water has been widely advocated as a possible treatment regime based on theoretical and laboratory/small trials. Various methods of heating the ballast water on board vessels have been previously used. The length of time the water was heated varied from 20 h at temperatures in excess of 35 °C, 15 h at 42 °C and 80 h at more than 30 °C [5, 7].

Previous experiments carried out on board vessels have achieved a 90 – 100% reduction of the phytoplankton and zoo-plankton by using waste engine heat to treat the ballast at 35 – 38 °C for 20 h [6] and a 100% kill rate of zoo-plankton by heating the ballast water to 38 °C for 12 h [5, 7]. Instant exposures at high temperatures (40 –65 °C) have already been tested in the laboratory with successful results for phytoplankton and zoo-plankton [8, 9, 10].

This pre-project dealt with the application of this high temperature treatment under operational conditions. The aim was to assess the extent to which this method was able to treat the organisms smaller than 50 µm (phytoplankton and bacteria) in the ballast water.

Based on the previous investigation and the research work in the lab. The process of designed ballast water treatment system is shown in Figure 4-1

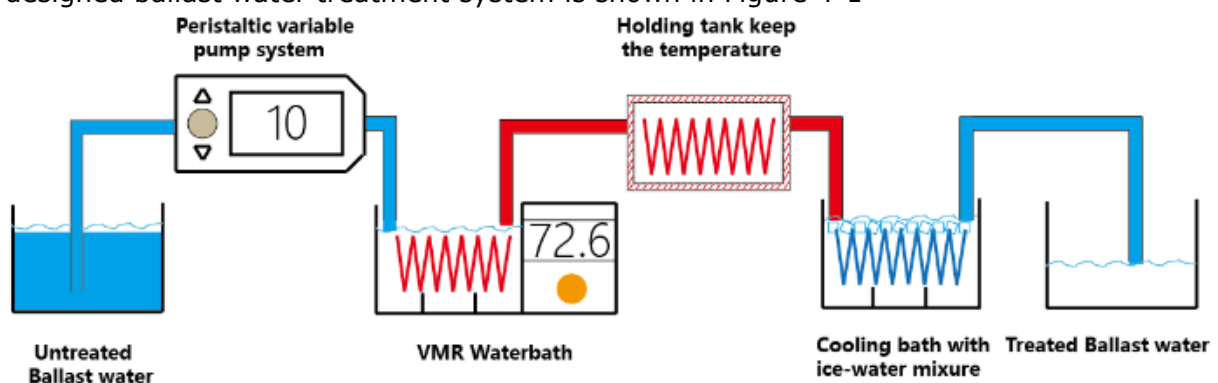


Figure 4-1 BWT system illustration

The experiment adapted in this experiment will be introduced in the following chapters. The whole system are composed of three parts (heating, heat holding, cooling). The untreated ballast water will be pumped from the storing tank to the heating water bath which the heating temperature is pre-configured. Then, after the water being treated, in order to save the energy, the heated water will be keep in an insulated environment to reduce the heat transfer losses. Then the heated water will flow through the cooling water bath to be cooled to cater the needs of controlled experiment. Then the treated water was sent to biological lab for further analysis.

4.2 Experiment equipment

The experiment system set up is shown in the following figure 4-2. The whole experiment process are composed of four different parts. The pumping process, heat treatment process, heat holding process and cooling process. The pumping process is the power source of the whole system, which could provide required volume flow to the system. Additionally, the treatment time is also affected by pump. The heating process is the main part of the system. The holding process is adapted to extend the treatment time and save the energy for heating, which will keep the output temperature from the heating coil at an almost constant level to extend the time of heat treatment process without energy consumption. The cooling process is adapted to control the time of heat treatment. Different heating time will affect the living of micro-organisms. So the heating time should be controlled to cater the requirement of experiment. The principle, heating time and temperature is based on the previous tests with tubes.



Figure 4-2 Lab experiment

Due to the uncertainty of seawater and the other condition. The experiments were carried on two samples.

- Freshly collected sea water from "Åsefjord".
- Lab cultivated sample.

Table 4-1 Equipment check list

Equipment	Model	Remarks
VMR water bath	EN-MX Immersion	20 liter 85° Max
Peristaltic variable pump	FH100	Flow based on selected hose
Heating Coil		Diameter 6mm Length 1.8m
Holding Hose		Diameter 8mm Length 2.431m
Cooling Coil		Diameter 6mm Length 3m

- VMR water bath

The VMR Water bath aims to provide a constant water environment for experiment. The total volume of the water bath is 20 liter. The immersion circulator could not only heating the water, but also circulate the water in the water bath. The target temperature required for this experiment is based on previous testing, which will be illustrated in the following chapters.

- Perstalic Variable Pump

The volume flow in the system was launched by FH100 Peristaltic Variable Pump System which provides continuous pumping of fluids while power is supplied.

The flow rate is determined by the size of the hose in the Pump Head. Different size of the hose will provide different flow. From the manufacturer provided hoses, the one with 9.5mm outside diameter was selected for the experiment. The connection of the pump is shown in the following figure. While, different length of hose will cause different volume flow. In the experiment the length of hose was defined as 23cm in order to keep a constant volume flow.

- Heating coil and cooling coil

The coil was adapted two times in the system. The first one was used for heating, the untreated ballast water will be pumped through the coil. The coil parameters was shown in the following figure.

Table 4-2 Coil Information

Coil Information	Inside Diameter	Outside Diameter	Length	Volume
	0.006m	0.008m	1.8m	$3.533 \times 10^{-5} \text{m}^3$

Table 4-3 Heat transfer information

Coil Heat Transfer Information	Length	Inside Area	Outside Area
	1.8m	0.02826m^2	0.045216

The total volume of the heating coil will affect the heating time of water in the process, which also depends on the volume speed of the pump. The volume of coil is obtained based on the measurement which is more accurate than calculation. The measure has been applied six times to avoid the deviation.

Table 4-4 Coil volume measurement

	Coil weight	Coil+water	Correction	Water Weight	Average
1	350	396	2	43	44.17
2	351	396	0	45	
3	351	392	0	41	
4	351	399	1	48	
5	351	397	0	46	
6	351	393	0	42	

- Holding Hose

The holding hose was assembled with hose and insulation material. The length is based on the measurement of pumping system and the holding time which will be introduced in the later chapters. The holding volume and holding hose length is shown in the Table

Table 4-5 Holding volume calculation

Holding Volume (ml)		
T_hold/Pump S	10	20
30s	30.5	61.1
60s	61	122.1

Table 4-6 Hose length

Hose Length (m) with 8mm diameter			
T_hold/Hose length			
30s	0.607	1.215	2.431
60s	1.214	2.431	
120s	2.431		

From the previous figure it is obvious that, with the hose length of 2.431m, different treatment time could be achieved based on the change of pump speed. It means the system will only need to be assembled for one time, which avoid leakage and deviation. Then the hose is curved and wrapped with insulation material which could reduce the heat transfer with environment and heat loss.

4.3 Experimental parameters calibration and setup

Before the formal experiment, some pre-experiments were applied to test the essential parameters. The essential parameters contains the pump volume flow, the water bath heating temperature and the heat transfer coefficient. The whole experiment was carried two times based on the results biological analysis.

4.3.1 Pump volume flow

The pump volume flow is measured three times then calculate the average value for later use. The pump speed configured on the control panel range from 0 to 400. For the pump speed in the higher range, the pump system is not very stable and the bigger volume flow doesn't fit the heating and holding environment. As a consequence, in this pre-experiment, the pump speed will set from 0 to 120.

The structure of the peristaltic variable pump determine the working hose around the rotor will affect the volume. Based on the controlled experiment theory, the length of the hose will be keep at 23cm. In table shows the pump speed and the corresponding volume flow.

The pump speed in the previous tables present the corresponding volume flow measured from experiment. The selected hose with diameter 9.5mm and length 23cm. The volume flow data is shown in table 4. The data was collected from the experiment. In order to minimize the deviation, each measurement of pump speed is carried three times then calculate the average value.

Table 4-7 Pump speed measurement

Hose diameter	9.5mm	Length	23cm	Volume flow(ml/s)
Pump Speed	100ml	200ml	300ml	
10	101.93	97.63	99.91	1.001769793
20	49.58	49.77	49.75	2.012072435
30	32.89	33.33	33.08	3.021148036
40	24.8	24.92	24.66	4.033342296
50	19.79	19.99	19.92	5.025125628
60	16.6	16.78	16.54	6.009615385
70	14.22	14.1	14.04	7.082152975
80	12.43	12.35	12.26	8.099352052
90	10.61	10.87	11.1	9.208103131
100	9.96	9.73	9.95	10.12145749
110	8.99	8.82	8.69	11.32075472
120	8.06	7.79	7.84	12.66357113

4.3.2 Water Bath temperature

- Experiment February 2

Table 4-8 Water bath temperature

Pump Speed/Output T	10	20	40
50	50.5	51	53
60	61.5	62.5	64.5
70	N/A	72	74.5

- Experiment February 5

Table 4-9 Water bath temperature

Pump Speed/Output T	10	20	40
50	50.8	51	N/A
55	56.2	57	59
60	61.2	63.7	66

4.3.3 Pre-experiment and heat transfer coefficient

The heat transfer coefficient is related to many factors which could not be fully considered. In order to define the heat transfer coefficient regular pattern, two sets of pre-experiments were carried under 50° and 85°. The pre-experiments are simulated under a simplified model which only consists of heating process. The simulation result provided and compared with experiment result. The result is shown in Table 4-11 and 4-12.

Table 4-9 Pre-experiment result under 85

Experiment data								Simulation Result		Deviation
Volume Flow(m ³ /s)	T1	T2	T2-T1	Water Bath T	Qw(J)	T_Average	Area	U	T	
1.01632E-06	15.6	82.5	66.9	85 °	2.86E+02	20.12879943	0.04523	3.14E+02	82.16	0.34
2.03545E-06	15.2	81.5	66.3	85 °	5.67E+02	22.15264176	0.04523	5.66E+02	81.2	0.3
3.03781E-06	14.7	78.2	63.5	85 °	8.10E+02	27.18497425	0.04523	6.59E+02	78.1	0.1
4.03119E-06	14.5	74.8	60.3	83.4 °	1.02E+03	28.97793003	0.04523	7.79E+02	74.78	0.02
5.02339E-06	14.8	71.5	56.7	83 °	1.20E+03	31.85218734	0.04523	8.31E+02	71.76	-0.26
6.02218E-06	14.9	68.6	53.7	82.5 °	1.36E+03	33.95040152	0.04523	8.85E+02	69.11	-0.51
7.03538E-06	14.6	65.3	50.7	81.9 °	1.50E+03	36.22055856	0.04523	9.15E+02	65.84	-0.54
8.07076E-06	14.5	62.2	47.7	81.2 °	1.62E+03	37.98478458	0.04523	9.41E+02	62.96	-0.76

Table 4-10 Pre-experiment result under 50

Experiment data (Water bath 50 °)							Simulation Result		Deviation
Volume Flow(ml/s)	T1	T2	T2-T1	Qw	T_Average	Area	U	T	
1.02E-06	16.9	48.8	31.8	1.36E+02	9.6165101	0.04523	313.1564	47.81	-0.99
2.04E-06	16.4	47.7	31.3	2.68E+02	11.672062	0.04523	507.0084	46.59	-1.11
3.04E-06	16.2	46.1	29.8	3.81E+02	13.845899	0.04523	609.3522	44.95	-1.15
4.03E-06	16.2	44.2	28	4.74E+02	15.885598	0.04523	660.0021	43.07	-1.13
5.02E-06	16.5	42.5	26	5.49E+02	17.372219	0.04523	698.3478	41.47	-1.03
6.02E-06	16.4	40.9	24	6.20E+02	18.755957	0.04523	730.698	39.94	-0.96
7.04E-06	16.4	39.5	23.1	6.83E+02	19.859849	0.04523	760.1171	38.68	-0.82
8.07E-06	16.5	38.3	21.8	7.39E+02	20.723288	0.04523	788.6227	37.49	-0.81
9.14E-06	16.3	37.2	20.9	8.02E+02	21.589734	0.04523	821.5197	36.54	-0.66
1.02E-05	16.2	35.9	19.7	8.47E+02	22.532672	0.04523	831.5323	35.32	-0.58
1.14E-05	16.3	35	18.7	8.94E+02	23.102174	0.04523	856.2327	34.62	-0.38
1.26E-05	16.2	34.5	18.3	9.68E+02	23.472951	0.04523	911.7314	34.3	-0.2

In the previous Table 4-9, 4-10, the simulation result is obtained from later simulation.

The output temperature should be higher than the required 80. So the experiment under 85° only applied to the maximum volume flow at 8.07ml/s due to the water bath temperature reduction.

● Heat transfer coefficient

The heat transfer coefficient is used in calculating the heat transfer, typically by convection or phase transition between a fluid and a solid. There are numerous methods for calculating the heat transfer coefficient in different heat transfer modes, different fluids, flow regimes, and under different thermal conditions. Often it can be estimated by dividing the thermal conductivity of the convection fluid by a length scale. The heat transfer coefficient is often

calculated from the Nusselt number (a dimensionless number). Experimental assessment of the heat transfer coefficient poses some challenges especially when small fluxes are to be measured. The heat transfer coefficient in this project is obtained from the experiment result calculation, which also are coded into "table" function in 20sim (set a relationship between heat transfer coefficient and pump speed). The heat transfer coefficient calculation process is explained in the following text.

$$Q_w = V_f * \rho * (T_{coldOUT} - T_{coldIN})$$

Q_w : The total energy absorbed by the fluid.

V_f : The volume flow from the pump to the system.

ρ : The density of the heating fluid.

$T_{coldOUT}$: The output temperature of the fluid.

T_{coldIN} : The input temperature of the fluid.

The average temperature difference in a heat transfer process depends on the direction of fluid flows involved in the process. The average heat transfer temperature can be calculated with the following function. The primary and secondary fluid in a heat exchanger process may:

- Flow in the same direction-parallel flow or concurrent flow
- In the opposite direction – countercurrent flow
- Or perpendicular to each other – cross flow

The heat transfer average temperature can be calculated in the following equation.

$$T_{average} = ((T_{hotIN} - T_{coldIN}) - (T_{hotOUT} - T_{coldOUT}))/\log((T_{hotIN} - T_{coldIN}) - (T_{hotOUT} - T_{coldOUT}))$$

$T_{coldOUT}$: The output temperature of the cold fluid.

T_{coldIN} : The input temperature of the cold fluid.

T_{hotOUT} : The output temperature of the hot fluid.

T_{hotIN} : The input temperature of the hot fluid.

In this project the model could be considered as parallel or counter flow single-pass heat exchangers. The following sketch depicting the general temperature variation experienced by each fluid stream. There are four such profiles which are shown and labelled in the following figure.

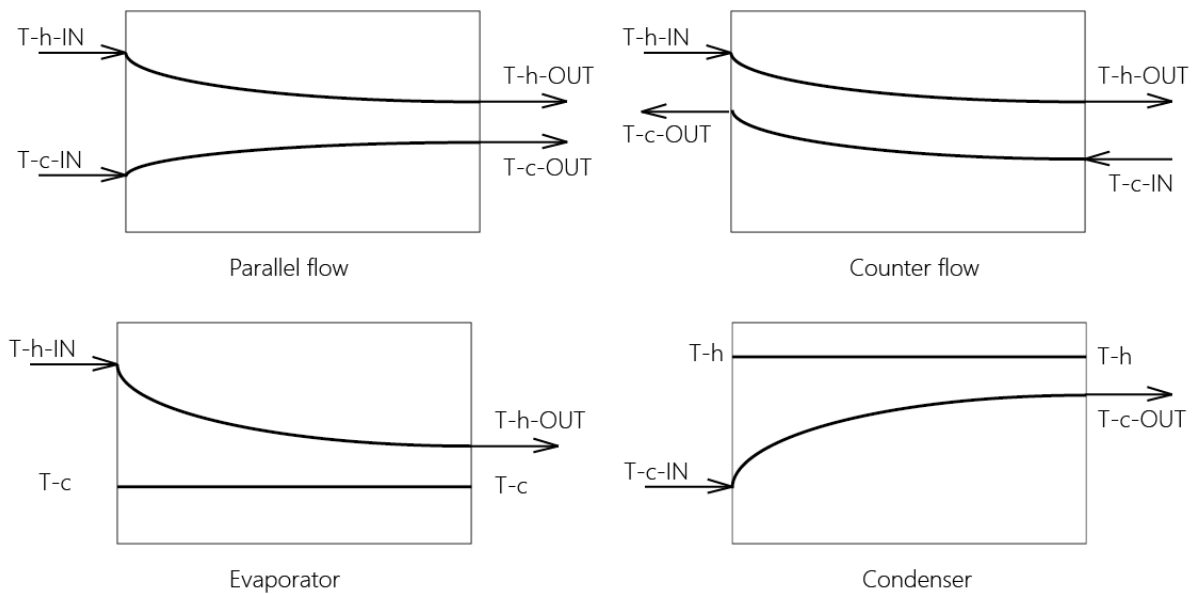


Figure 4-3 heat transfer theory

The experiment could adapt the condenser theory which means one of the fluids remains at constant temperature while exchanging heat with the other fluid whose temperature is changing.

Then the heat transfer coefficient could be calculated with the following function.

$$U = Q_w / (A * T_{average})$$

U : Heat transfer coefficient.

A : Heat transfer area.

$T_{average}$: The average heat transfer temperature.

From the result of pre-experiments, it could be obviously find that the heat coefficient is related to the volume flow. The heat transfer coefficient has an increasing linear trend with the pump speed. With the increasing of volume flow, the heat transfer coefficient also increase. The pre-set pump speed, coil information and the holding volume is calculated based on the measurement from experiment and equipment. From the pre-test on the heating with pump speed from 10-120, the appropriate pump speed for the experiment is range from 10 to 40. Hence, the pump speed is set at 10, 20, 40. With different pump speed and the fixed holding volume, different holding time could be achieved.

4.4 Experiment modelling

In this part of the project, we will develop simulation models for the experiment equipment carried in the lab. And doing the simulation with the same parameters from the experiment to investigate the relations and parameters of heat transfer. The whole system is composed of three parts. The aim is to investigate the detail of the heating process which could not be achieved from the experiment.

The schematic of the whole process is shown in the figure 4-4

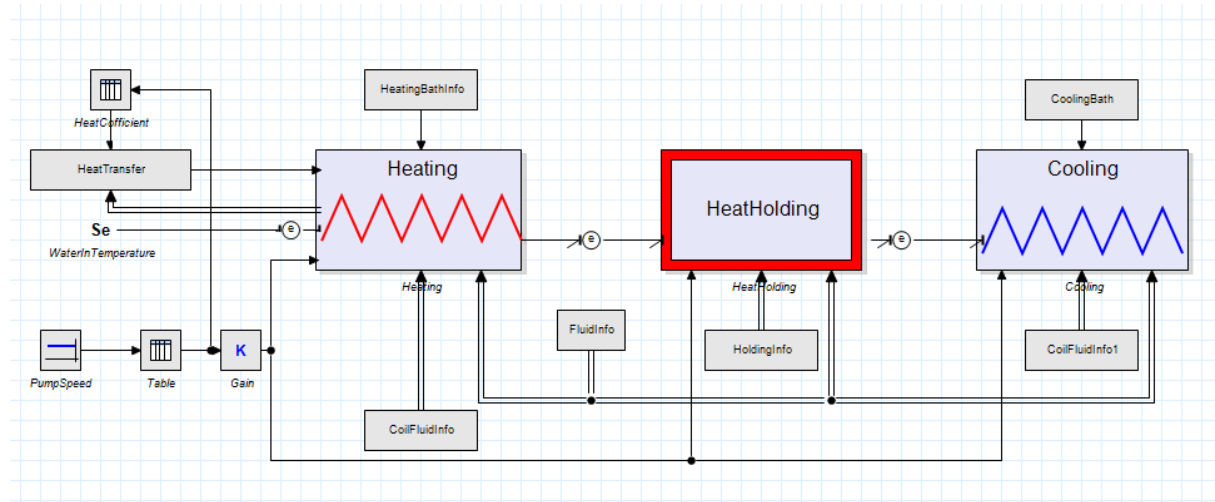


Figure 4-4 Experiment simulation model

The simulation model has exactly the same configuration as the experiment. The system is modelled using Bond Graph method in the 20sim environment.

Different parameters about the heating, holding and cooling can be modified in the corresponding model. The parameters inside the heating bath model is the water bath temperature. The parameters in the coil information model is : total volume of the heating coil, the inside and outside diameter of the heating coil, length of the coil, heat transfer area, number of elements.

From the left side, the pump speed could be set up according to the requirement. The data inside the pump speed model is from the pre-experiment which has been introduced in the previous chapters. With the function of "Table" in the 20SIM, the software could output a fitting curve based on the given data. Then different pump speed configuration can output different volume flow.

4.4.1 Heating Process

The information of heating coil and water bath are connected to the corresponding elements. The element number present a way of modelling the flowing and heat transferring process. If just one element adapted, the dynamic simulation of flowing is not properly presented. The more elements divided in the model, more heat transfer with the water bath. So the number of elements is defined by the test in the simulation model. If the output temperature is not enough, then the coil should be divided into more elements. If the output temperature is high than the test value, the elements should be reduced.

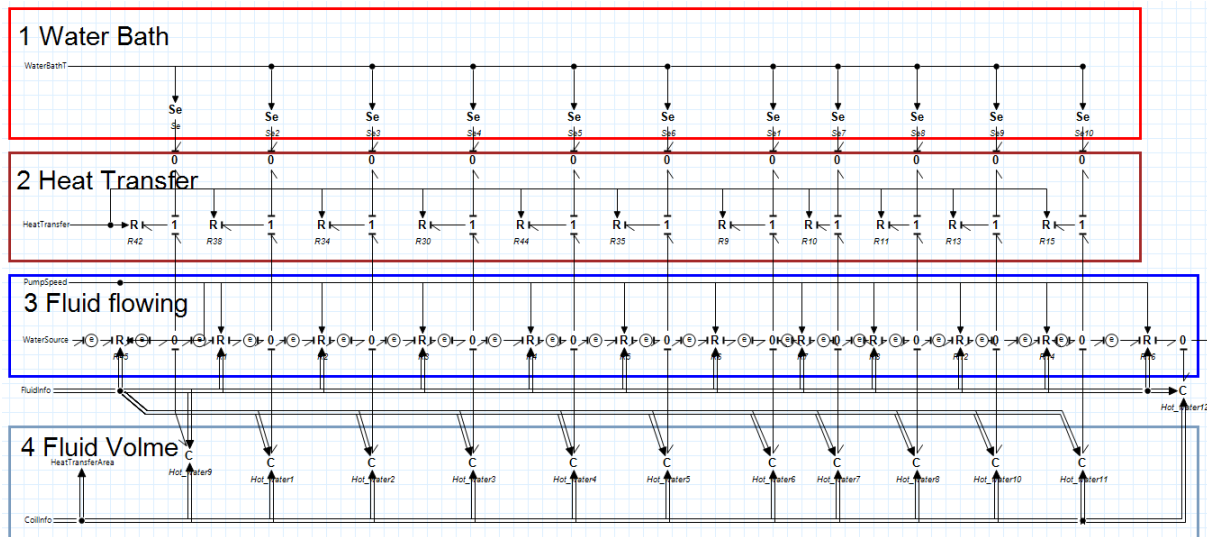


Figure 4-5 Heating process model

The model was built up based on thermal domain. The **Effort (e)** means the temperature. The **flow (f)** means the entropy flow. The heating contains three parts. First the water bath temperature which is presented as an **Se** element in the 20sim. Then the heat transfer unit which is presented as **R** elements which connect the water bath and coil. The coil was modelled with **R** and **C** elements. The **R** element for the coil transfer the fluid and energy from input to output. The **C** element present the volume in the coil which store the fluid and energy

In the heating process model, the system has been divided into four parts. First is the water bath part, the modelling method of water bath and coil is different. Because the water volume in the water bath is much larger than the volume in the coil. On the other hand, the water temperature in the water bath is almost constant, so the water flowing in the water will not affect the result. Here the effort source element was adapted here. In the thermal domain, the effort source is the temperature which is the water bath working temperature.

But for the coil part, a different modelling way is adapted. The fluid temperature in the coil will change with the heat transferring process. So the fluid flowing process is simulated. In each **R** element, the volume and mass of fluid pass the coil element unit is calculated. For bond graph, also the relationship between effort and flow should be set up. In this condition, the flow is the entropy flow, and the effort is the temperature. So in the equation, every second, the fluid energy will be calculated. The volume of the coil will also affect the temperature heat transferring, hence, **C** element is used for storing the fluid (energy). The parameters of the coil is lead in the **C** element, the coil has been divided into 11 elements

Then during the process, the fluid in the coil is always heat transferring with the water bath. While the water bath is always keeping at a balanced pre-set temperature. The detailed parameters are attached in the Appendix.

4.4.2 Heat Holding Process

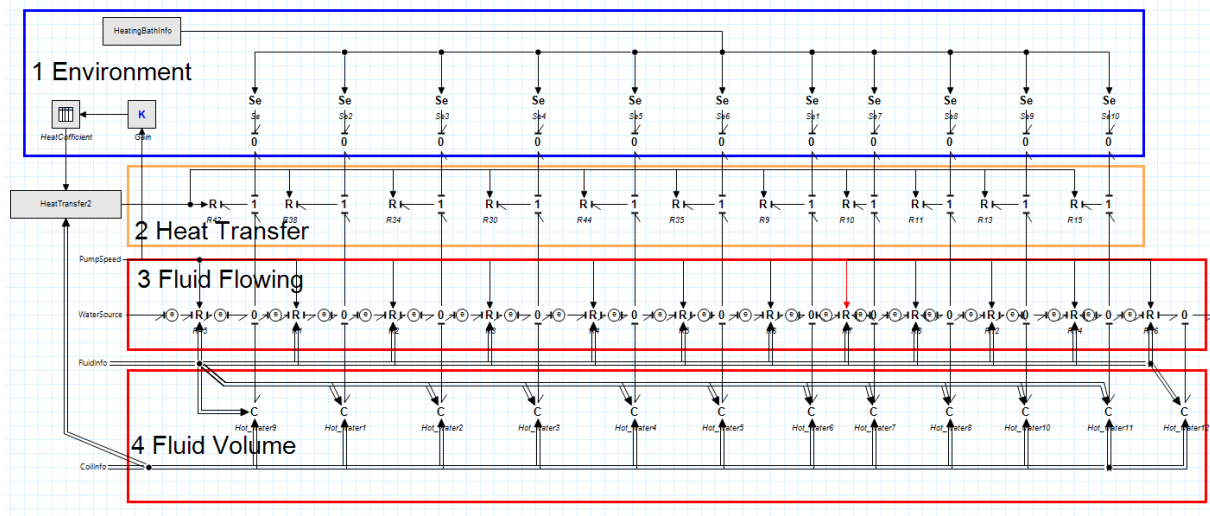


Figure 4-6 Heat holding process model

For the holding tank, it adapts almost the same structure of the heating coil. The same four parts, instead of water bath, the environment affects the simulation. The effort source present the environment temperature. While, the input information is different. The heat holding process aims to keep the energy inside away from heat transferring with the environment. In the experiment, much insulation material is wrapped around the holding hose. Aims to keep the reduction of output temperature as small as possible from reducing the heat transfer loss with the environment. The water bath temperature in the heating part has been changed to the environment temperature. The heat transfer coefficient still keeps a relationship with the volume flow. While, the heat transfer coefficient in the holding part is much smaller than the heating coil. The heat holding process tries to reduce the heat transfer loss with the environment, hence, the heat transfer coefficient is much smaller compared to the heating model. It means only limited heat is transferring between holding "tank" and environment.

The fluid flowing has the same configuration and parameters because the same fluid source. While the fluid volume is different, because the different diameter and volume of holding hose. The parameters of holding hose can be modified in the corresponding model. The detailed parameters are attached in the Appendix.

4.4.3 Cooling Process

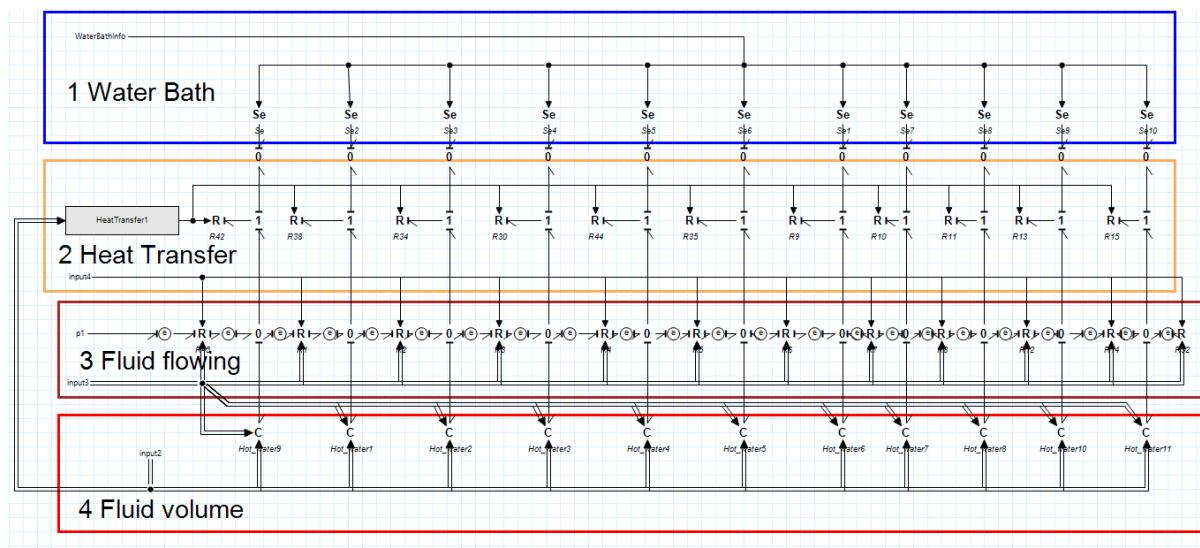


Figure 4-7 Cooling process model

In the cooling part, the water bath in the experiment is filled with water-ice mixture, so the temperature in the cooling bath is always 0. So the corresponding parameter has been configured. The heat transfer coefficient is also attributed to a relationship with volume flow. Higher volume flow will work with higher heat transfer coefficient. Here the same heat transfer coefficient has been adapted as the heating process. The length of cooling coil has been changed to 3 meter, so the corresponding parameters (volume and heat transfer area) should be modified. In the simulation model temperature has been set to 0. The fluid flowing part adapts the same configuration in which the fluid energy is calculated.

4.5 Experiment simulation

4.5.1 Simulation controls

In the previous chapter, the parameters about the experiment has been already introduced. The simulation work has been carried several times for different purposes. First in the pre-experiment, the simulation work was carried to test the basic heating sub-model works properly or not. Then the whole experiment simulation was carried. The simulation time is 50 seconds, in which the temperature will be balanced.

20sim provide several integration methods, different integration method has its corresponding advantages and disadvantages. For this project, the models have derivative causalities and algebraic loops, hence, it is better to adapt the BDF method. Back Differentiation Formula (BDF) is an implicit multi-step variable-order, first-order derivatives method. It is Gear's backward differentiation formula, which is up to fifth order, so 1 to 5 model calculations are needed per time step. The code of the Dassl library is used. It is suitable for models having derivative causalities and/or algebraic loops. This simulation algorithm has 4 parameters: Integration error, Step size, Initial (the step size for the first simulation step default: 0.1), and Maximum (the maximum size of a simulation step default: 1).

Additionally, before the simulation, the corresponding parameters should be taken into the model. The whole simulation process has been applied to the second experiment in which

the sea water was treated. With the model described in the previous chapter. The simulation process has been applied to the second experiment in which the sea water has been treated. In the second experiment, the water was heated to 60° and holding for 30s, 60s and 120s. 55° holding for 30s, 60s, 120s. 50° holding for 60s, 120s. The heat transfer coefficient is calculated with the method mentioned in previous chapter based on the experiment data. For the second experiment, the freshly collected sea water keeps at 7°, and the experiment is carried in 30 minutes continuously which aims to keep a balanced input temperature. The pump speed is configured to 10, 20 and 40 to obtain the corresponding holding time.

4.6 Simulation results and analysis

The results of the simulation are presented in Figure 4-8, 4-9, 4-10. The plot in the figures is the effort of the element, which is also the fluid temperature in the element. The detail data tables are attached in the Appendix. In the tables, all the simulation result is included. While, in the 20sim simulation output plot only one set of data is shown, the other data is include in the tables.

4.6.1 Heating Process

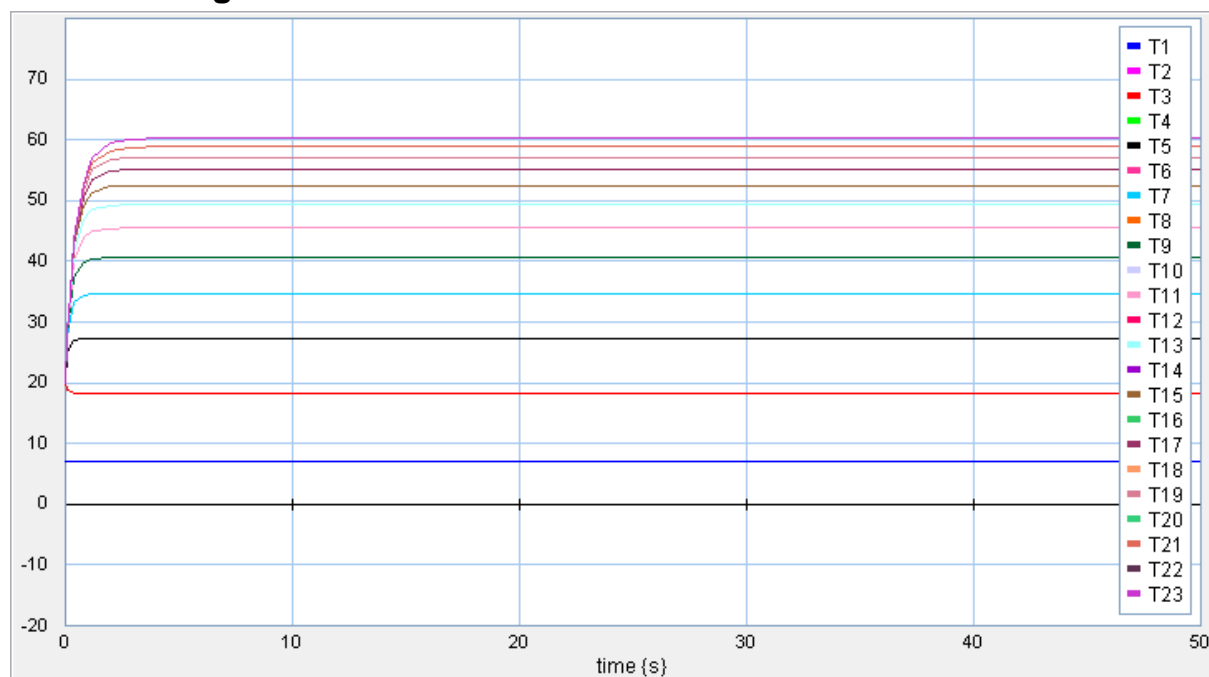


Figure 4-8 Simulation result-heating process

From the simulation curve it can be seen that, in the heating process, when modelling the system, an assumption has been set that inside the system exists the fluid with the initial temperature of 20 degree. The input temperature is 9 degree. The temperature in the element 1 is 9 degree, because there is no heat transfer for element 1. The temperature in element 2 and 3 were a little lower compared to the initial fluid temperature, because the heating process is not enough. But for the later element, the later the element is, the higher the fluid temperature will be. But the maximum temperature is lower than the water bath set temperature. After about 5 seconds, all the element temperature is balanced.

4.6.2 Heat Holding Process

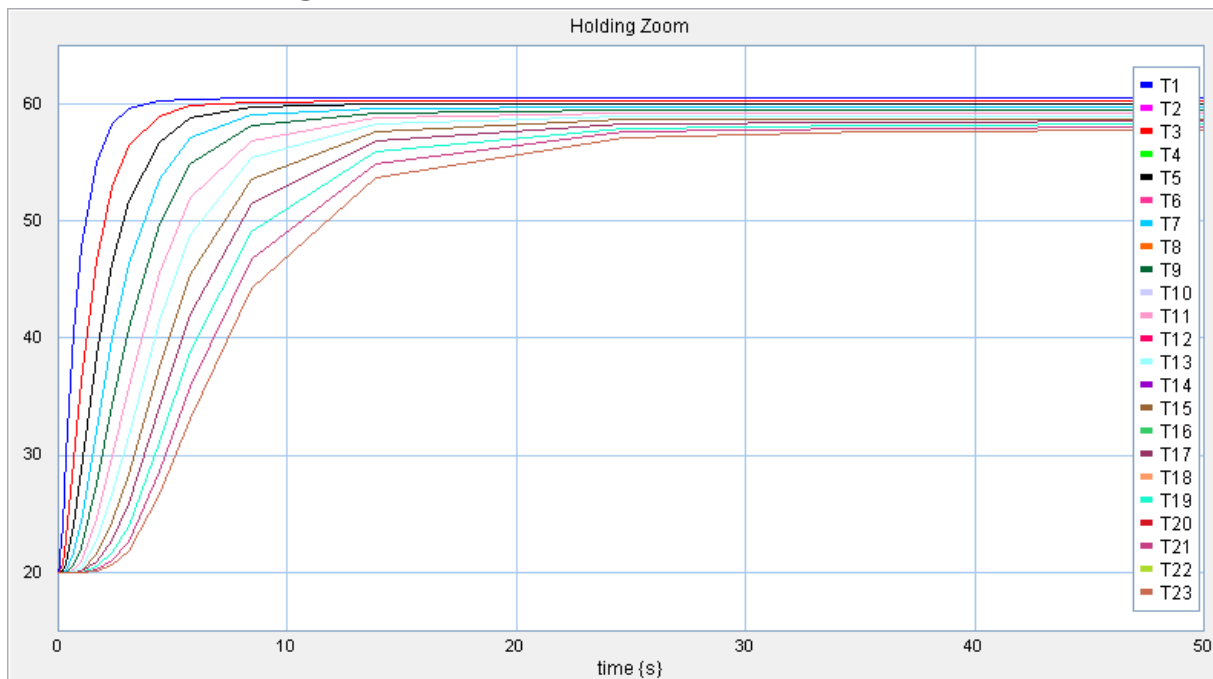


Figure 4-9 Simulation result-holding process

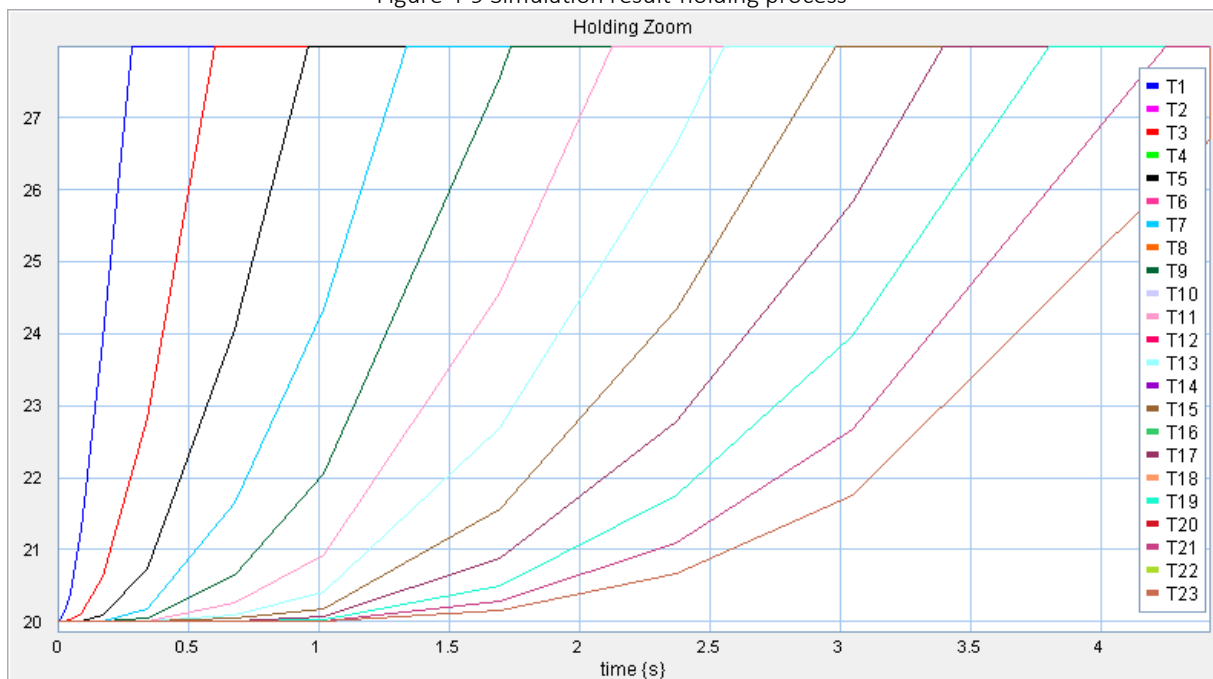


Figure 4-10 Simulation result-holding process zoom

In the heating holding process, the fluid temperature in different are always increasing. The element near the heating part has the fast temperature increasing acceleration. The later element have a smoother curve than the previous element. After the temperature is balanced the previous element will have a higher balanced temperature. Because the previous element have less heat transfer with the environment. The fluid in the last element will have several times heat transfer with the environment. So the temperature is the lowest compared to the others.

4.6.3 Cooling Process

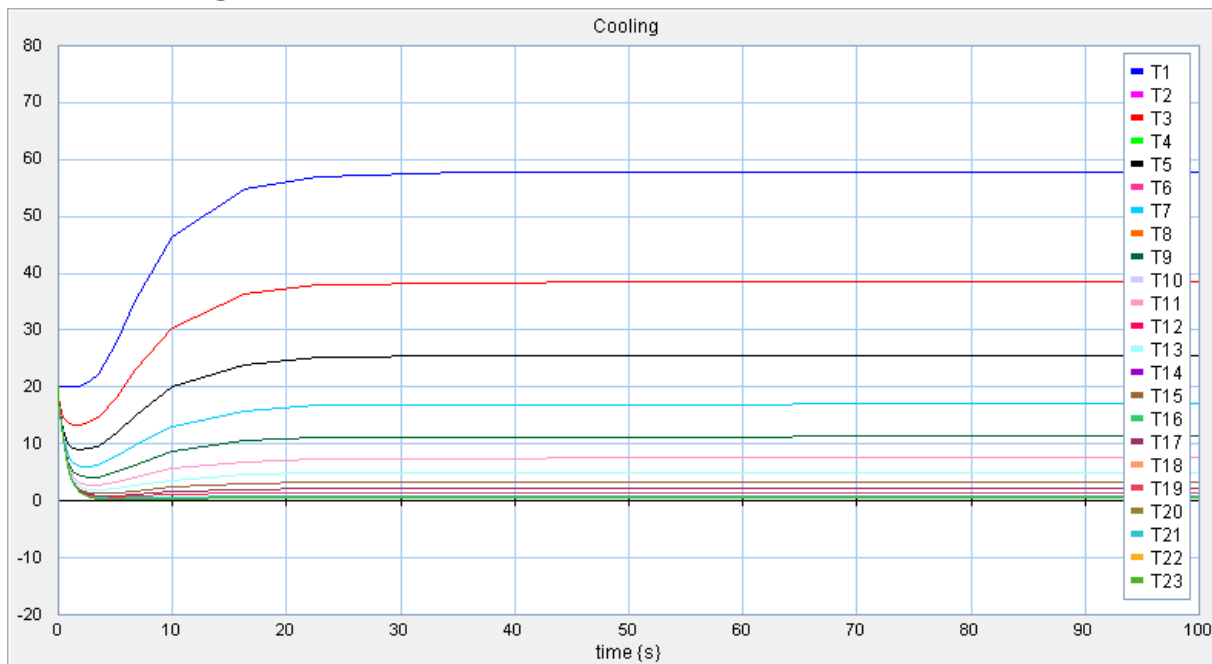


Figure 4-11 Simulation result-cooling process

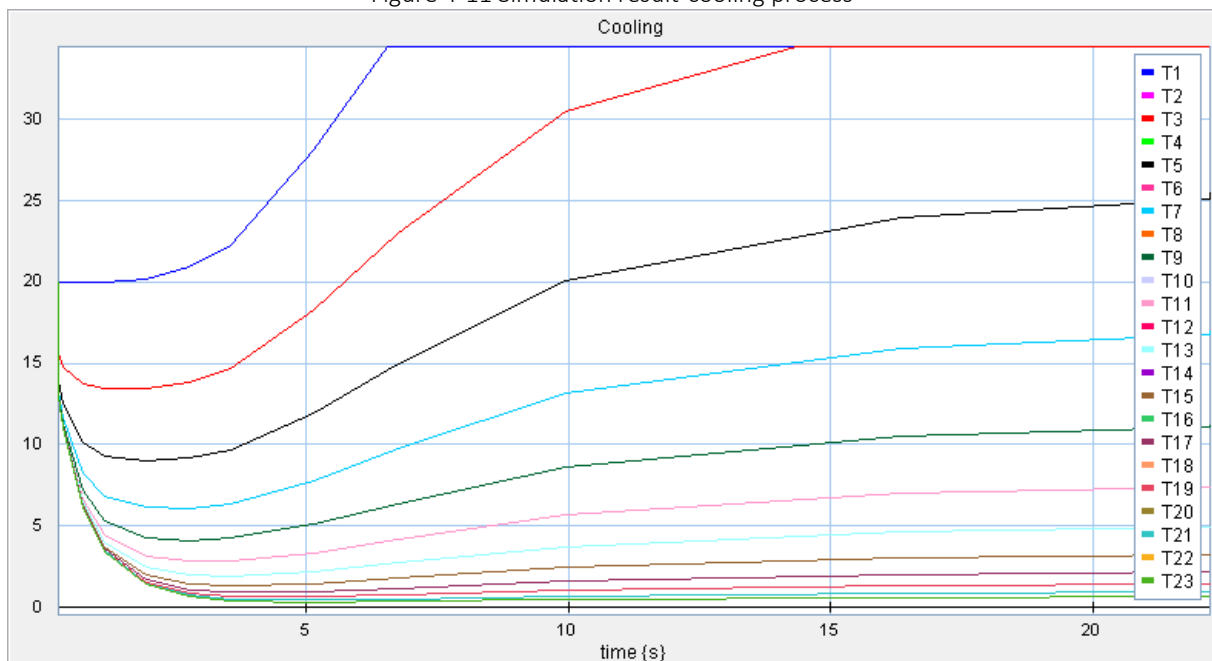


Figure 4-12 Simulation result-cooling process zoom

In the cooling process, the previous element will have a higher balanced temperature due to less heat transfer with the ice-water. The later the element is, the lower the temperature will be. If just focus the temperature changing trend of the second or third element, the initial fluid temperature is 20, then the fluid will heat transfer with the cold environment, so the temperature reduce a bit. Then the higher temperature fluid from the holding will flow in which make the temperature in the element increasing. When the fluid inside the element has a balanced heat transfer with the cold environment, the element temperature will be balanced. For the later element which has more heat transfer with the cold environment. Even though the fluid input temperature is high, after several times cooling, the final temperature will close to the cold environment temperature. On the other hand, this means the simulation curve of later element will be smoother.

4.6.4 Whole process Analysis

From previous explanation and analysis, the plotting result from 20sim just present the temperature in each process element. The relationship between different processing unit could not be defined. The trend could be obtained from the plot, however, the relation could not be clearly defined. In order to analysis the heating process and temperature variation, the element temperature from 20sim are listed and plotted in Excel to show the relation and process. In the excel plot, the holding time of 30s, 60s, 120s with the same water bath heating temperature are presented.

The whole process of heating is shown in the following figures. The three different lines means three different holding time (30s, 60s, 120s). The horizontal direction is the element number or time schedule. The vertical direction is the scaling of temperature.

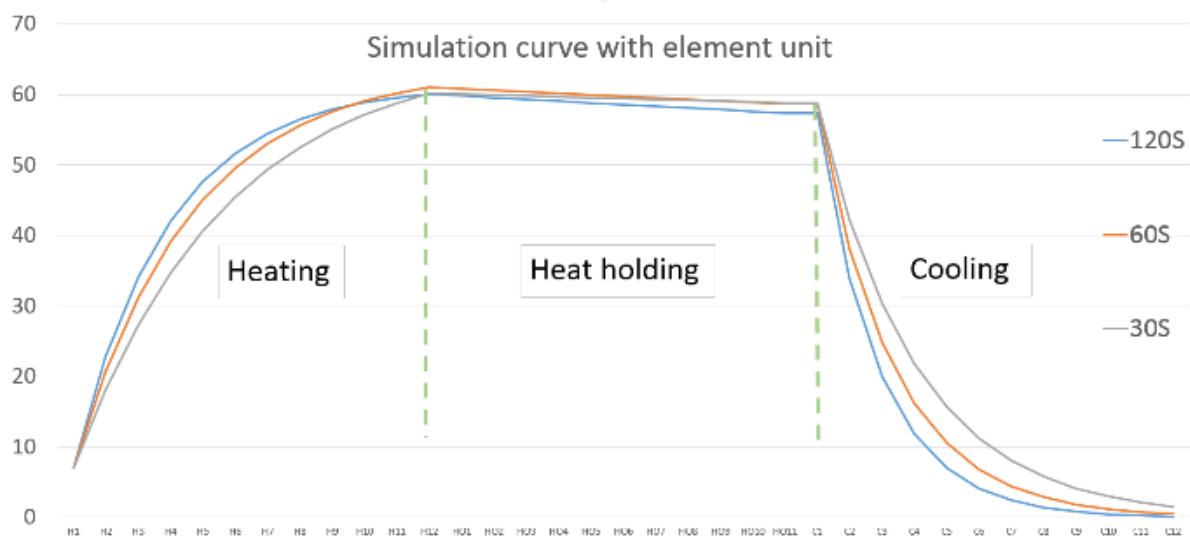
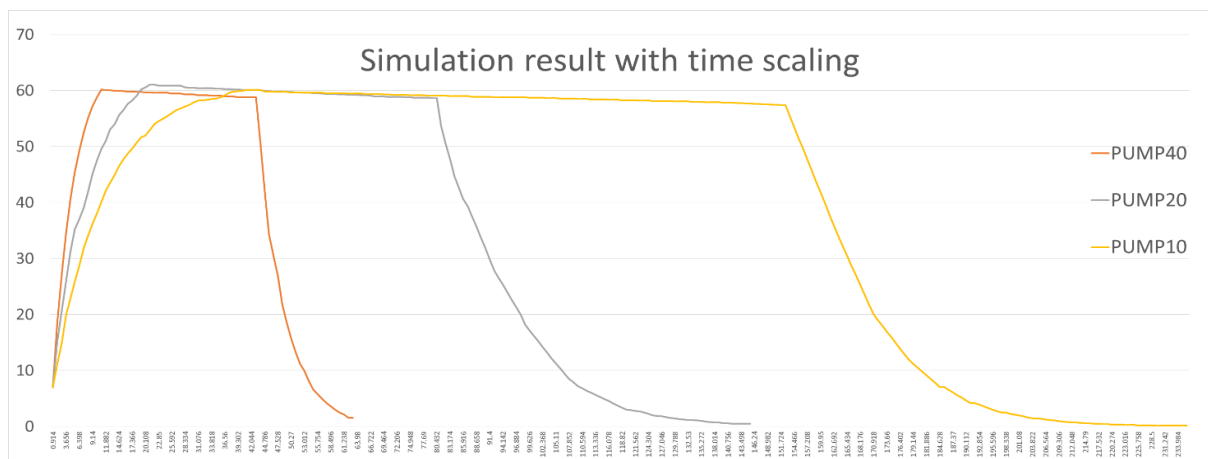


Figure 4-13 Simulation result curve with element unit scaling

The whole process is presented in Figure 4-13. In the same element position, the longer heating time (lower pump speed) have higher temperature. Because the same amount of heat transfer energy, so less amount of fluid will have higher temperature or shorter heating time. The acceleration of heating is reducing through the heat process. Because the higher the temperature, the higher heat losses. So the heating acceleration is decreasing. The temperature in holding process is reducing approximately linear. The insulation material try to reduce the heat transfer with the environment. Hence, the temperature variation of temperature is tiny. So the heat transfer curve is almost linear. The simulation result is almost the same as the result measured from experiment (input holding and output holding). The cooling process shows the same trend as heating. In the initial stage, the temperature decrease dramatically, with a higher de-acceleration. When the fluid pass just 1/3 of the cooling element, the temperature reduce almost 4/5 of the entire variation. As the temperature difference decreasing, the temperature reduce more slowly. Then finally the cooling temperature is balanced.



4.7 Experiment results and analysis

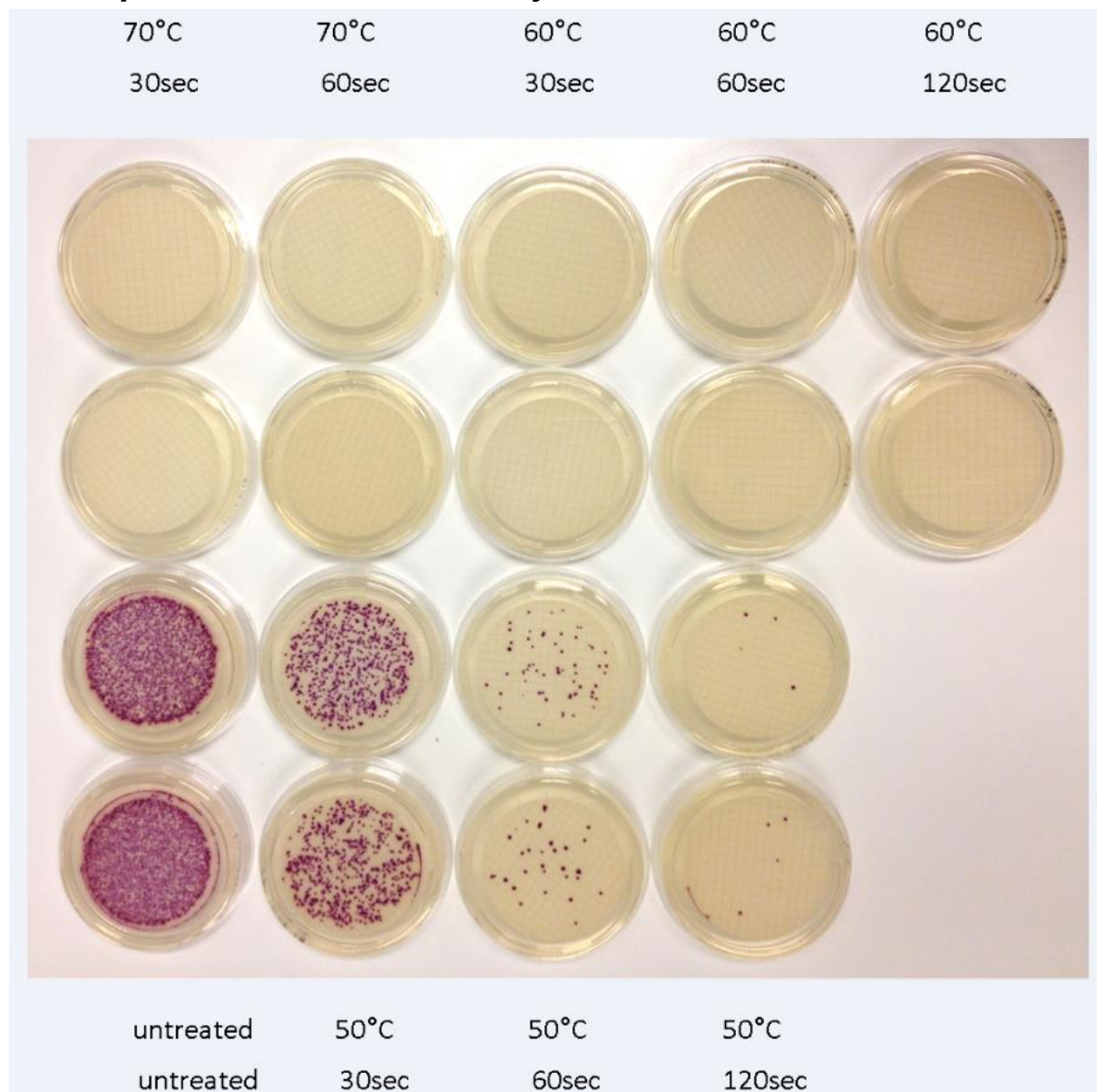


Figure 4-15 February 2 experiment result

In this project, the biological analysis is applied by Yanran Cao who is a researcher at the Faculty of Life Science at Aalesund University College. The experiment has been carried two times. In the Figure 4-15 shows the result carried in February 2.

Under the heating temperature of 70°C, the holding time are 30s and 60s. Almost all the bacteria has been killed under this situation. So it is effective to adapt this treatment temperature. Then the heating temperature are reduced to 60°C, the holding time are 30s, 60s, 120s. Because the reduction of the heating temperature, the longer holding time is used to compensate the treatment. For this situation, it is also effective to adapt this heating temperature and holding time. In order to save the energy, and make the system efficiently, the last experiment under 50°C is adapted. The result of 30s holding time compared to the untreated sample, it is not very effective, almost 40 percent left. The 60s result is much better compared to 30s. On the other hand, the 120s holding time samples almost kill all the bacteria, but still could not kill all of them. As a consequence, the temperature of 50 is not high enough for the treatment.

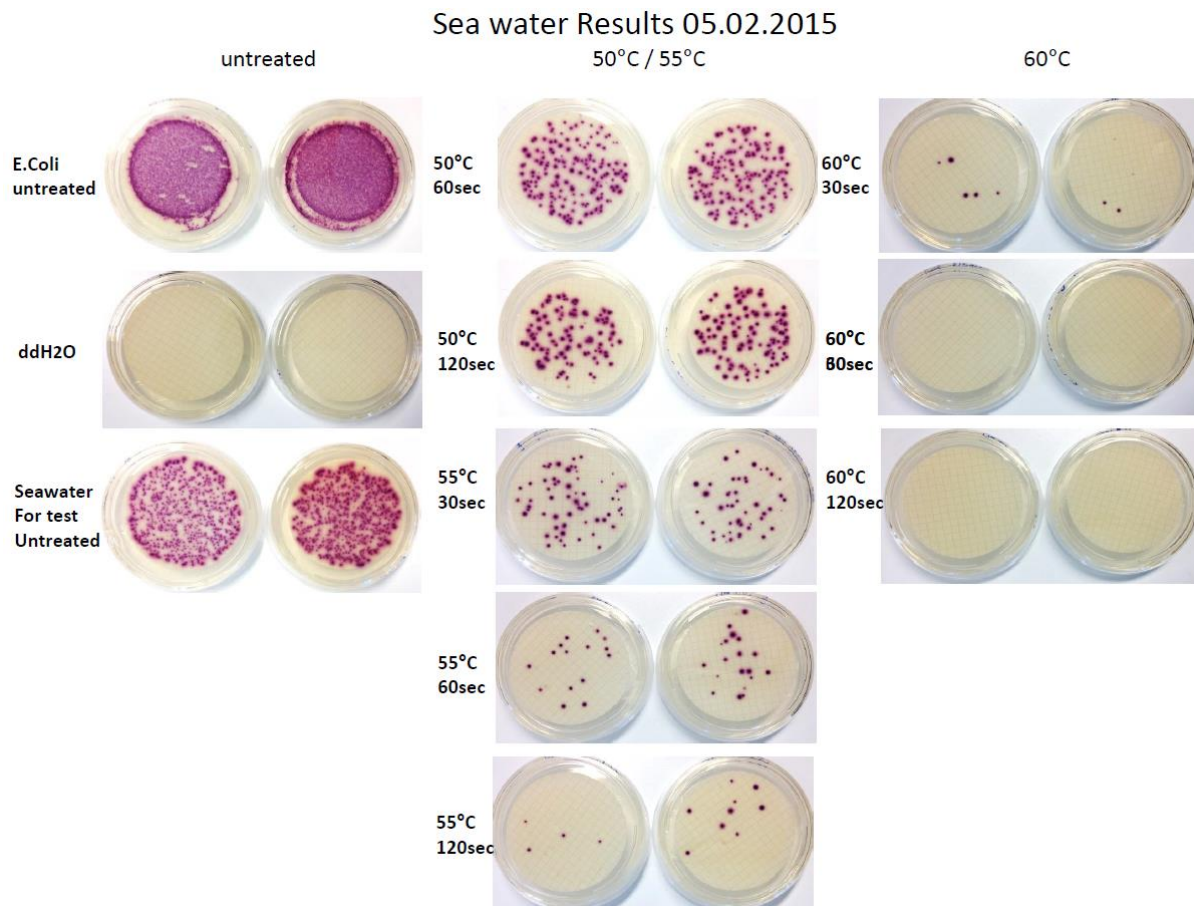


Figure 4-16 February 5 experiment result

From the experiment result carried in February 2, the lowest effective heating temperature is 60°C. Even though, the heating temperature 50°C is not effective, but the heating temperature between the 50°C and 60°C has not been tested. So a new set of experiment was carried in February 5, the experiment result is shown in the Figure 4-16.

From the result figure, it can be seen that, the 55°C heating time could not kill all the bacteria even though the longest holding time 120 seconds is carried. Under the heating temperature of 60°C, the result shows the same trend as the experiment in February 2. However, the holding time 30 seconds in the February 5 did not kill all the bacteria as the same configuration in February 2. So additional experiment and test should be investigated and carried.

5 MACHINERY SYSTEM SIMULATION

5.1 Machinery system introduction



Figure 5-1 Ship machinery system

The trend today shows that marine machinery system designs tend to head for more complex solutions as more decisive factors are implemented such as the operational profile, higher investment costs, stricter rules and regulations, and increasing amount of available optional configurations and solutions regarding system and component selections.

From a designer's point of view, in the early phases of the design, it is important to narrow down the amount of concept solutions and to present the best ones or the best one for further evaluation. This is a challenge designers are facing now and in the near future.

In this part of the thesis aims to develop propulsion system in the 20sim environment. The propulsion system consists of diesel engine, generator, gear box, thruster, governor and so on. Compare to other simulation software, such as Simulink in Matlab and Simulation X, in the 20sim the user could modify and define the parameters and functions based on individual needs without any limitations.

From the propulsion machinery system library, the user could built up different machinery system for the target ship. Then simulate the propulsion system working condition, and calculate different results which are beneficial for modification and optimization. Then the ship behavior will be set up to simulate different working condition of the ship, which will present different load on the machinery system.

Key components in propulsion library

5.1.1 Diesel Engine

Most of the engine operate on the vessel is the diesel engine which is a kind of internal combustion diesel engine. In the combustion room, the mixed gas is compressed, resulting in increase of temperature and pressure. Air is compressed in a cylinder by the piston,

generally to a compression ratio of 16:1 to 23:1. When the compressed air reaches a superheated state, around 538°C, diesel fuel is injected and ignites. The ignition causes an internal combustion which forces the current cylinder volume to expand. The expansion in the cylinder volume forces the piston down transforming some of the heat energy into mechanical power. This can be explained by the pressure-temperature law; the cylinder volume increases, hence the gas temperature decreases. The higher the compression ratio, the greater the expansion of the gases on the power stroke. The average thermal efficiency is typically 30%-40%, due to heat loss through exhaust gas, cooling systems and the engine surface. Compared to the gasoline engines, the diesel engines have higher

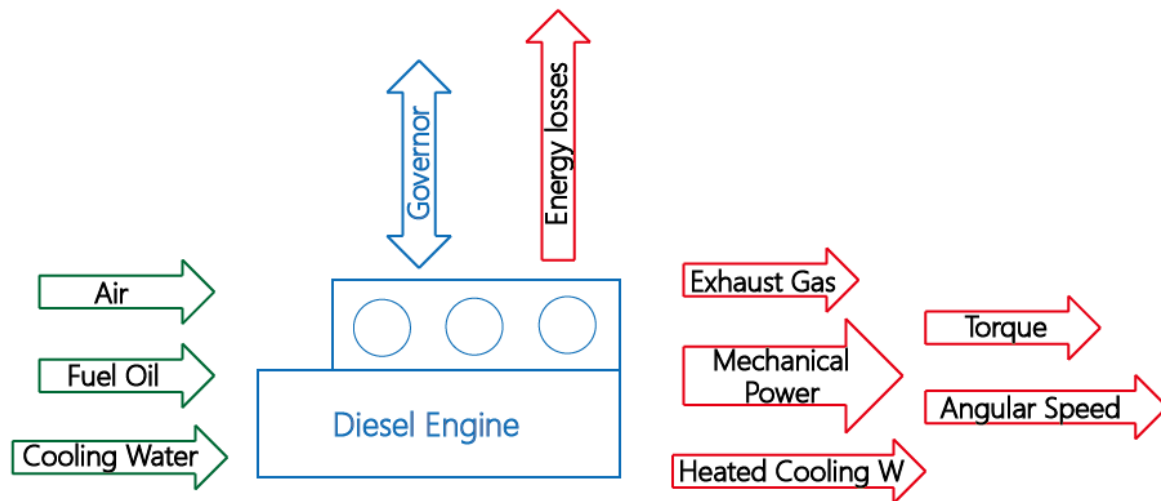


Figure 5-2 Diesel engine energy flow

compression ratios, so the diesel engine systems have higher thermal efficiency.

- 2-stroke cycle diesel engine

The piston starts at the top of the cylinder on its compression stroke. The cylinder is filled with pressurized, superheated air. Diesel is injected and ignites. The cylinder is forced down. When it is close to the bottom the exhaust valve is opened and most of the exhaust gases rush out of the cylinder. As the piston continues to descend it uncovers a series of ports in the cylinder wall. Air is blown through these ports by a supercharger or a turbocharger, pushing the rest of the gases out of the cylinder and refilling it with a fresh air charge. The exhaust valve closes and piston moves upwards.

As the piston moves up it closes the air inlet ports and compresses the fresh air. When it reaches the top of the cylinder the fuel is injected and the cycle is repeated.

- 4-stroke cycle diesel engine

The 4-stroke engine is a bit different compared to the 2-stroke engine. The inlet valve opens. The piston starts at the top of the cylinder descending down drawing air into the cylinder. When the piston reaches the bottom of the cylinder the inlet valve closes. The piston travels upwards compressing the enclosed air to 31 to 48 bars. The compression causes the temperature rise to 538°C or more. At the top of the compression stroke fuel is injected. The temperature increases rapidly to 760°C and the pressure increases to 58 to 69 bars. This reaction forces the piston down causing a sudden drop in both temperature and pressure.

When the piston reaches the bottom, the exhaust valve opens. The piston travels up forcing the gases out. When the piston reaches the bottom, the exhaust valve opens. The piston travels up forcing the gases out. When the piston reaches the top, the exhaust valve closes and the cycle is repeated.

To simulate the diesel engine, different simplified level will be applied on the modelling. The library will have different kinds of diesel engine for different simulation purposes. The diesel engine could model on pressure distribution of cylinders, also can be modelled on fuel consumption.

5.1.2 Governor

The governor is an important component for the engines. It controls the engine speed by controlling the amount of fuel injection. It provides the engine with the feedback mechanism to change speed and most important to maintain a desired speed, dealing with load variations.

Typical governor for diesel-electric system has mainly two operation modes; droop and isochronous mode. The droop mode, also called speed droop, allows for the steady-state

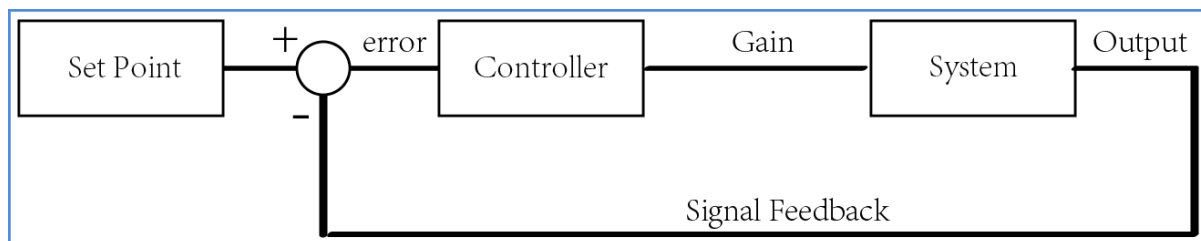


Figure 5-3 Governor control theory

frequency to drop proportionally to the active load. This mode is common in load sharing between generator sets. The isochronous mode keeps the frequency at a set point by utilizing a regulator with an integral effect.

On the other hand, the governor is a **PID** controller. PID control means Proportional, Integral and Derivative control. A standard control loop is shown in the figure below. The controller tries to steer a process in a way minimizes the difference between a given set point and the output of that process.

Set point

The set point (SP) is where the process output should match. In this model set point is the reference value.

The controller is an algorithm within a control system. The basic principle is to control the input to a system to get the desired output. The controller gets or calculates the difference between the desired output (set point) and the actual output. This is called the error. The error is a measure for how much the process deviates from the desired set point, and thus how much the controller should respond to get the reference point.

- Proportional Control

The proportional action of a controller generally refers to the proportional gain. The action means that the controller moves in proportion to the error between set point (SP) and measured variable (MV):

$$\text{Controller output} = k * \text{error}$$

- Integral Control

With integral action, the controller output is proportional to the amount of time the error is present. Integral action eliminates offset that remains when proportional control is used.

$$\text{Controller output} = \frac{1}{T_i} * \text{int}(\text{error})$$

Where the parameter T_i is called the integral time. Integral action is also known as reset and the parameter T_i as reset time. But if the system works with integral control may lead overshoot.

- Derivative Control

With derivative action the controller output is proportional to the rate of change of the measurement or error. Some manufacturers use the term rate or pre-act instead of derivative. Derivative, rate and pre-set are the same thing. The controller output is calculated by the rate of change of the error with time.

$$\text{Controller output} = T_d * \frac{d(\text{error})}{d(t)}$$

Where the parameter T_d is called derivative time.

In summary, the PID controller equation can be described as:

$$\text{Controller output} = k * \text{error} + \frac{1}{T_i} * \text{int}(\text{error}) + T_d * \frac{d(\text{error})}{d(t)}$$

5.1.3 Generator

Typical generators in an AC power plant for diesel-electric machineries are synchronous machines with a magnetizing winding on a magnetizing winding on a rotor which carries DC current, and a three-phase stator winding where the magnetic field from the rotor current induces a three-phase sinusoidal voltage when the rotor is rotated by the prime mover. The frequency, f , for induced voltage is proportional to the rotational speed of the DE, n , and the pole number, p , in the synchronous machine.

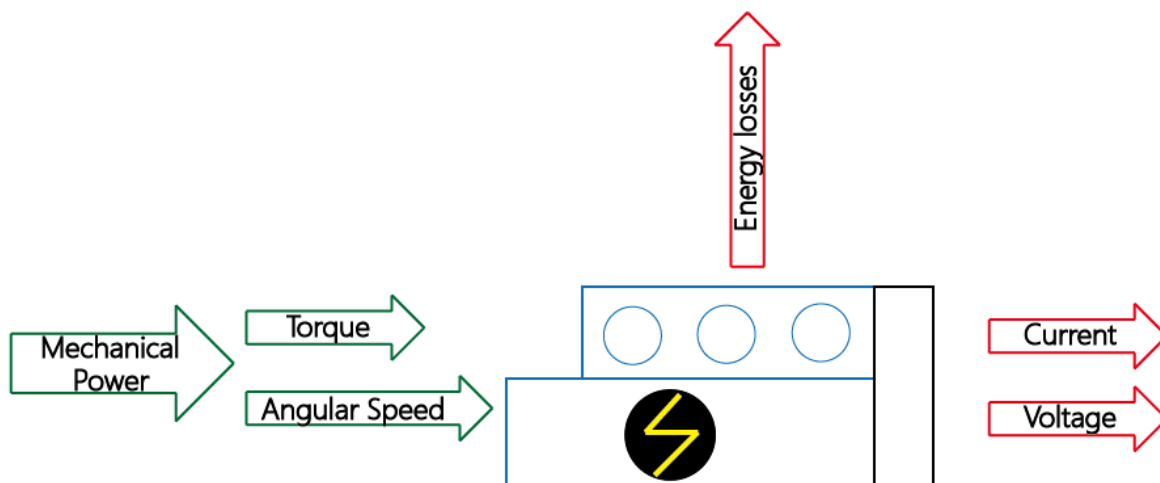


Figure 5-4 Generator energy flow

Mostly, the prime mover will be a large medium speed diesel engine normally work at 720 RPM for a 60 Hz Network. The DC current is transferred to the magnetizing windings on the rotor by slip rings, brushed or brush less excitation. The latter reduces downtime and maintenance.

The brush-less excitation machine is an inverse synchronous machine with DC magnetization of the stator, rotating three-phase windings, and a rotating diode rectified current is then feeding the magnetization windings. Cooper damper windings are installed in order to introduce an electromagnetic damping to the stator and rotor which removes large oscillations in frequency and load sharing for any variations of the load.

The automatic voltage regulator (AVR) controls the excitation. It senses the terminal voltage of the generator and compares to the reference value. The controller has PI characteristics with stationary limited integration effect that results in a voltage drop depending on the generator load. This effect define what voltage variations are acceptable. This applies for stationary voltage variations and voltage variations due to large transient loads. The AVR assures these requirements by a feed-forward control function based on measuring the stator current.

The generator modelling is based on the diesel engine. The generator are composed of a medium sized diesel engine and a generator, which will convert mechanical energy into electrical energy.

5.1.4 Electric motor

Electric motors are the most common drive in diesel-electric machineries for transforming electric power to mechanical power such as propulsion, winches, pumps, etc. There exists many types of electric motors, but the most common is the asynchronous (induction) motor which is considered the workhorse of the industry.

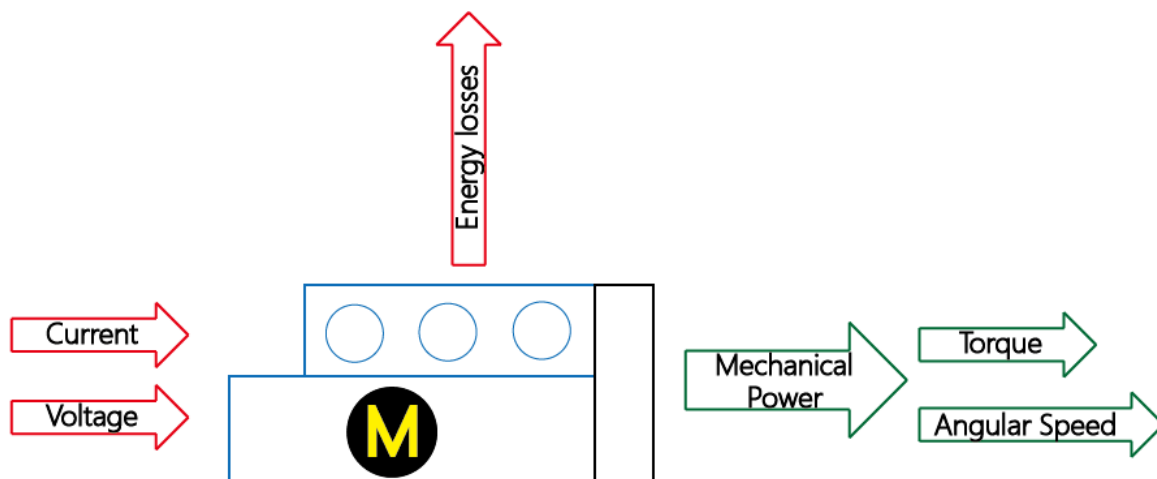


Figure 5-5 Motor energy flow

The asynchronous motor is rugged and simple in design which results in a long lifetime, minimum of break-down and maintenance. The motor can run at constant speed directly connected to the network or at variable speed with feed from a static frequency converter. The three-phase stator windings are constructed similar to a generator. The cylindrical rotor has an iron core and a short-circuited winding similar to the damper winding in a synchronous machine.

When the motor is run as a constant speed, direct-on-line motor, at no load, the voltages imposed to the stator winding will set up a magnetic field in the motor. The magnetic field crosses the air gap and rotates with a speed given by the frequency of the imposed voltages, which is called synchronous frequency, f_s . The synchronous speed, n_s , in RPM is given by:

Currents are induced in the rotor windings as the shaft gets loaded since they are rotating relatively to the synchronous rotating magnetic field from the stator windings. The lag of the motor speed to the synchronous speed is defined as slip.

For propulsion and pumps there is a potential for saving power by reducing the no-load dependent losses in operations. This can be achieved by variable speed drives. The variable speed drives have a high capital cost but a lower operational cost than the constant speed drive.

The most common variable speed drives are voltage source inverter (VSI), current source inverter, cycloconverter, consist of a rectifier, which rectifies the line voltage, and an inverter, which generates the variable frequency and variable voltage source for the motor.

The motors are controlled by a controller which contains speed control and controller for switching elements of the rectifier and inverter. The motor controller measures motor speed and current or voltage based on signals and feedback signals from sensor.

5.1.5 Central Cooling system

Introduction

The diesel engine, generators and the other machinery components, could not work independently. During the process of operation, the machinery system need to operate with cooling system. The primary objective of cooling system is to remove heat energy

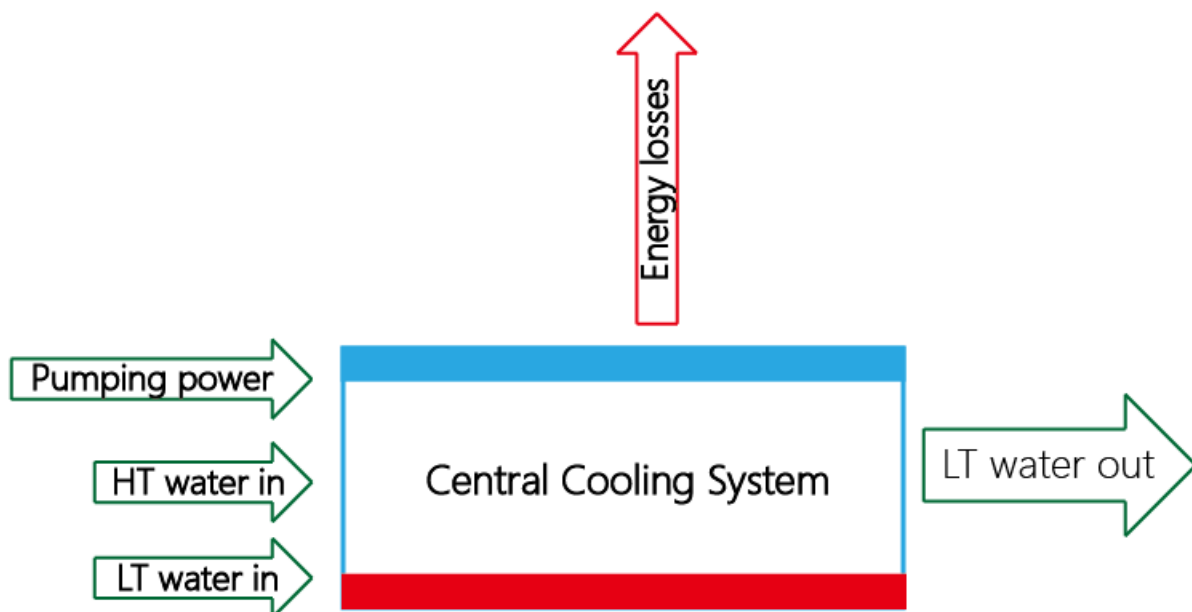


Figure 5-6 Central cooling system energy flow

from a system or a equipment. It consists of heat exchangers, pumps, pipes, valves and filters. The system configuration varies with different engine configurations, desired effect, and economic and environmental restrictions. The cooling process in the cooling system originates in the heat exchangers.

Due to energy utilization concerns, it is desirable for the heat exchanger to operate with the lowest possible temperature difference. On the other hand it is desirable to reduce the pressure loss for cooling agents and as a result reduce the energy demand for the pumps. This indicates that there are dependencies in the system configuration, which means that one component not only have to be effective by itself, but contribute to a total effectiveness of the whole system, also regarding the economic aspect.

A cooling system for a DE can in many cases be relatively large and complex with a high number of components such as listed above which can be controlled both automatically and manually. As a result, a lot of different system solutions emerge with different technical and economic properties.

A cooling system has at least two circuits for different cooling purposes. One is low temperature cooling system (sea water), and one high temperature cooling system (fresh water).

Cooling system requirements

- The work load on the pumps has a relation with the load on the machinery components. Different components will have different temperature range, this results in a set requirements which the cooling system must comply with. Some of these requirements are presented below:
- Remove heat from engine cylinders, cylinder head, turbo-charger, and pistons. The coolant in the high temperature (HT) circuit, in the range 65-90 C degree, must be fresh water. Under high temperature, the sea water will cause corrosion and fouling.
- Remove heat from the charge air cooler after the turbo charger. The charge air is cooled down to 40-50 degree, hence the coolant must be relatively cold. Sea water or cooled fresh water is used for this process.
- The sea water circuit's, the low temperature (LT) circuit's, main functions is to circulate through the heat exchangers and cool the fresh water (HT) and lubrication oil. The temperature in LT circuit should be kept below 50, due to risk of fouling.
- The cooling system should also in some designs remove heat from auxiliary components such as; auxiliary engines, compressors and condensers, if there is not already established a separate cooling system.
- Values introduce a risk of corrosion due to turbulence in the flow. In order to reduce the risk, limitations for maximum flow velocities must be established.
- Only treated fresh water can be used for cooling the engines in order to prevent corrosion. A corrosion inhibitor can be added to the fresh water in order to prevent this.

The LT cooling system is an open circuit. Sea water is pumped through the sea chest by a sea water pump and at the end pumped over board back into the ocean. The sea water is first run through a de-aerator in order to avoid low vacuum levels. When flow through the charge air coolers, sea water flow at low temperatures comes before coolers such as the fresh water coolers with high temperatures. After the sea water is run through the coolers, it is pumped over board or to the sea water pump if the sea water is very cold.

The HT cooling system is a closed circuit. The fresh water is pumped through the circuit at a constant flow rate cooling the engines. If the temperature in the fresh water becomes too low, it will cause a risk of creating sulfur compounds which will cause corrosion on the

cylinder sleeve. On the other hand, it's possible to bypass the coolers, by a three-way valve, to obtain the desired temperature. Due to required redundancy in the cooling system, double sets of lube- and freshwater coolers are built.

The heat exchanger is the main component in the cooling system. It can be arranged in series, parallel, or a combination of the two. The different configurations will have different pressure losses over the heat exchangers which must be taken into account in the design process.

5.2 Machinery components modelling

In this project, different machinery components is modelled separately and simulated in different assemble configuration. Maybe the machinery system assemble together and simulated will have more accurate result of dynamic system. But due to the limitation of the software environment of 20sim and the computer performance, the simulation speed is too slow to present and the whole system simulation is unstable. Maybe in the future, if needed this part of the simulation can be separately simulated in different computer and combine together. Or with the other appropriate solution.

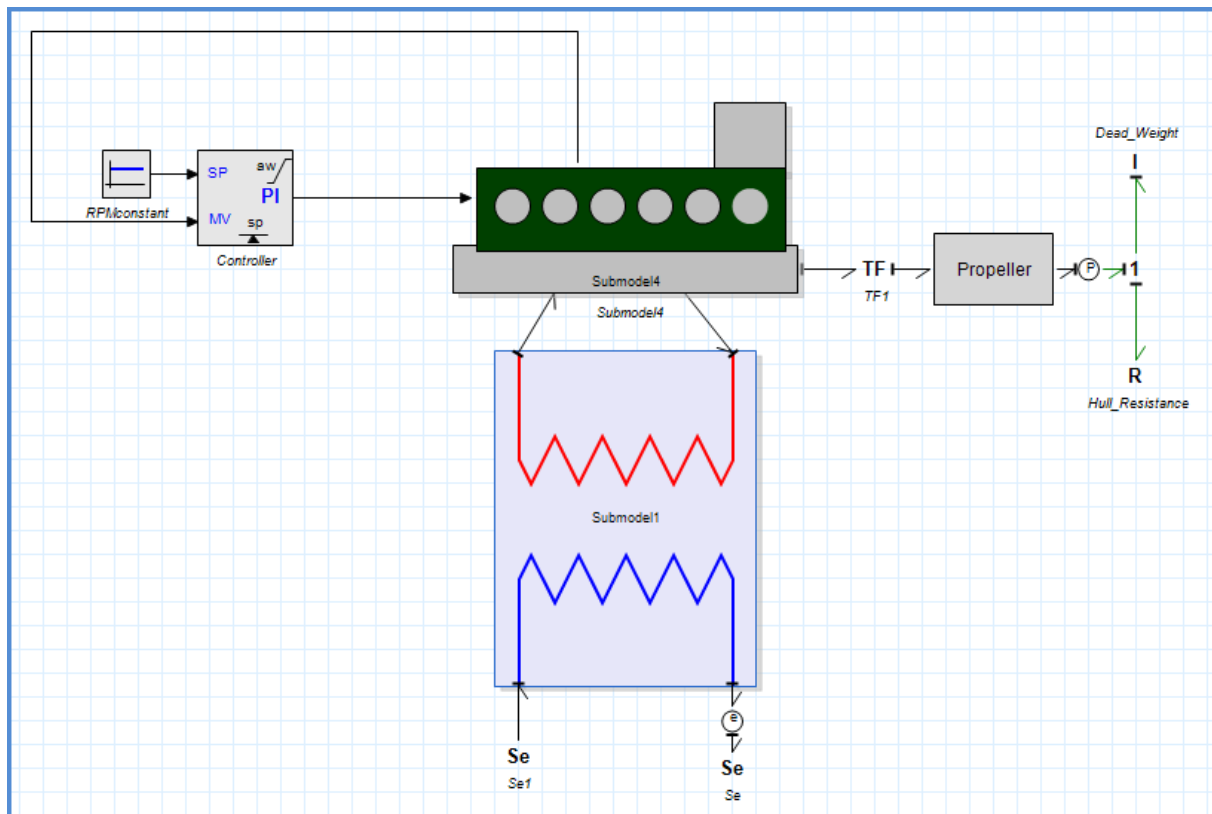


Figure 5-7 Diesel Engine directly propulsion system

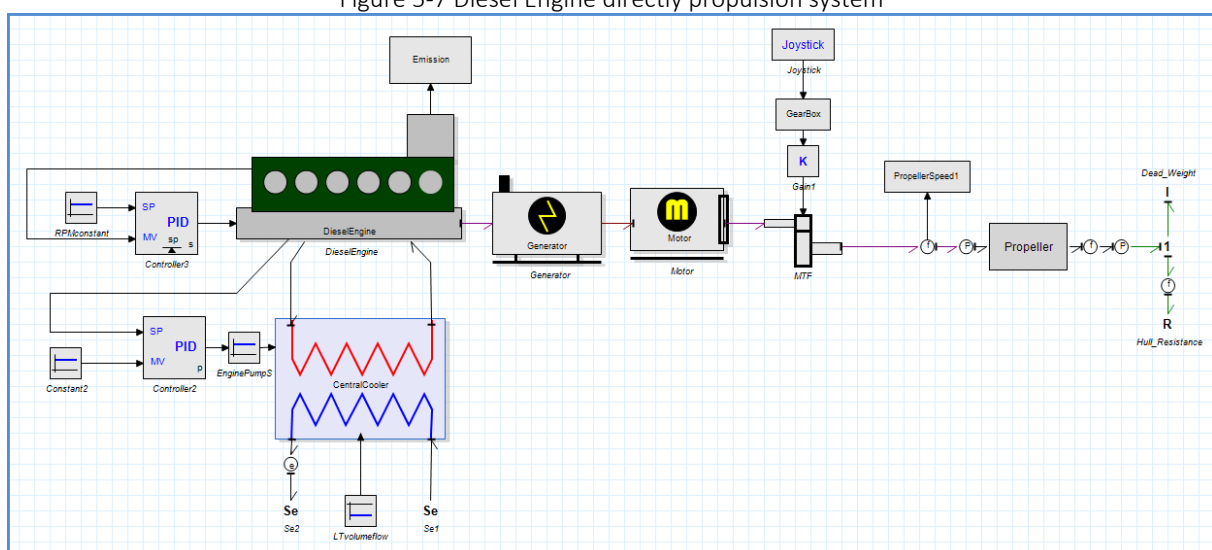


Figure 5-8 Diesel-electric propulsion system

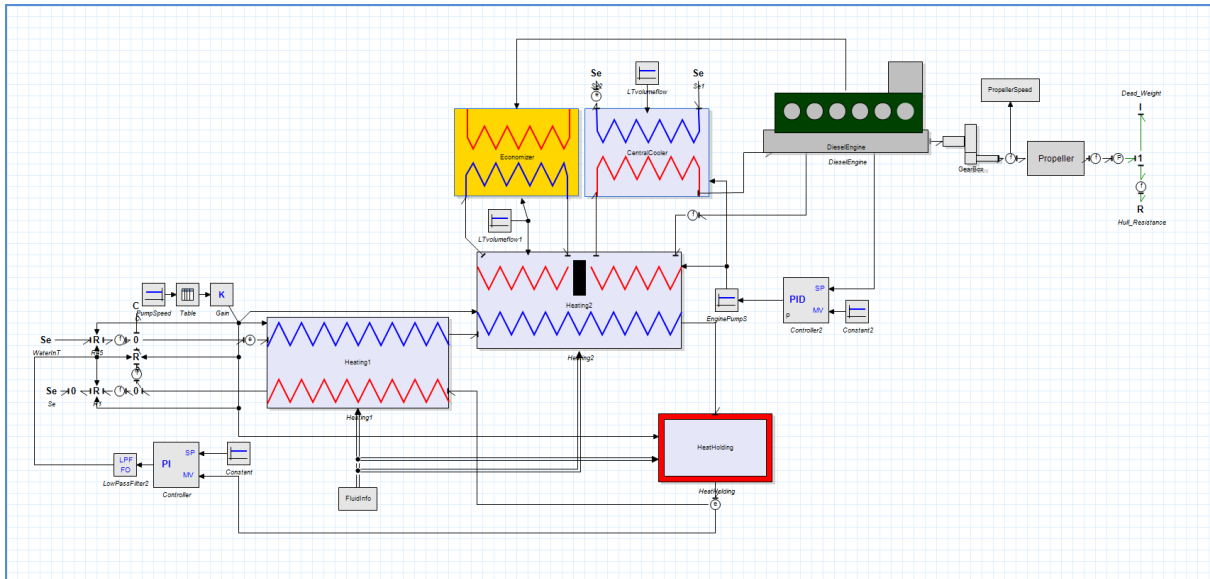


Figure 5-9 Waste heat recovery system

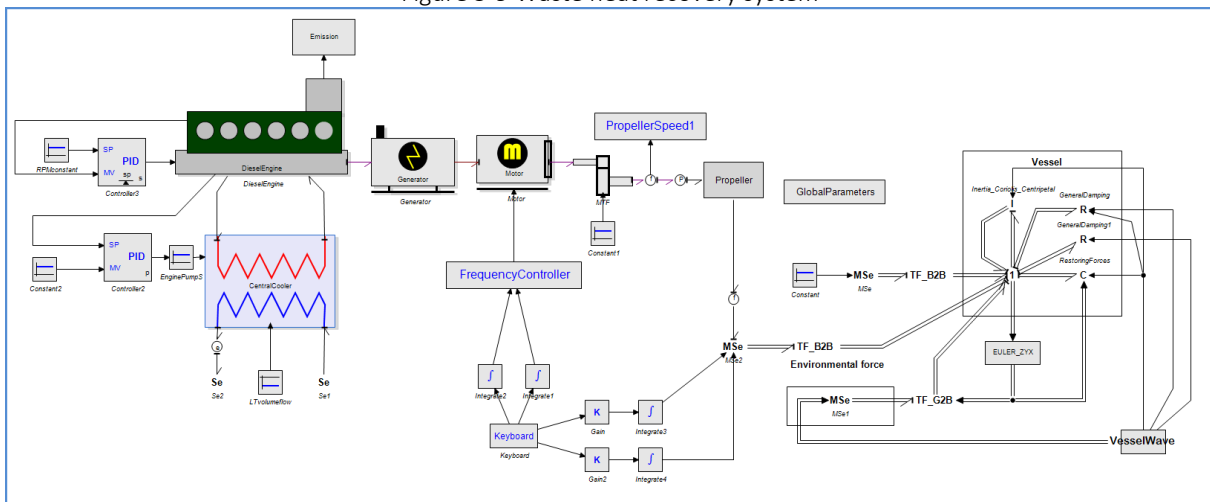


Figure 5-10 Vessel behaviour simulation model (Control Real time simulation)

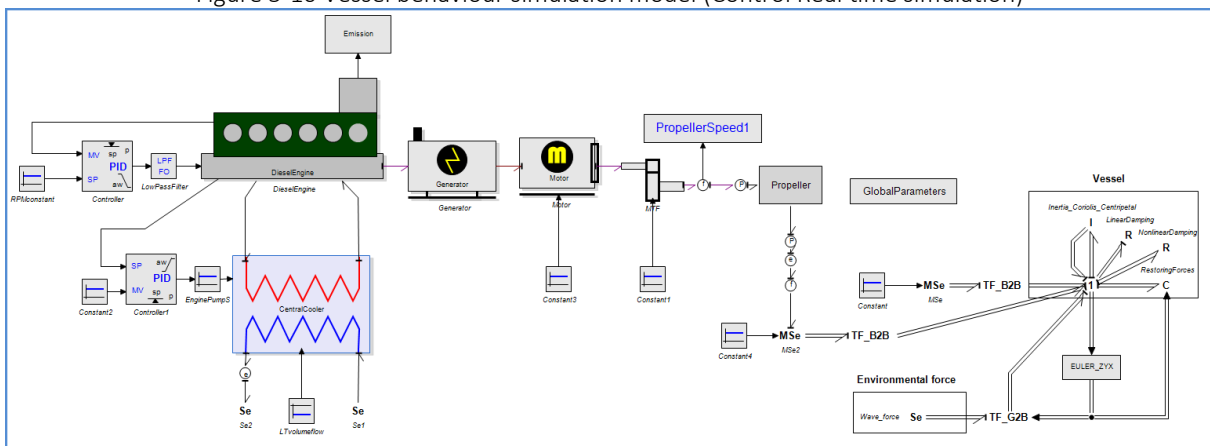


Figure 5-11 Vessel behaviour simulation model

In the previous figures, just show the layout of different machinery assemble examples. The detail modelling method and simulation will be introduced in the following text.

5.2.1 Diesel engine modelling

The diesel engine aims to provide the required torque and angular speed required. In the project, the diesel engine is connected with the generator, in order to keep the constant voltage and current into the motor. The fixed RPM of the diesel engine should be controlled by the governor. The energy into the diesel engine is the fuel oil chemistry energy. Then through the combustion process, the chemistry power will change into mechanical power. The layout of the model in the 20sim is shown in the following figure.

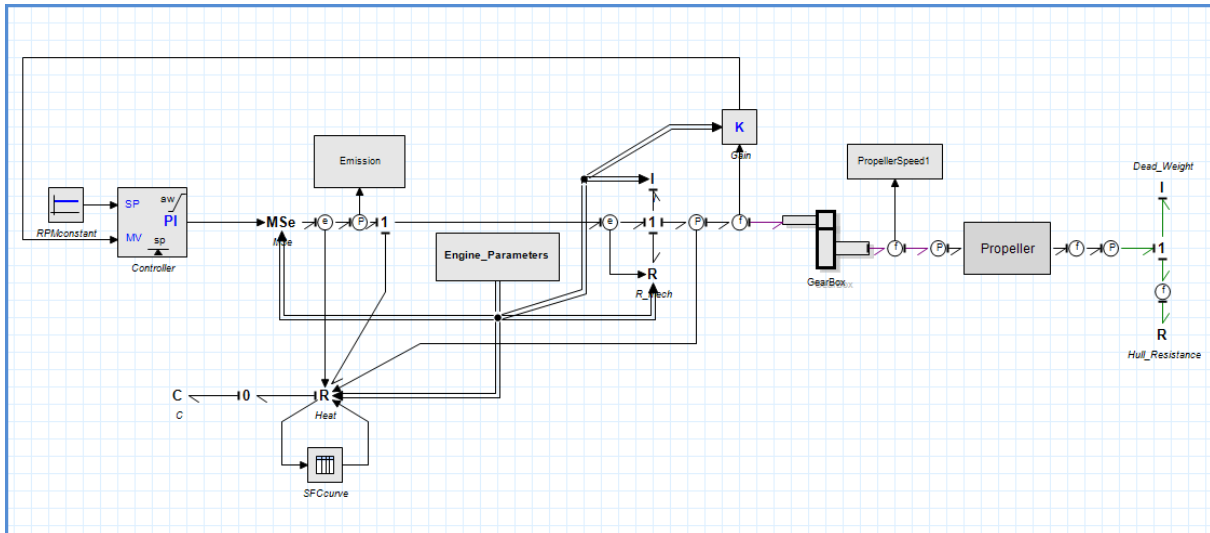


Figure 5-12 Diesel Engine model

In order to apply for the whole simulation and flexible assemble, the diesel engine modelled here does not consider so much detail about the diesel engine inside. Such as different number of cylinder, pressure variation. On the other hand, if the complex diesel model is adapted, the simulation speed will be very slow. So, based on appropriate simplification, this diesel engine model is set up.

In this diesel engine model, the governor is adapted to keep a constant RPM output. Thermal losses and vessel loads is included in order to simulate the engine operation condition. The bond graph structure shows that the diesel engine consists of an **I** element which means the inertia of the engine (shaft, cylinder or the other components). **R** element presents the mechanical and thermal losses. Then pass the **TF** element which present as the gear box.

Working principle of the diesel engine:

- The output torque is provided by the fuel inject controlled by the governor. Then the torque will power the vessel load. Due to the mechanical power transmissions and the combustion process with in the engine, the mechanical and thermal losses is applied. Part of the losses is the thermal losses, this part of energy is removed by the engine cooling system. The engine cooling water inside the cylinders circulates and absorbs the heat energy. Then take the waste heat out of the engine transfer to the central heat exchanger.

Related equations:

1. Fuel injected per-cycle:

$$m_{fuel} = s * MCR * SFC_{MCR} * \left(\frac{0.001}{3600}\right) / (RPM_{MCR} / (60 * N))$$

- s : Governor control signal
- MCR : Maximum continuous rating power
- SFC_{MCR} : Specific fuel consumption under maximum continuous rating power
- RPM_{MCR} : RPM under maximum continuous rating power
- N : For 2-stroke equals 1, 4-stroke equals 2

2. Torque Output

Theoretical torque output:

$$T_t = \frac{P_t}{\omega} = \frac{m_{fuel} * h_n}{2\pi * N}$$

Indicated torque output

$$T_i = T_t * \left(1 - \frac{1}{\eta_m * h_n * SFC_{indicated} / 3600}\right)$$

$$SFC_{indicated} = SFC_{MCR} + SFC_{calculated}$$

- m_{fuel} : Fuel injected per-cycle into the cylinder
- h_n : Heat value for the
- N : For 2-stroke equals 1, 4-stroke equals 2
- η_m : Mechanical efficiency
- $SFC_{indicated}$: Indicated specific fuel consumption
- $SFC_{calculated}$: SFC calculated based on the fuel consumption curve

For the $SFC_{calculated}$ calculation, is based on the Model element in 20sim. In the SFC curve model, the user could output their own condition of the SFC curve, then the model will output a SFC curve, update the fuel consumption during simulation.

In the model the inertia and mechanical/thermal losses is simulated in the **R** and **I** element, based on the basic bond graph theory.

The engine and propeller speed in the 20sim is radius per second, it's not very obvious to compare the speed, so the flow has been converted to RPM to compare the result

5.2.2 Gear Box and Flexible Coupling

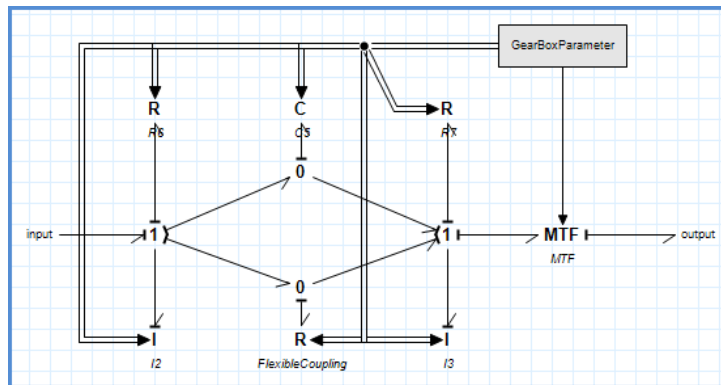


Figure 5-13 Gear box model

In order to make the simulation more accurate. In the gear box sub-model, the gear box shaft flexible coupling is considered.

In the C-element, the stiffness of the gears and gear shaft is calculated based on the input gear box parameters. In the R element, the damping parameters is taken in and then calculation. Using C and R elements, the dynamic properties are included and connected to 0-junction. Then transfer the energy to the propeller.

Gear box parameters

Table 5-1

r_GearBoxloss	0.02
i_Gearinertia (kgm ²)	0.09
Thickness of gear(m)	0.05
Diameter of gear(m)	0.25
Modulus of elasticity	8393
material damping ratio of steel	0.015
stiffness youngs modulus(GPa)	200
Mass of gear(kg)	0.2
GearRatio	5

5.2.3 Propeller model

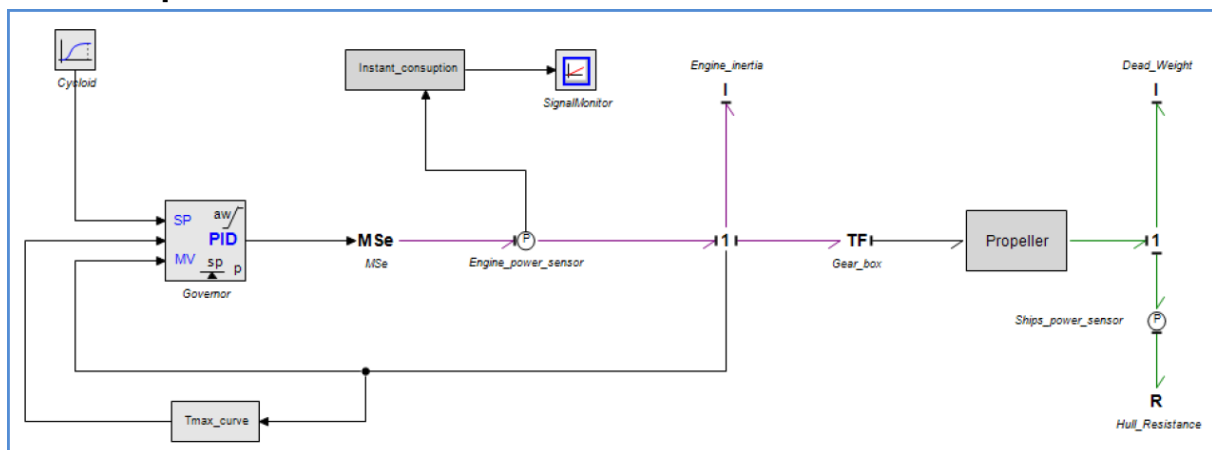


Figure 5-14 Propeller model

The propeller model was made by previous graduate student[9]. The main topic of this thesis is modelling and simulation of a simple propulsion machinery. In the machinery part, the author just use the basic configuration. On the other hand, in the propeller part, the

author introduced more detailed knowledge about the propeller, from different point of views, such as propeller geometry, propeller performance characteristics. After these, a propeller bond graph model was input into 20sim and simulated. Then by analyzing the plots, the propeller performance such as propeller coefficients and efficiency were explained.

There are four parameters in the propeller model.

- A_E/A_0 : Blade area Ratio
- D : Diameter of the propeller
- P_{over_D} : Pitch divide diameter
- Z : Number of blades

In the later system, the propeller parameters has been changed several times to cater the requirements. From the bond graph theory, the causality relationship of the propeller means it take in the torque and then feedback the angular speed.

5.3 Waste heat recovery modelling

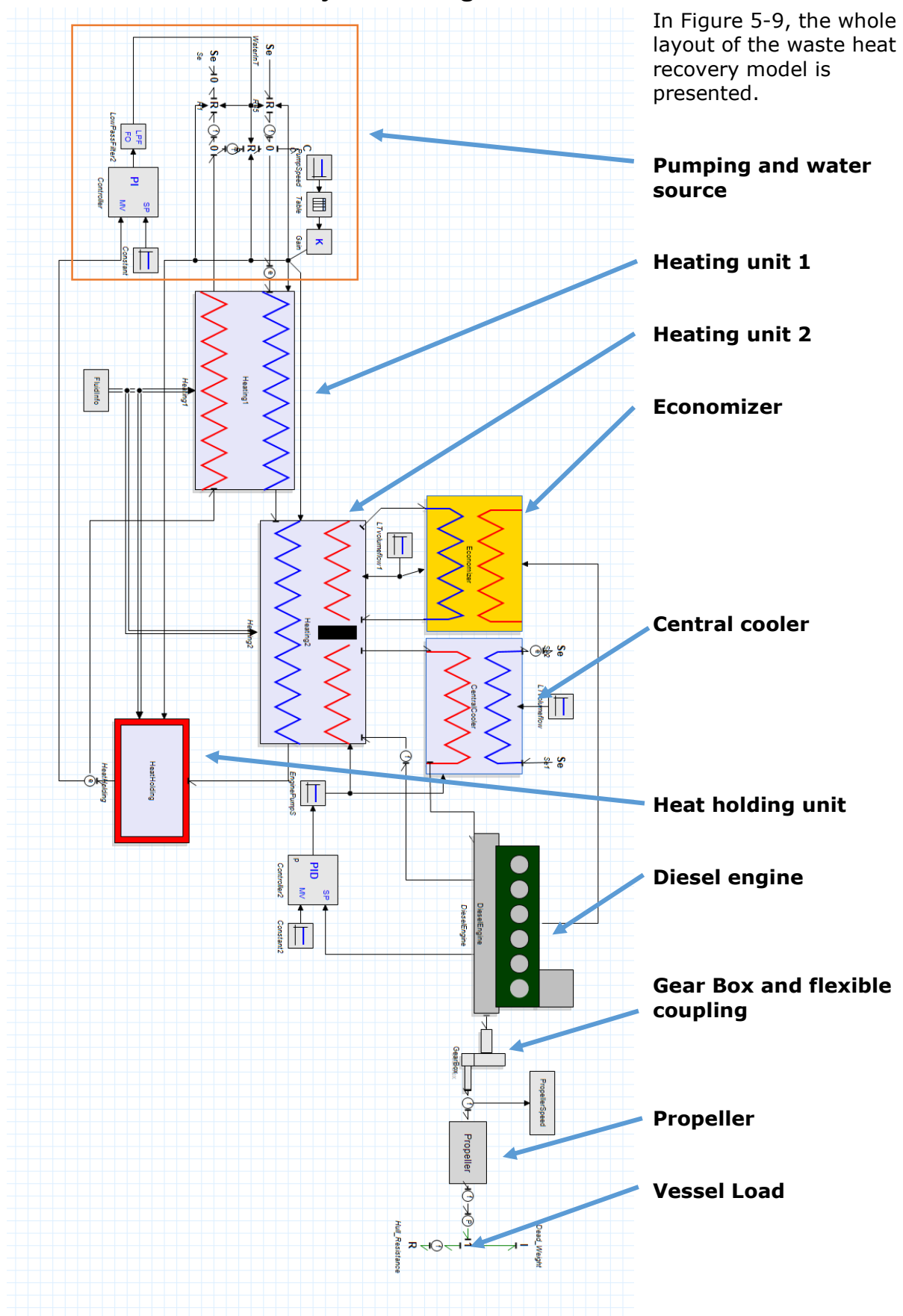


Figure 5-15 Waste heat recovery model

5.3.1 Heating unit 1

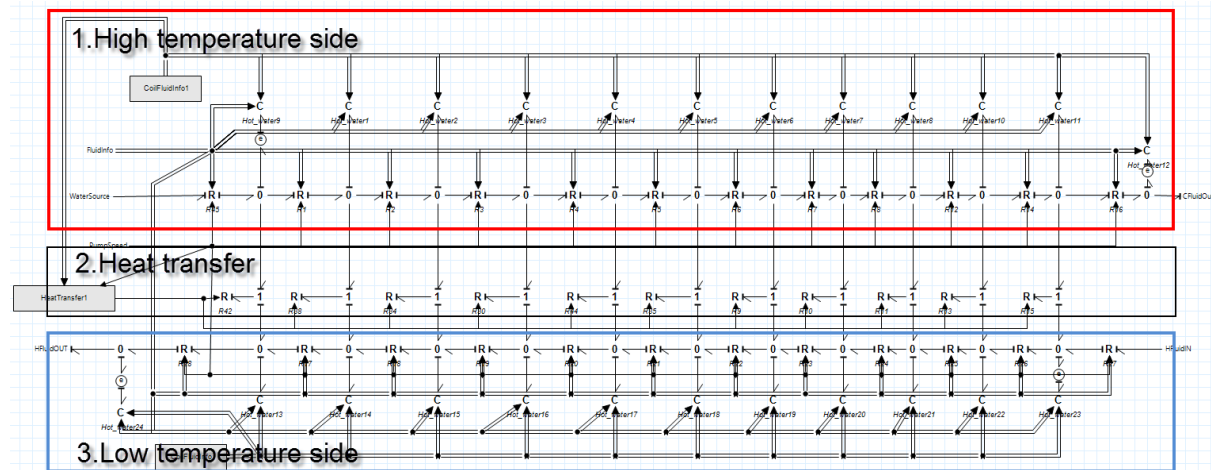


Figure 5-16 Heating unit 1 model

The model was also built up based on thermal domain. The **Effort (e)** means the temperature. The **flow (f)** means the entropy flow. Compared to the ballast treatment model in Chapter 4, the heating unit 1 contains three parts. First is the high temperature side. In the BWT model, this part is the water bath temperature, in which the water volume of water bath is much larger than the cold water in the pipe. Here, in the heating unit 1 which simulate a heat exchanger, so the water volume in both side should be considered. So, both sides adapts the same configuration. Second is the heat transfer unit which is presented as R elements which connect the high temperature and low temperature side. Both sides of the heat exchanger were modelled with R and C elements. The R element for the coil transfer the fluid and energy from input to output. The C element present the volume in the plates of heat exchanger store the fluid and energy

The fluid temperature in the plates will change with the heat transferring process. So the fluid flowing process is simulated. In each R element, the volume and mass of fluid pass the coil element unit is calculated. For bond graph, also the relationship between effort and flow should be set up. In this condition, the flow is the entropy flow, and the effort is the temperature. So in the equation, every second, the fluid energy will be calculated. The volume of the coil will also affect the temperature heat transferring, hence, C element is used for storing the fluid (energy). The parameters of the coil is lead in the C element, the coil has been divided into 12 elements

Then during the process, the fluid in the LT side is always heat transferring with the HT side. The detailed parameters are attached in the Appendix.

5.3.2 Heating Unit 2

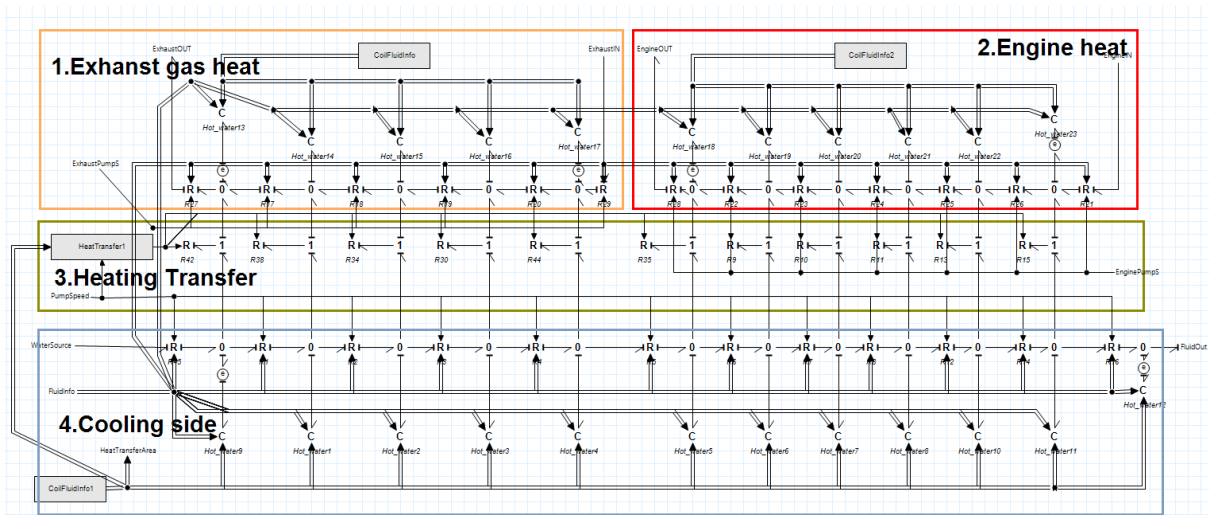


Figure 5-17 Heating unit 2 model

The modelling structure in the heating Unit 2 can be divided into 4 parts which is a bit complicated compared to the other models. The main function of this part is to collect the waste heat energy from exhaust gas and engine heat. Then transfer this amount of heat energy to the cooling side.

First part of this model is the exhaust heat part, the heat energy from economizer collect and flowing inside this system. This system is a closed circuit system, which could reduce the maintenance work. The fluid transferring here is the fresh water. The second part is the engine heat part. In this part, the HT water from central cooler is collected and transfer the heat with the cooling side. The heat transfer bridge the HT and LT side. In the cooling side, the pre-heated water from heating unit 1 will obtain more heat from the exhaust gas and central cooler.

5.3.3 Economizer

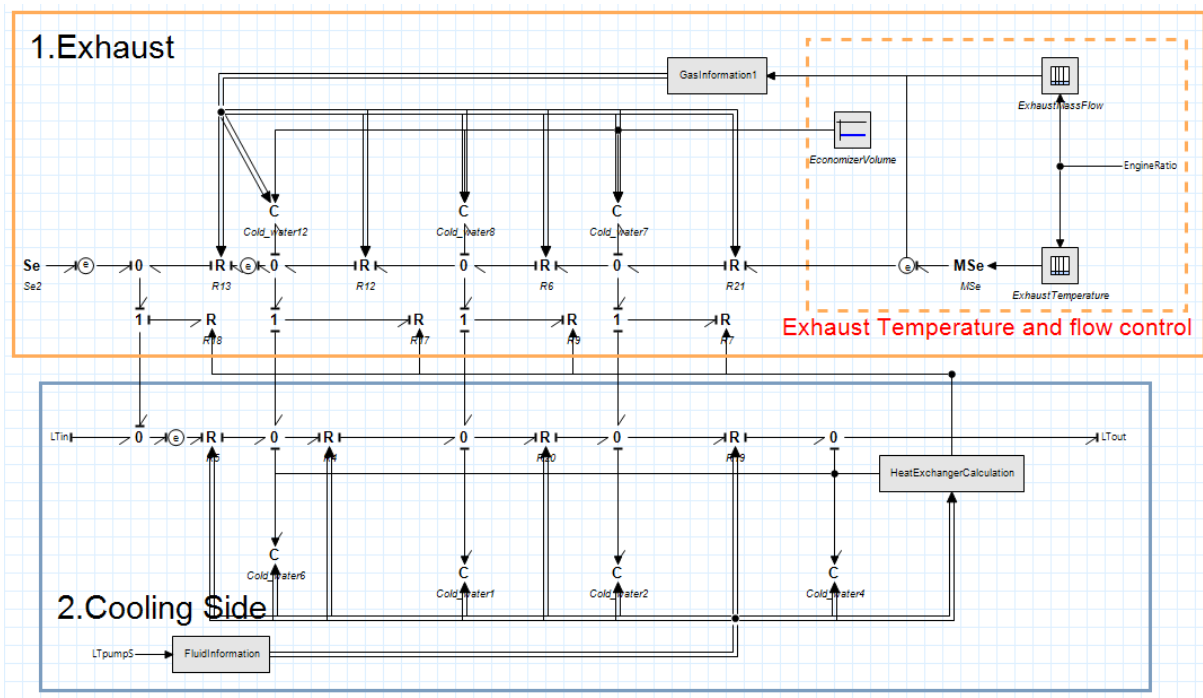


Figure 5-18 Economizer model

Economizers are mechanical devices intended to reduce energy consumption, or to perform useful function such as preheating a fluid. The term economizer is used for other purposes as well. Boiler, power plant, heating, ventilating, and air conditioning (HVAC) uses are discussed in this article. In simple terms, an economizer is a heat exchanger.

For most of the existing economizers in the market, they will work with the waste boiler and steam turbine. Then the waste energy from exhaust will be converted into electric energy. While in this model, the economizer model here just uses its thermal energy, maybe in the future, this model could be fulfilled and updated.

In the exhaust side, the waste exhaust gas flow through the system, the exhaust temperature and flow is based on the engine ratio. The engine ratio means the real output power divide the MCR power. The relationship of the temperature and flow is also based on the Table model in 20sim. Several pre-defined points were attached in the model. The user could also update the data based on their own requirements. In the cooling side, the water source is the heating unit 1. As described previously, this is a closed circulation system. The optimization could be applied for further application. The cooling side absorb the energy from the exhaust gas. The volume flow rate and pressure in the part are relatively high which could prevent the water change into steam and lead cavitation. The cavitation will damage the system and shorten the life cycle.

5.3.4 Central Cooler

The central cooler is just an heat exchanger, which connect the fresh water cooling system and the sea water cooling system. The engine need a strict working environment. If the temperature is too high or too low, the engine will not properly.

5.3.5 Heat holding unit

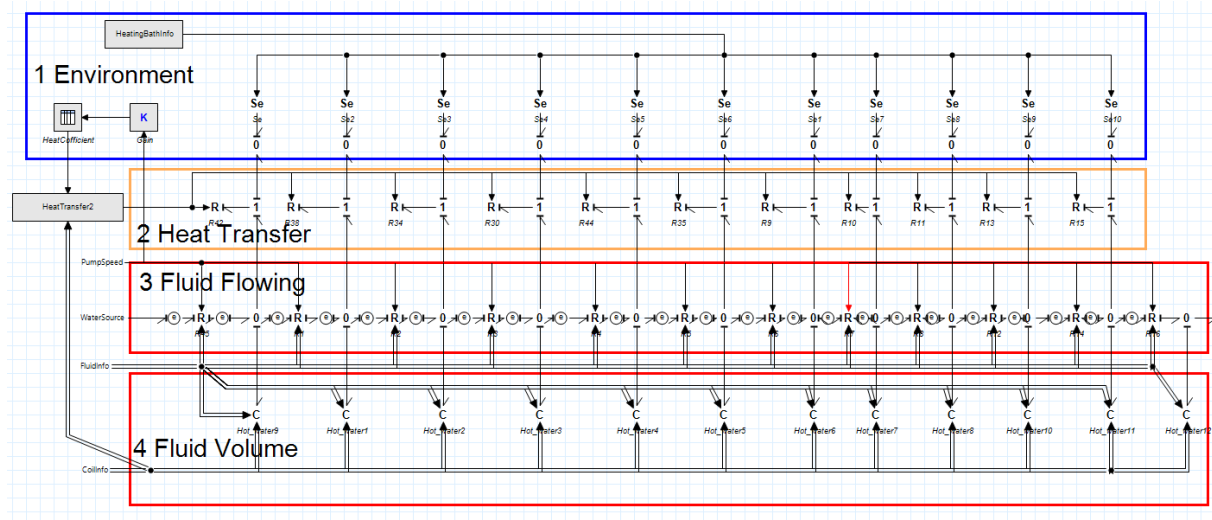


Figure 5-19 Heat holding unit model

This part of the waste heat recovery system adapt the same structure as described in the Chapter 4. The difference here is that, the volume of heat holding tank will be much larger. The environment temperature will be relatively higher due to the limited work space on the vessel, which will increase the performance of this system.

The effort source present the environment temperature. While, the input information is different. The heat holding process aims to keep the energy inside away from heat transferring with the environment. The outside of the holding tank will wrapped with insulation material. Aims to keep the reduction of output temperature as small as possible from reducing the heat transfer loss with the environment. The heat transfer coefficient still keeps a relationship with the volume flow. The heat holding process tries to reduce the heat transfer loss with the environment, hence, the heat transfer coefficient is much smaller compared to the heating unit. It means only limited heat is transferring between holding "tank" and environment.

The fluid flowing has the same configuration and parameters because the same fluid source connect with the Heating unit 2 (LT) output and Heating Unit 1 (HT) input. While the fluid volume is different, because the different diameter and volume of holding hose. The parameters of holding hose can be modified in the corresponding model.

5.3.6 Machinery components

The machinery components consists of the diesel engine, gear box, propeller and vessel load which has been introduce in the early this chapter.

5.4 Waste heat recovery simulation

5.4.1 Simulation parameters

- **Engine parameters:**

Maximum continuous rating (MCR) Power: **3600kW**

Revolutions per minute (RPM): **720rev/min**

Specific Fuel consumption (SFC) under MCR: **200g/kWh**

Mechanical Efficiency: **0.85**

Heat value of the heavy oil: **46MJ/kg**

SFC curve is configured in the 20sim table model, and attached in the Appendix.

- **Propeller and Gear box**

Area Ratio: **0.65**

Diameter of propeller: **5m**

P/D: **1.08**

Number of blades: **3**

Gear Ratio: **5**

- **Central Cooler parameters**

Low temperature (LT) water volume flow: **0.012m³/s**

LT water inlet temperature: **50°C**

High temperature (HT) inlet water temperature: From the heating unit 2 output.

HT outlet water temperature is the cooling water into the engine temperature.

HT water volume flow is controlled by the pump speed controller which will be introduced in the later text.

- **BWT-Heating Unit 1**

LT (untreated) water inlet temperature: **20°C**

LT water outlet temperature is the Heating Unit 2 inlet temperature

HT water inlet temperature is the outlet temperature of holding tank

BWT water volume flow: **0.0694m³/s**

- **BWT-Heating Unit 2**

HT water temperature from Economizer is based on the exhaust temperature

HT water temperature from central cooler is based on the engine working temperature

LT water inlet temperature is the outlet temperature of Heating Unit 1

LT water outlet temperature is the inlet temperature of holding tank

HT water volume flow from Economizer: **0.02m³/s**

HT water volume flow from central cooler is controlled by the pump speed controller which will be introduced in the later text.

- **Heat holding tank**

Inlet temperature is the temperature from Heating Unit 2 LT outlet

Outlet temperature is the temperature inlet the heating Unit 1 HT

Volume flow in the tank is the same as BWT water volume flow: **$0.0694\text{m}^3/\text{s}$**

- **Other parameters**

Table 5-2 Other simulation parameters

Engine Ratio	Exhaust gas mass flow Kg/s
0	0
0.5	6.3
0.75	9.0
1.0	11.6

Table 5-3 Exhaust temperature data

Engine Ratio	Exhaust temperature
0	0
0.5	385
0.75	351
1	343

Gas density:

$$\rho_{gas} = 1.293 * \frac{273}{273 + gasT} * 1.015$$

Gas volume flow:

$$V_{gas} = m_{gas} / \rho_{gas}$$

Internal volume flow in Economizer: **$0.02\text{m}^3/\text{s}$**

Engine cooling pump:

1. Control Signal: Minimum **0**, Maximum **2**.
2. Pump Volume flow: Minimum **$0.0025\text{m}^3/\text{s}$** , Maximum **$0.0075\text{m}^3/\text{s}$** ;

Fluid information:

Specific heat capacity: **$4200\text{J}/(\text{kg} \cdot \text{K})$**

Water density: **$1000(\text{kg}/\text{m}^3)$**

- **Valve control**

If the temperature in the holding tank reach the required temperature (**80°C**), then the fluid will fluid out. If it is lower, then the fluid will fluid back to the system and treat again until it is qualified.

1. Output valve

$$V_{out} = V_{set} * (1 - Signal_{valve} + 0.001)$$

2. Input valve

$$V_{in} = V_{set} * (1 - Signal_{valve} + 0.001)$$

3. Return valve

$$V_{return} = V_{set} * (Signal_{valve} + 0.001)$$

0.001 presents the leakage of the valve. The $Signal_{valve}$ is the signal from the PID controller in which the temperature are compared between set point and holding tank.

5.4.2 Simulation Result analysis

The whole simulation process was applied for 3000 seconds when all the simulation result reached a balanced level.

- Engine working simulation

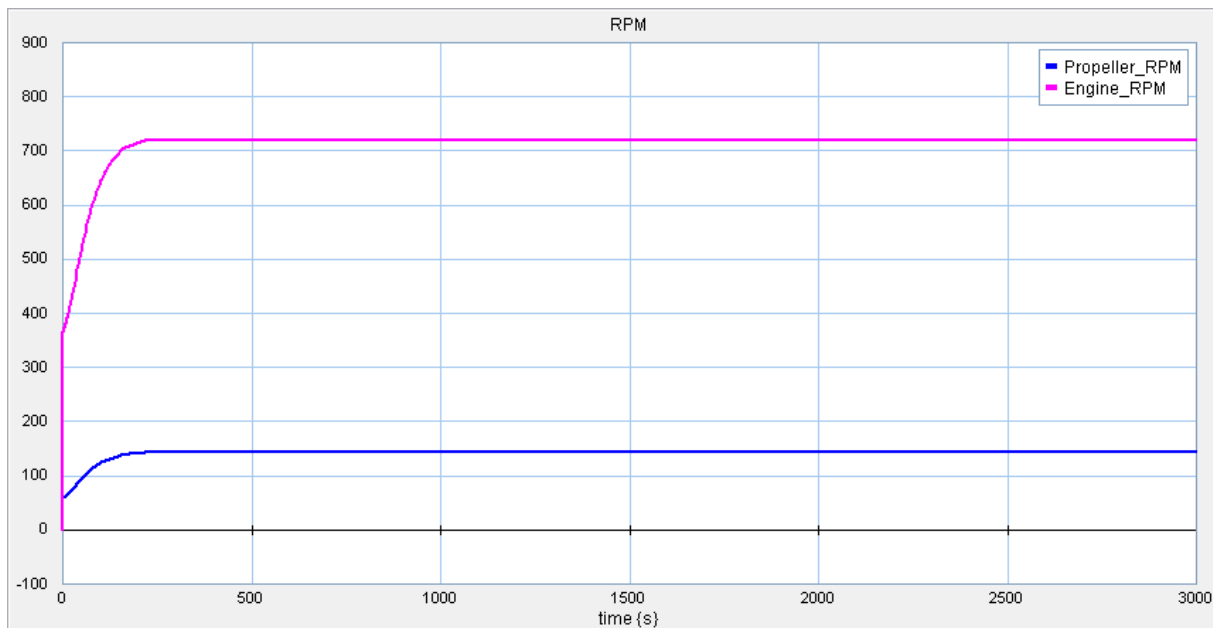


Figure 5-20 Engine and propeller working RPM

Figure 5-14 shows the RPM of the engine and propeller, with a gear ratio of 5. The machinery configuration adapted here is the engine connect with the gear box, then the gear box connect with the propeller. So the RPM of engine will be 5 times of the RPM of propeller. The governor control the fuel injected into the cylinder to control the RPM of engine. If the RPM than the set point, then less fuel will be supplied to the engine. Because of the appropriate ratio of engine size and propeller size, the engine RPM curve does not present a reduction trend. If the engine has a bigger volume which connect with a small propeller, the governor will reduce the engine speed a bit.

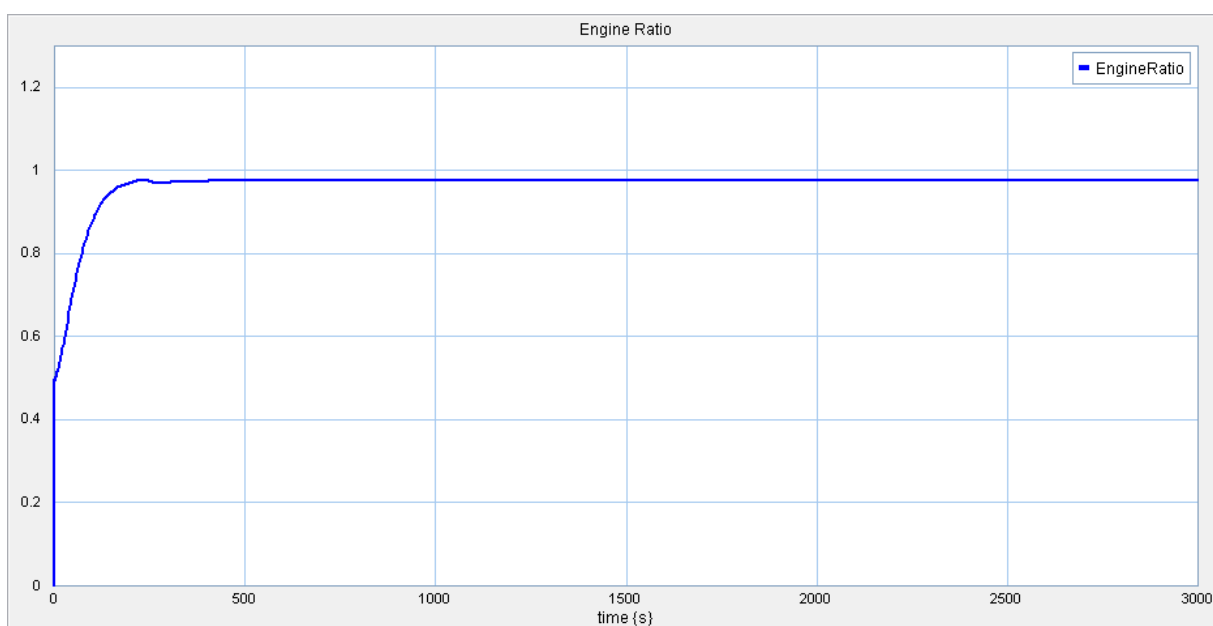


Figure 5-21 Engine ratio

In Figure 5-15 presents the engine ratio curve. The engine ratio equals the actual output power of engine divide the MCR power. If the engine ratio over 1, it means the engine is overload. In this simulation scenario, more attention is attached in the thermal part, in order to get a higher temperature, a relatively small engine is selected to get a higher engine ratio. When start the engine, due to the large mass and inertia of the vessel and resistance, the engine was a bit overload. After the ship moves, the engine has fewer load, hence, the engine ratio drop down to a balanced level. Then the engine will thrust the vessel moving ahead.

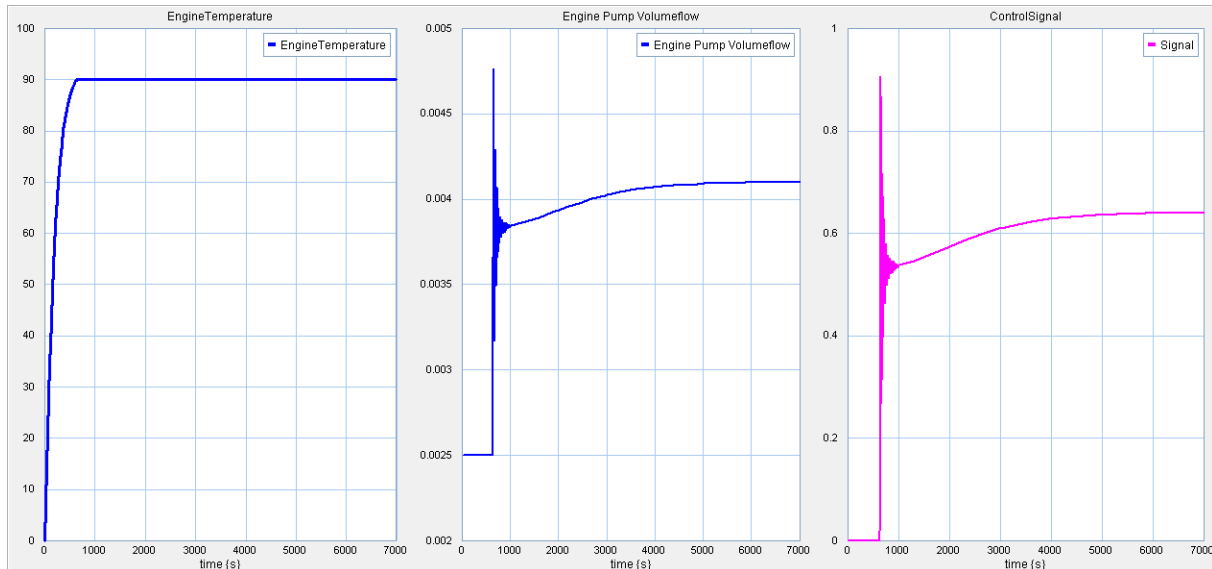


Figure 5-22 Engine cooling

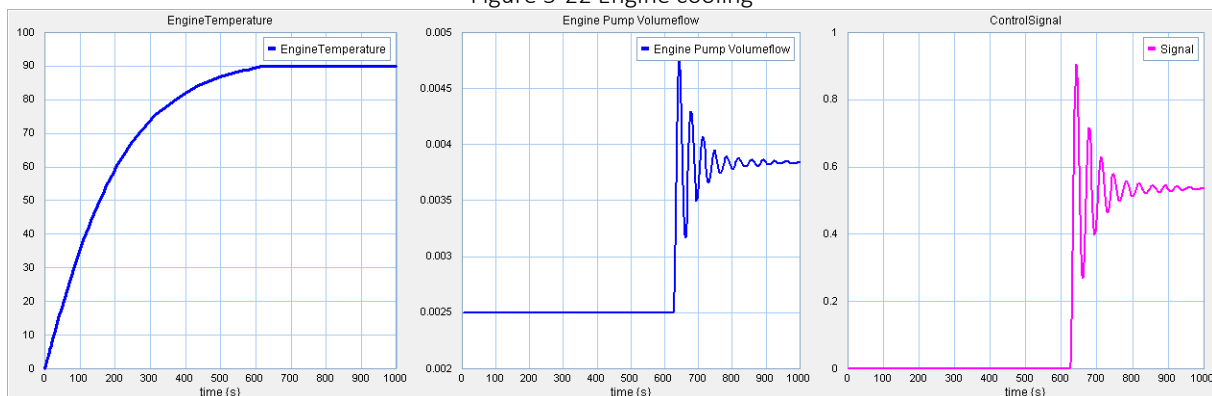


Figure 5-23 Engine and cooling zoom

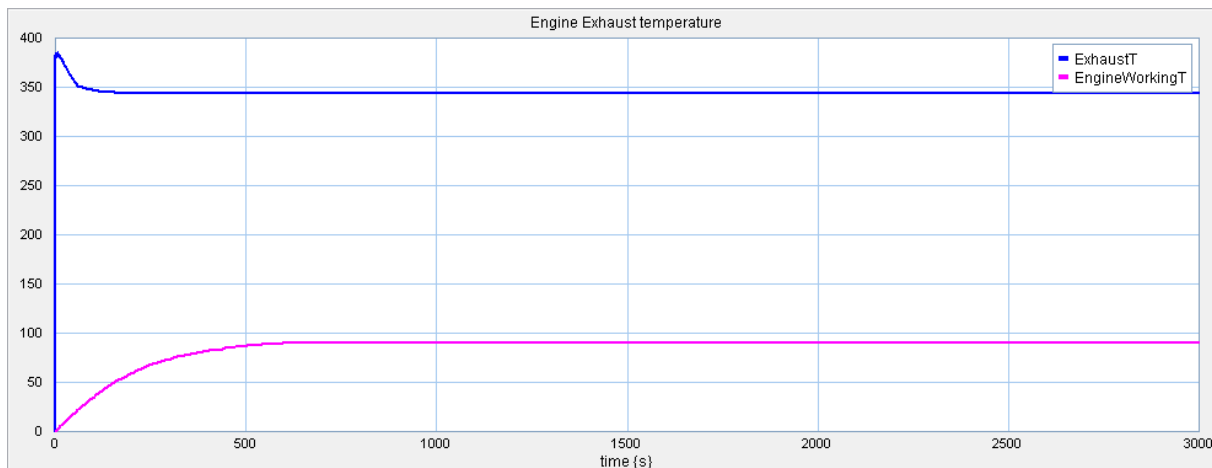


Figure 5-24 Engine and exhaust temperature

The first plot in Figure 5-16 is the engine working temperature. This temperature is affected by the engine working condition and cooling water volume flow. The maximum allowed working temperature is 90. So the controller is set at 90, then the controller will compare the working temperature of the engine and then control the volume of the engine cooling pump. In Figure 5-19 shows the engine and exhaust temperature. The engine working time first increasing with the engine operation, then balanced with the load and cooling system provide continues power out. The exhaust temperature shows a different trend, because in the starting stage, the fuel efficiency is low and not completely burned. But with the engine ratio increase, the fuel efficiency is increasing then to a balanced level. As a consequence, the exhaust temperature first increase then decrease.

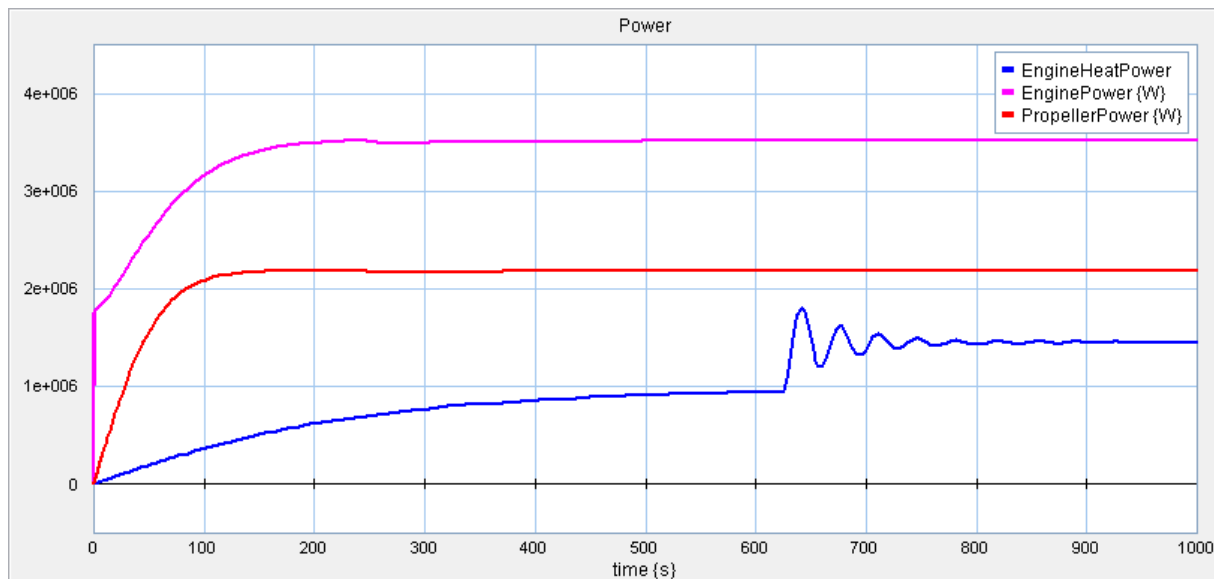


Figure 5-25 Engine and Propeller Power

In Figure 5-17, the engine power, propeller power and engine heat power were plotted. The engine power and propeller power are affected by the working condition of the propulsion system, so they shows the same trend as the increasing trend. The engine heat

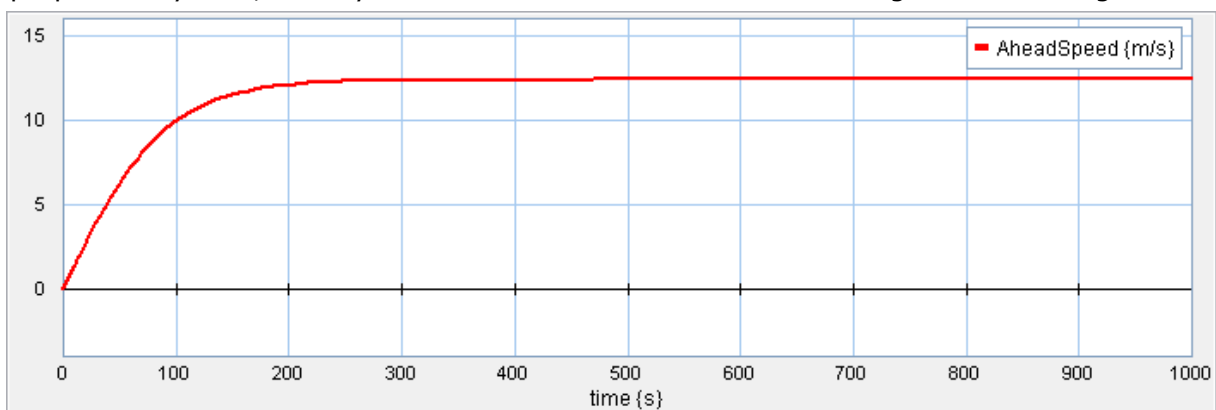


Figure 5-26 Vessel Speed

power shows balanced curve which is based on the engine working condition.

The vessel speed is related to vessel load and machinery system volume. Under this simulation scenario, the maximum ahead speed is 12.5m/s. The speed curve first accelerate then to a balanced level with the same trend of propeller RPM.

- Heating Unit 1 simulation

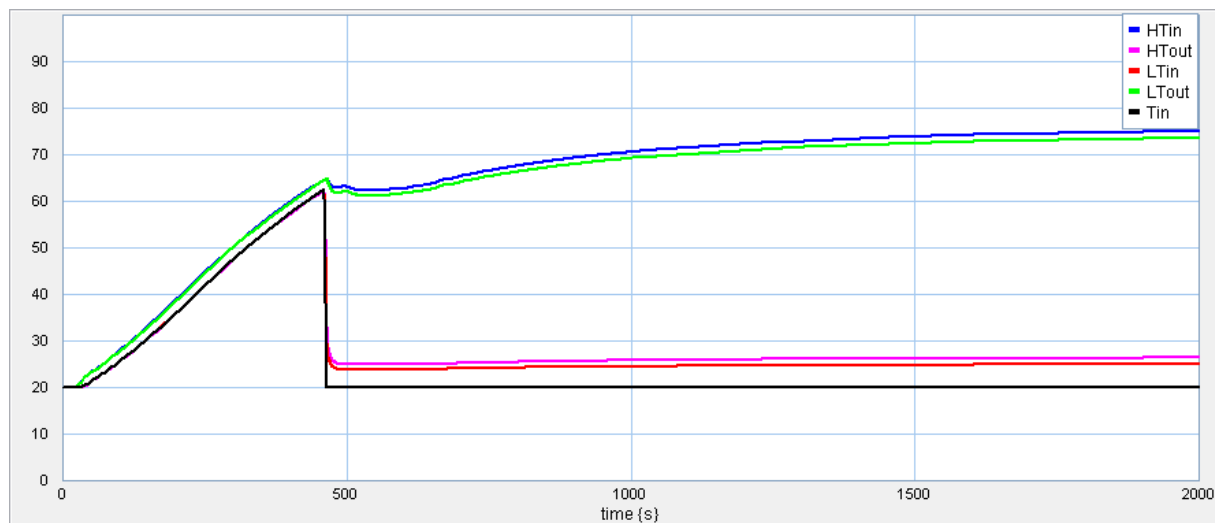


Figure 5-27 Heating Unit 1 temperature

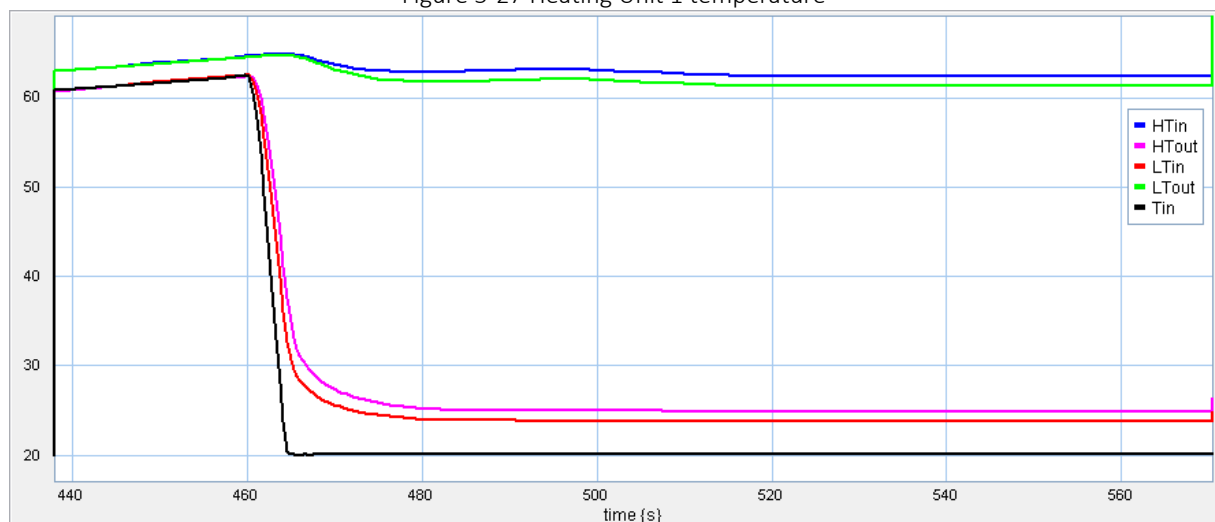


Figure 5-28 Heating Unit 1 temperature zoom

As introduced in the previous chapter, the heating unit one connect the untreated ballast water and control the output of treated ballast water. In the initial stage, the treated ballast water does not reach the temperature set point (Heat holding tank), so the ballast water will not flow out of the system. The ballast water will flow back to the inlet of the system and circulate again until it is qualified.

When the temperature in the holding tank reach the set point, the control valve will open the output of the system to let the qualified ballast water flow out. On the other hand, the controller will close the flow back valve and open the inlet valve to let the untreated ballast water flow into the system and being treated, at the same time prevent the qualified treated ballast water flow back.

● Heating Unit 2 simulation

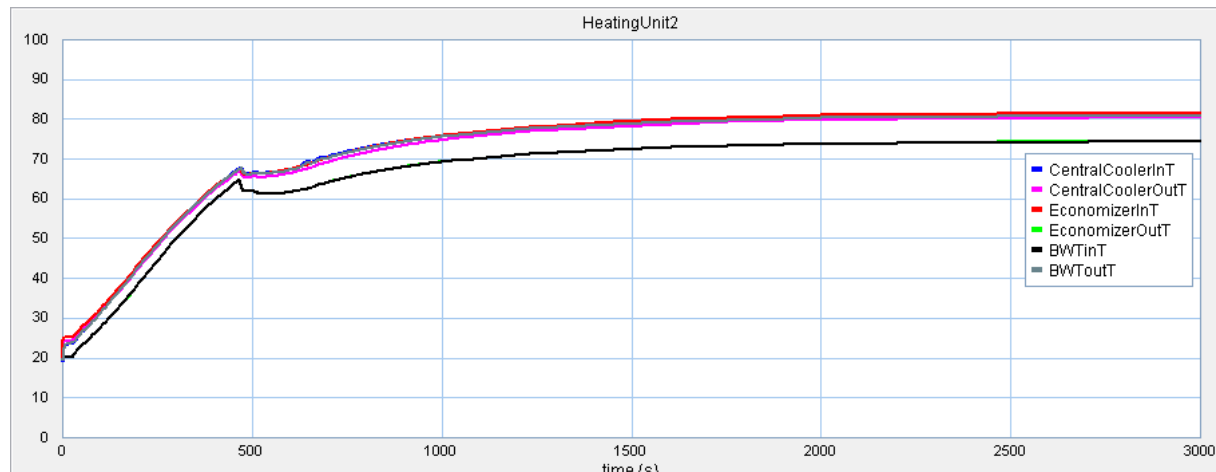


Figure 5-30 Heating Unit 2 temperature

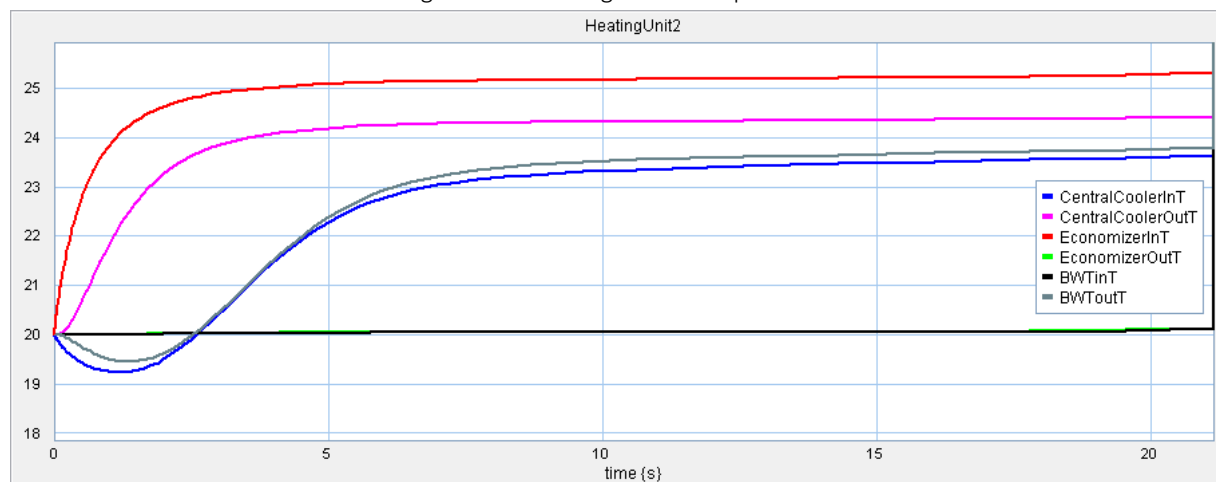


Figure 5-31 Heating Unit 2 temperature zoom 1

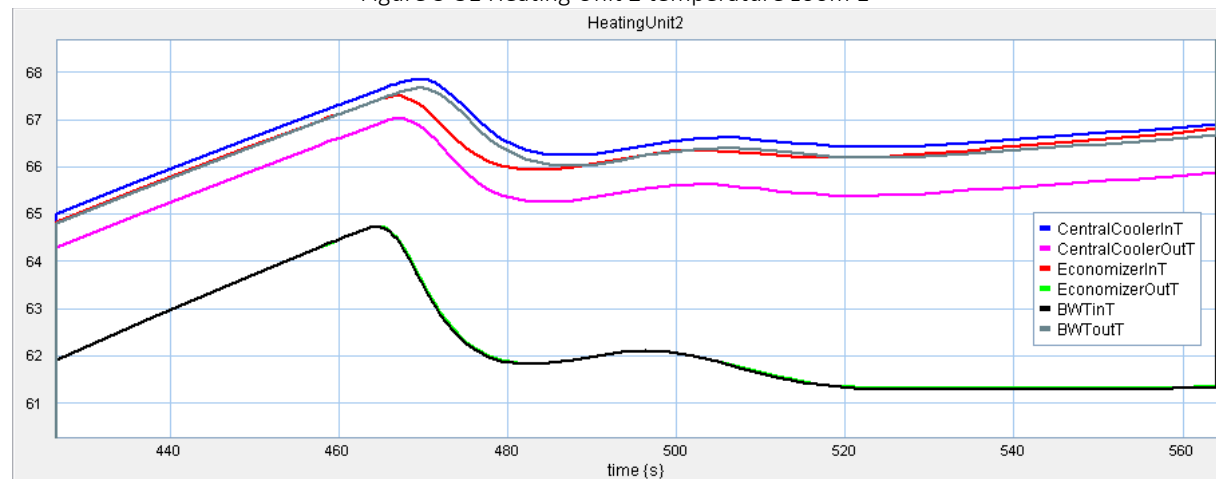


Figure 5-29 Heating Unit 2 temperature zoom2

In the heating unit 2, the ballast water will heat transfer with the HT water from the engine and economizer. The whole simulation process could be seen in the Figure 5-29. Figure 5-30, 5-31 zoom in to make it more obvious of the plot. In Figure 5-30, in initial time, the water from engine and outlet of BWT system drop a bit below 20 because of the engine start from stop condition which is very cold, with the operation continuing, the temperature is increasing. The temperature BWT-inlet also increase with the process because of the internal circulation. As introduced in the previous text, when the treated ballast water is qualified the treated ballast water will flow out and untreated ballast water will flow into

the system. From Figure 5-31, it can be clearly seen that the ballast water inlet temperature decrease then to a balanced level. Due to the reduction of cold side (ballast water), the temperature in HT side all present a reduction trend, finally to a balanced level.

- Heat holding simulation

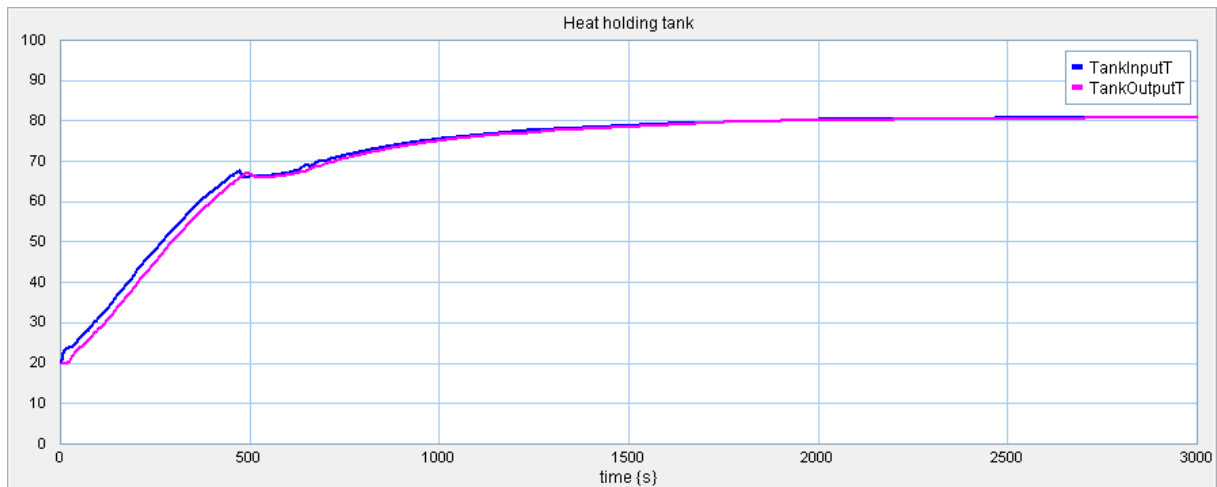


Figure 5-32 Heat holding temperature

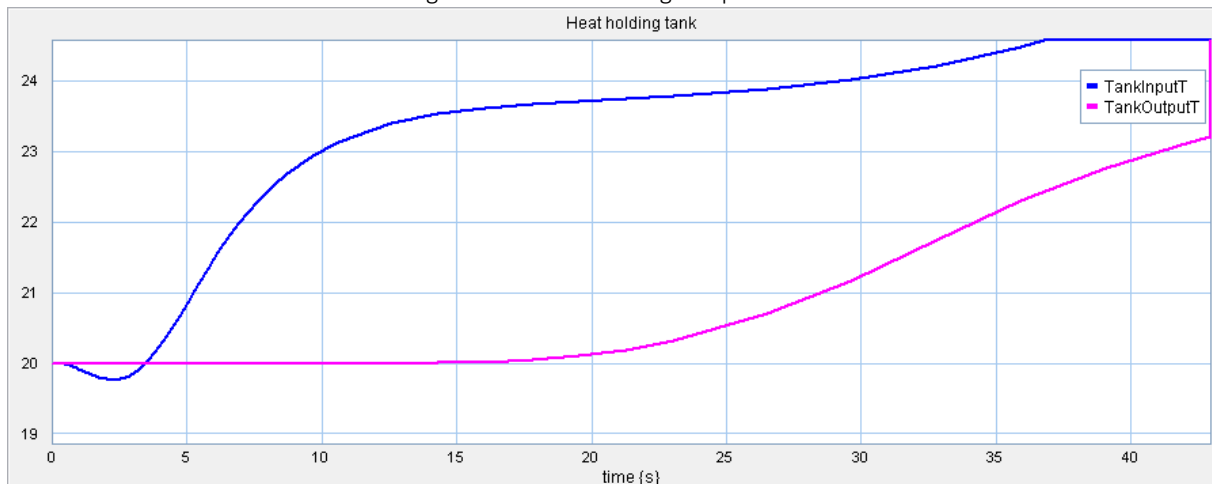


Figure 5-34 Heat holding temperature zoom 1

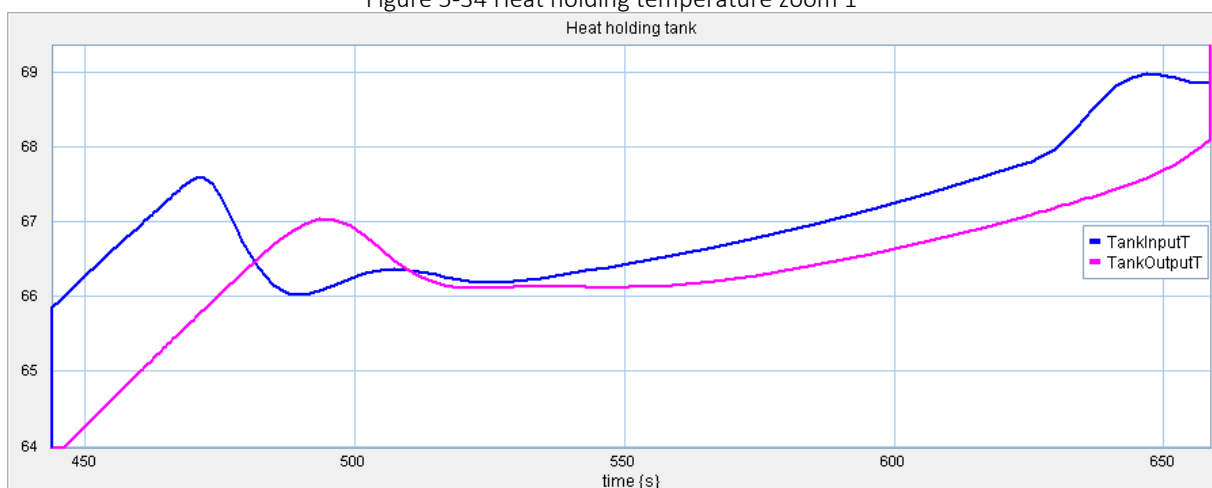


Figure 5-33 Heat holding temperature zoom 2

Figure 5-32, 5-33, 5-34 shows the whole and detail temperature information of the heat holding tank. The trend shows the same trend as the LT output temperature of heating unit 2. In the beginning, the tank input T drops a bit due to the low temperature of the

engine working initial stage. Then the tank inlet temperature is higher than the output temperature because the heat transfer with the environment (heat loss). While in the middle time, the tank inlet temperature suddenly drop and lower than the output temperature due to the untreated ballast water flow into the system. Then the system will continues working to a balanced level, finally the tank input temperature will be a bit higher than the output temperature.

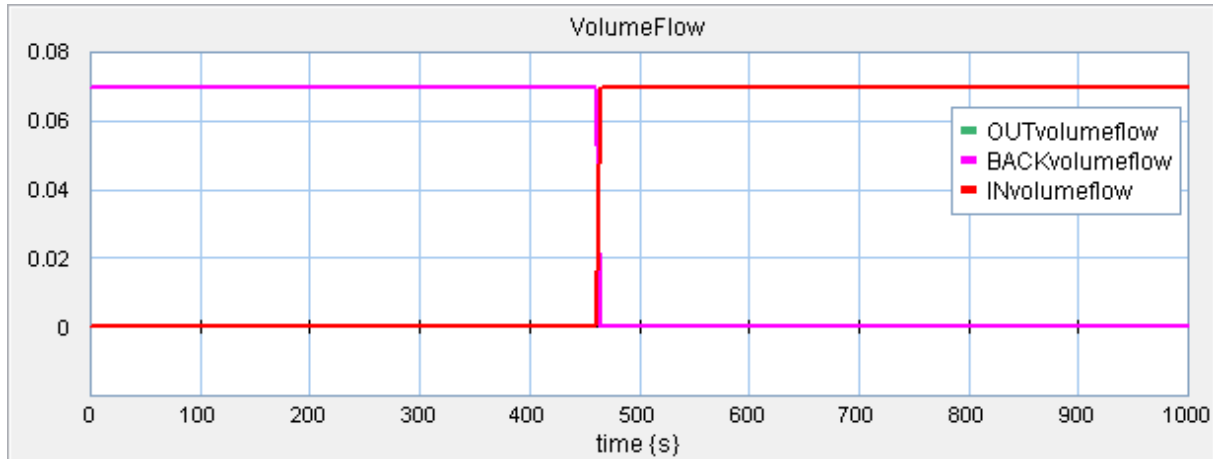


Figure 5-35 BWT volume flow

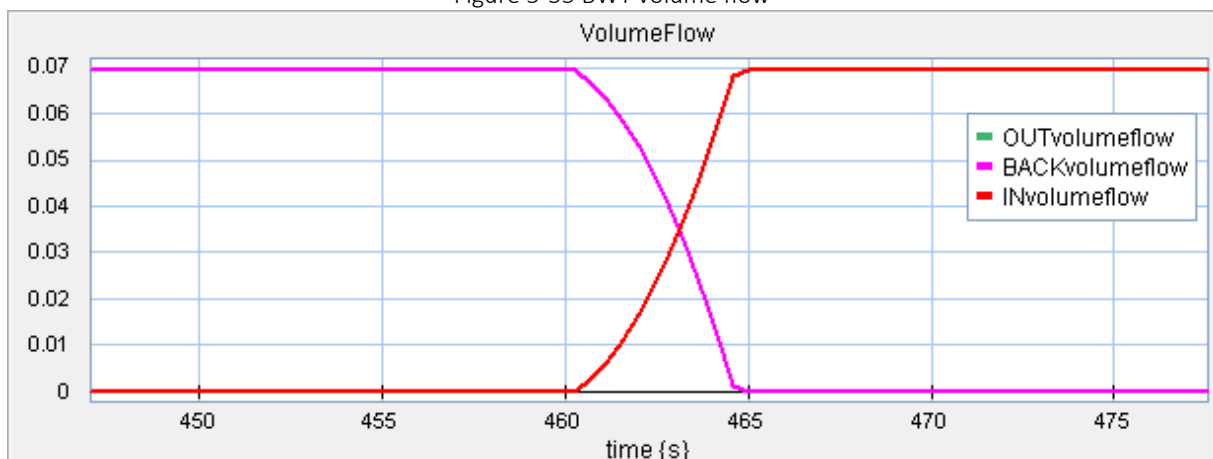
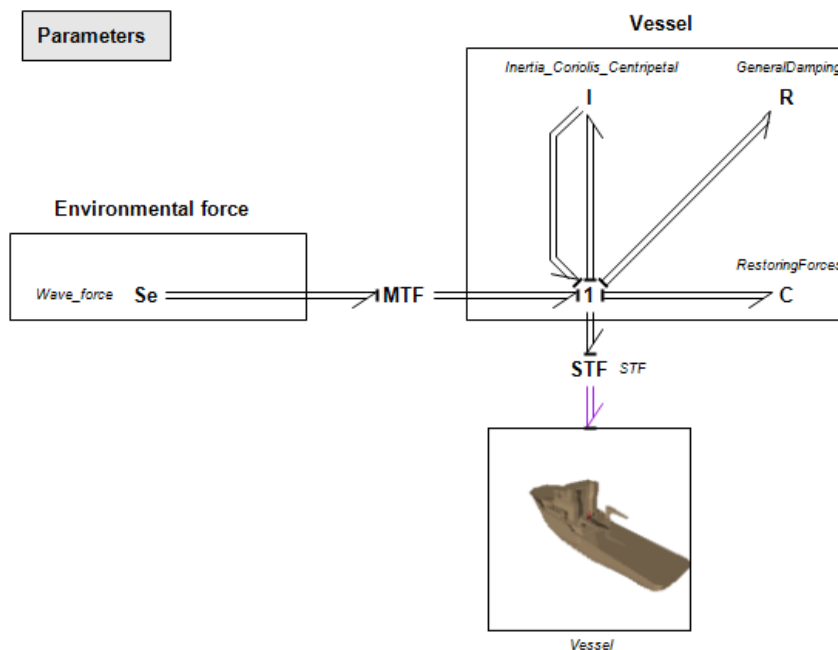


Figure 5-36 BWT volume flow zoom

In the figure 5-34, and 5-35 shows the volume flow of input, output and back of the system. The valves are controlled by the PID controller. The PID controller will compare the temperature set point and the temperature signal from holding process. If the temperature in the holding process reach the set point then the treated water will be defined qualified, so the output valve will open to let the qualified water out. On the other hand, if the temperature is lower than the set point, then the output valve will be closed and back valve will open to flow back the un-qualified water. Then the un-qualified water will circulate in the BWT system until it is qualified (Higher than the set point). The input valve will open as the same time of the output valve open.

5.5 Vessel behavior model connection



This part of thesis is based on the Dr.Jiafeng Xu's master thesis [10]. A generic modelling Approach for heave lifting marine operation. In order to simulate the machinery system more dynamic and accurate. Based on the vessel model provided by Jiafeng Xu, additional propulsion power and machinery components is connected.

Figure 5-37 Vessel model

5.5.1 Thrust force application

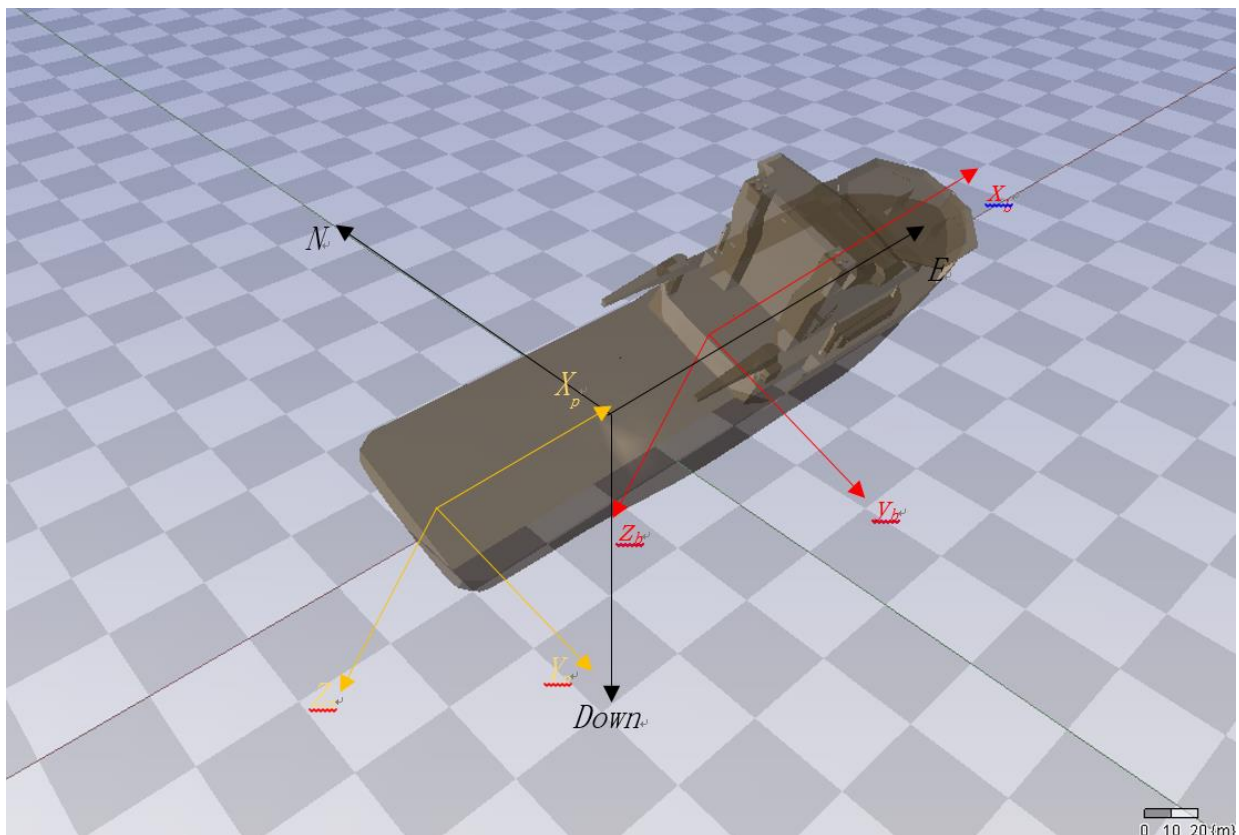


Figure 5-38 Vessel coordinate system

As shown in Figure 5-15, there are three coordinate system in it. The red coordinate system is the vessel center coordinate. The origin point of this coordinate system is the center of

gravity of the vessel. The black coordinate system is the global coordinate system. Every vessel behavior or wave movement is based on this coordinate system.

The yellow coordinate system is the propeller mid position coordinate system. This coordinate system is parallel with the vessel center system. While the position of this

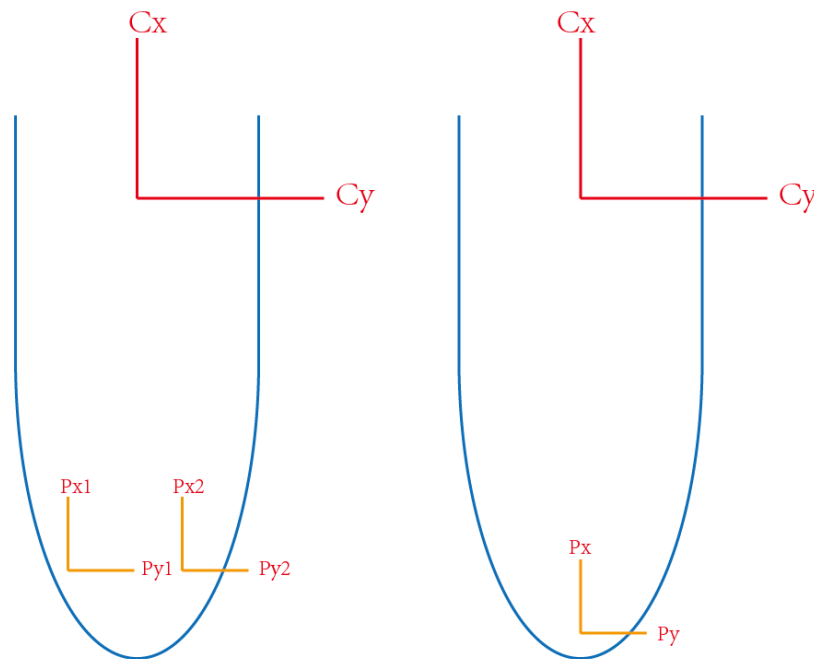


Figure 5-40 Propeller coordinate system 1

coordinate system is not fixed. And, if the vessel adapt several thrusters, will have the same number of this coordinate system

In the Figure 5-40, it shows different configuration of the propellers. The first vessel has two propellers on both sides of the vessel. The second one the vessel only have one propeller at the end of the vessel. This could be the directly coupling propeller or a Azimuth

thruster. Here comes the

question, if the vessel want to change direction, how should the propeller be.

5.5.2 Propeller direction variation

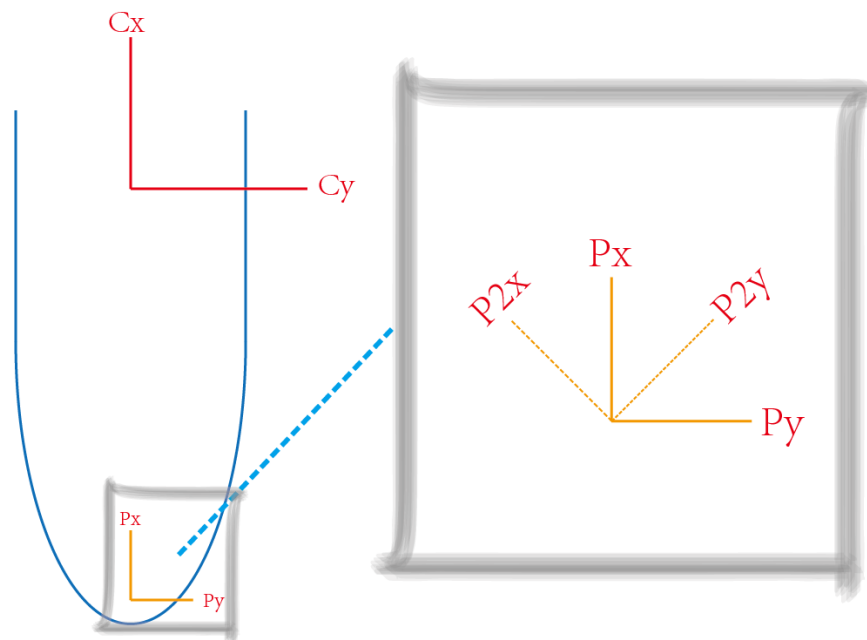


Figure 5-41 Propeller coordinate system 2

As introduced previously, if the propeller rotate, then another angel will appear as shown in Figure 5-41. Under this condition, the thrust force will not act direct follow the propeller

center coordinate. The transformation matrix should be adapted. The propeller force in the P2 coordinate system will convert to P coordinate system with the transformation matrix.

In the coordinate transformation theory, different rotation axis will have different transformation matrix. In this project, the propeller will only rotate around Z axis based on the mechanical structure requirements. Here assume the propeller rotate AngleR degree around Z axis, the transformation matrix should be:

$$T_{rotation} = \begin{bmatrix} \cos(AngleR) & -\sin(AngleR) & 0 \\ \sin(AngleR) & \cos(AngleR) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

With this transformation matrix the trust force could be converted to propeller center coordinate system. The output of this calculation should be a force vector with the force in X, Y, Z direction, and torque in X, Y, Z direction.

```
TrustF=inverse(RotationM)*[p1.e; 0; 0];
```

```
p2.e = [TrustF[1,1]; TrustF[2,1]; TrustF[3,1];0;0;0];
```

p1.e is the force received from propulsion system.

p2.e is the output vector which connect with the next transformation matrix.

5.5.3 Thrust force apply on center of gravity

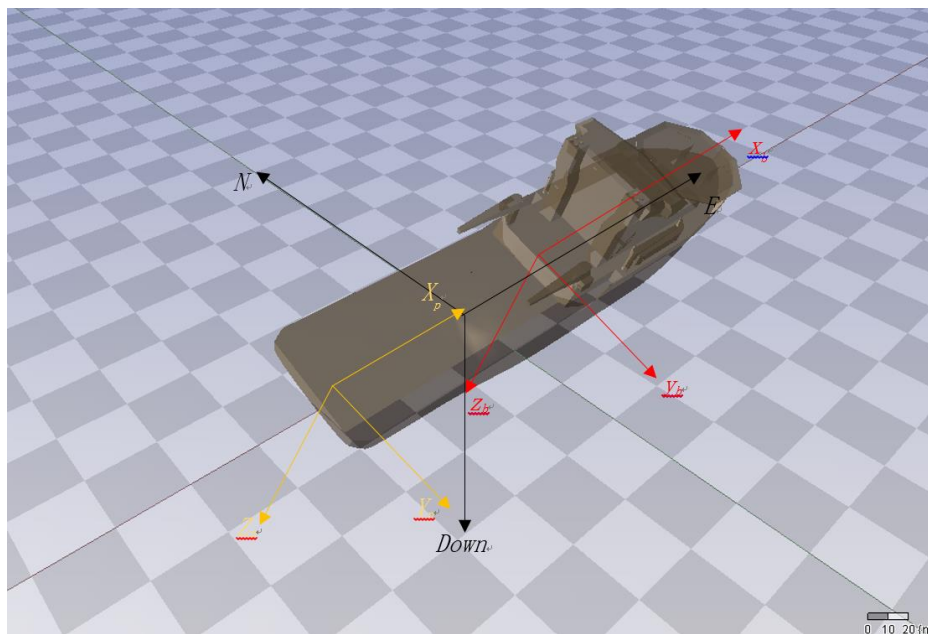


Figure 5-42 Vessel coordinate system

The thrust force has already been converted to the forces in the propeller center coordinate system. Hence, the force applied on the yellow coordinate system (propeller center coordinate system) convert to the force applied on the vessel's COG.

The input into this sub-model is the output of the force from yellow coordinate system, which is a [6*1] vector, three force and three torque in X,Y,Z direction.

Assume the thruster is positioned in 10 meter from the COG in X direction, and 3 meter deep, in the middle line of the vessel. The transformation matrix should be:

$$p2.e = \begin{bmatrix} Fx \\ Fy \\ Fz \\ Rx \\ Ry \\ Rz \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -Zp & Yp & 1 & 0 & 0 \\ Zp & 0 & -Xp & 0 & 1 & 0 \\ -Yp & Xp & 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} Fpc \\ Fpc \\ Fpc \\ Rpc \\ Rpc \\ Rpc \end{bmatrix}$$

Through this transformation matrix, the thrust force will be applied on the COG of the vessel.

In the bond graph theory, the provide the force (effort), then it will get velocity back, the equation is shown:

$$p1.f = \begin{bmatrix} Vx \\ Vy \\ Vz \\ \omega x \\ \omega y \\ \omega z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & Zp & -Yp \\ 0 & 1 & 0 & -Zp & 0 & Xp \\ 0 & 0 & 1 & Yp & -Xp & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} Vsx \\ Vsy \\ Vsz \\ \omega sx \\ \omega sy \\ \omega sz \end{bmatrix}$$

Then the model will get velocity back for the flow calculation. In the later chapter, the vessel will be tested with the machinery system under some operation profile.

5.6 Vessel behavior simulation

5.6.1 Simulation parameters

- **Engine parameters:**

Maximum continuous rating (MCR) Power: **9000kW**

Revolutions per minute (RPM): **720rev/min**

Specific Fuel consumption (SFC) under MCR: **220g/kWh**

Mechanical Efficiency: **0.85**

Heat value of the heavy oil: **46MJ/kg**

SFC curve is configured in the 20sim table model, and attached in the Appendix.

- **Propeller and Gear box**

Area Ratio: **0.65**

Diameter of propeller: **4.5m**

P/D: **1.15**

Number of blades: **3**

Gear Ratio: **5**

- **Central Cooler parameters**

Low temperature (LT) water volume flow: **0.12m³/s**

LT water inlet temperature: **50°C**

High temperature (HT) inlet water temperature: From the engine working temperature.

HT output water temperature is the cooling water out of the engine temperature.

HT water volume flow is controlled by the pump speed controller which will be introduced in the later text.

- **Vessel**

Vessel weight : **8118t**

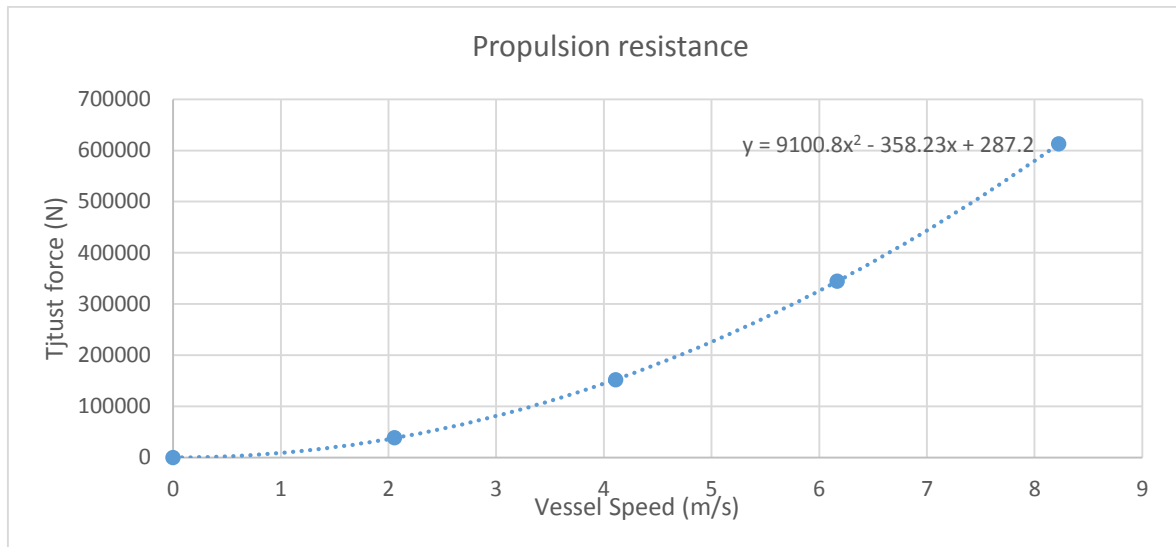


Figure 5-43 Propulsion resistance curve

In Figure 5-43, a propulsion resistance curve was assumed for the simulation.

Linear damping ratio: **-358.23**

Nonlinear damping ratio: **9100.8**

- **Wave force**

Direction	Value
X	0
Y	0
Z	0
Rx	0
Ry	100000000
Rz	0

The wave condition could be configured by the user based on their own requirements. In the future, the machinery model will be added an accurate direction controller to keep the moving direction of the vessel constant under different wave condition. On the other hand, the wave condition could be taken in from the ShipX data which was applied in Jiafeng Xu's thesis. In this project, a simple wave is added to simulate the wave effects on the machinery system.

5.6.2 Simulation result analysis

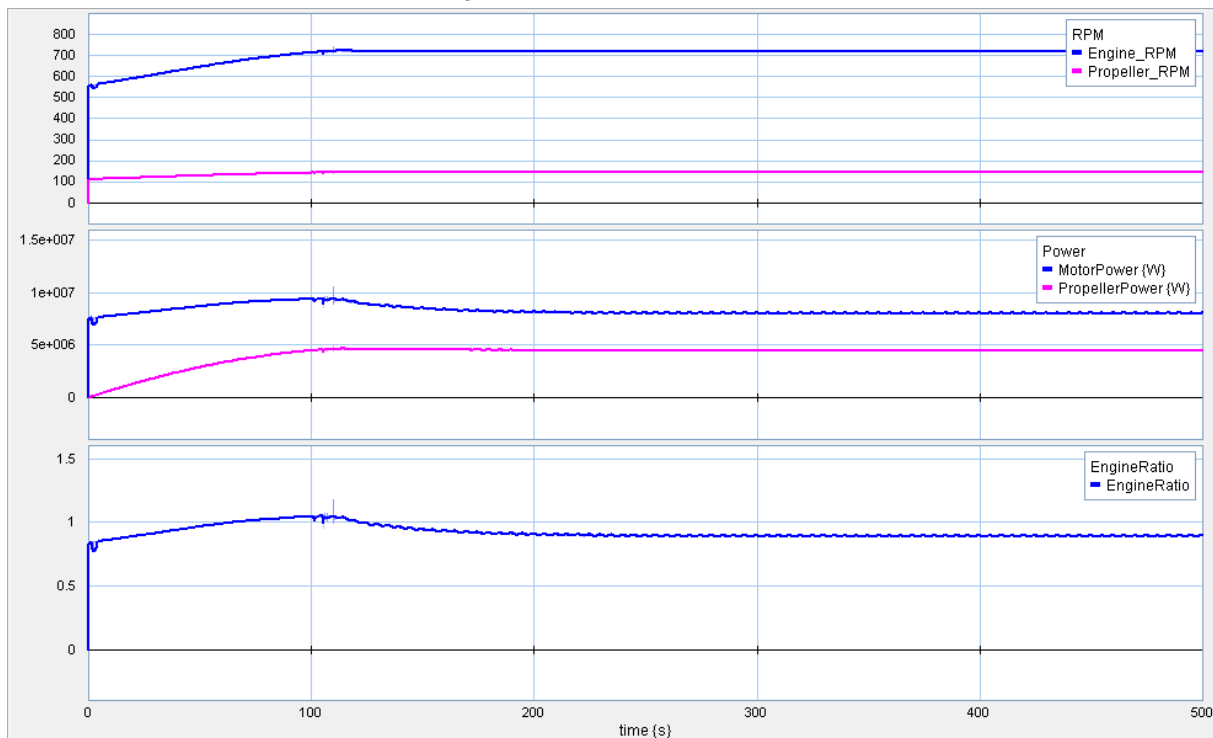


Figure 5-44 Engine working condition

In Figure 5-44, shows the engine working condition. The RPM of the engine is controlled by the speed controller. The controller will compare the actual RPM and RPM set point. If the actual RPM is higher than the set point, the controller will reduce the amount of fuel inject into the cylinder. On the other hand, if it is lower, then the engine will consume more fuel.

When the vessel is accelerating, the engine output power will gradually increase to a top value. Then the vessel speed will speed up to a balanced level, hence, the engine do not need to provide more power for acceleration, so the engine output power then reduced to a balanced value. The oscillation of the curve is due to the wave movement. The propeller power will gradually increase with the same trend as the RPM, when the RPM is fixed, the propeller output power reach a balanced value.

The engine ratio shows the load condition of the engine. During the acceleration period, the engine need to provide extra power, so the engine ratio is almost 0, which means the engine will work fully. But for the cruise, the engine will need 90 percent of its total power.

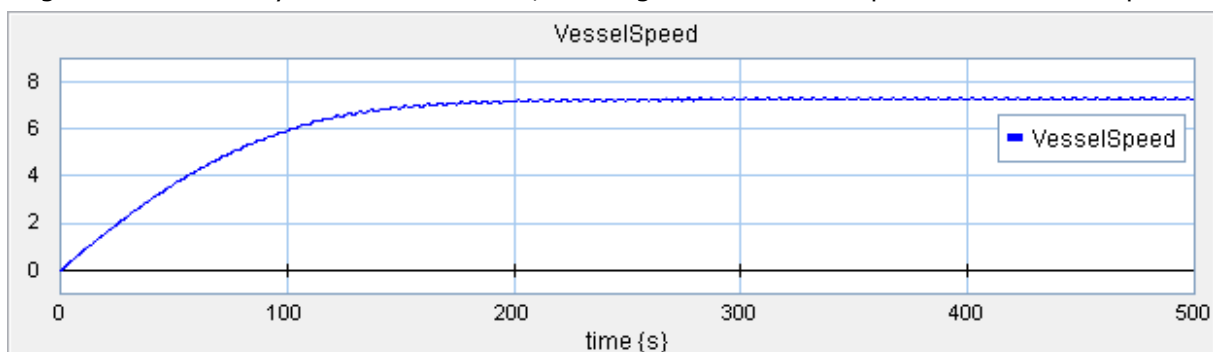


Figure 5-45 Vessel Speed

The previous shows the vessel speed, the speed is 7.3m/s /14knots, which is a common speed for OSV.

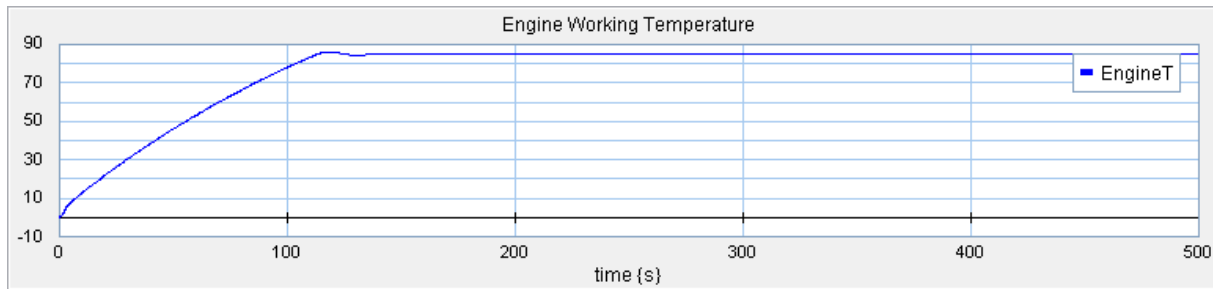


Figure 5-46 Engine working temperature

The engine working temperature is based on the engine ratio and the central cooling system. If the engine has more load, then the working temperature will be higher. If the cooling volume flow is higher or cooling water temperature is lower, which means the cooling system will take more heat, the engine temperature will be lower. The cooling water temperature and engine working temperature should be controlled at a balanced level. Too high will reduce the efficiency, cause cavitation or even damage the engine, too low will damage the shell or the cylinder of the engine.

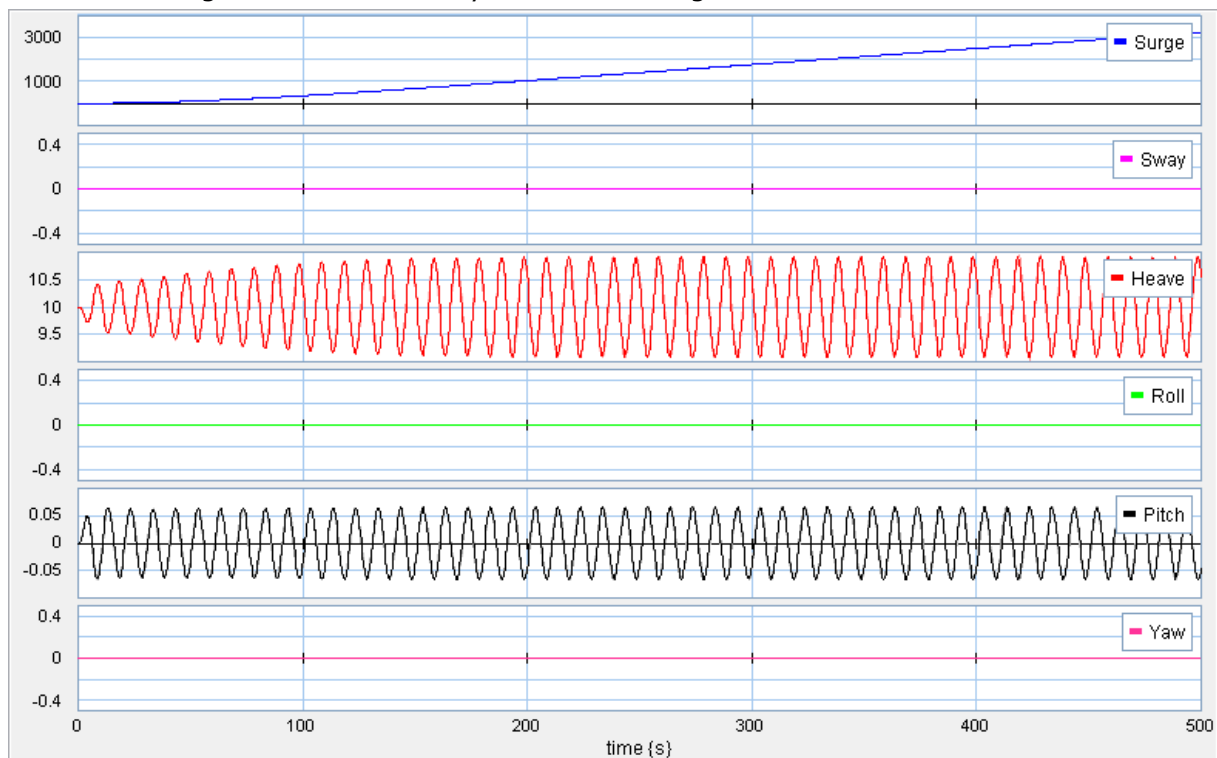


Figure 5-47 Movement of the vessel

Figure 5-47 presents the movement of the vessel in X,Y,Z direction and the rotation around X,Y,Z axis. As described in the previous text, the wave applied on this project will make the vessel moves around Y axis and up and down in Z direction with the wave. In X direction, the propulsion system will thrust the vessel moving ahead.

6 CONCLUSIONS

This thesis focus on the test of a newly-developed ballast water treatment system. Two sets of experiment in the laboratory were carried. The corresponding simulation model was built up to cater the data which could not be obtained during the process. On the other hand, a simplified machinery library was set up, different machinery components were modelled such as diesel engine, gear box, generator, electric motor, governor and so on. Then the machinery components were tested with the ship behavior model to acquire more accurate result.

In the first time experiment part, the heating time of 50°C, 60°C and 70°C were tested with different pump volume flow. Based on the variation of pump volume flow, different holding time were obtained. Then the collected samples were sent for biological analysis. Based on the result analysis of the first time experiment, second time test were applied. The heating temperature 50°C, 55°C, 60°C has been tested, which aims to save the energy and effectively kill the bacteria.

The ballast water treatment system was modelled in the 20sim to acquire the process temperature. From the experiment, only the input and output of the system could be measured. While, with the simulation model, the temperature during the process could be obtained. The plots and data from 20sim were re-arranged for further analysis.

The biological analysis were carried by Yanran Cao. In this thesis, the experiment result is briefly introduced and analyzed.

In the fifth chapter, the machinery system introduction and modelling were presented. The main topic of this thesis is the heat treatment, so the machinery model in this project is not very detailed. Then the waste heat recovery was applied based on the experiment theory.

Finally the machinery model is connected with Jiafeng Xu's vessel model to test the ship behavior affection on the machinery.

7 FURTHER WORK

As introduced in the previous text, this thesis is just a part of the ongoing research project, there are still so many experiments and tests need to be done. In the experiment part, more sensible equipment could be applied to improve the accuracy of the experiment. The factors and the relations ship between these factors and heat transfer coefficient should be further investigated. The experiment simulation model could be updated to make the model simplifier and more efficiency.

For the machinery system library, if possible the engine could be modelled more detailed to test the engine operation on the variable loads and cooling system. The electric system in the library does not consider so much knowledge of the electric, so additional detailed modelling work could be applied here. The users could configure their own machinery systems based on this library, in order to avoid the global parameters and local parameters error or misunderstanding, the parameters in this thesis is transferred with the matrix port. So the appearance of the modelling is a bit complicated but avoid many potential errors. Additionally, the parameters is already attached in the library, so the user do not need to configure the initial parameters with a lot of errors. In the future, this problem may come a better solution.

The experiment in the lab is just a small volume test, maybe in the industrial or actual vessel environment, the result maybe a bit different. So the onboard experiment or actual experiment could be applied to test the accuracy.

In the experiment simulation part, the model only consider the thermal domain. On the other hand, the model could be simulated combined with hydraulic and thermal together. In this project, a lot of the hydraulic parameters could not be defined, so only the thermal domain is applied. Future work could be done here to test and compare the result.

For the waste heat recovery simulation part, the cooling system is not fully simulated. In the real vessel, the cooling system will be divided into sea water (LT) cooling system and fresh water (HT) cooling system. The actual economizer will work with steam turbine which could generate the electricity for other uses. So the detailed modelling work could also be applied here. The propulsion system could also be converted to diesel-electrical system which could use the electric power produced by economizer.

The machinery-vessel could hopefully could be optimized, which means the user could modify the vessel parameters in the 20sim to get the corresponding simulation curve. Rather than, get the data from shipX then use matlab to take in the parameters into 20sim, which consume a lot of time. The simulation work on chapter 5.6 could adapt more machinery configuration to test the model.

The real-time simulation with different wave condition need more concentration on the control method. To acquire the control of the vessel need more investigation and test. In the future, the detailed and accurate control of the vessel will be applied.

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APPENDIX A MODEL PARAMETERS

Experiment simulation model

Model name	Common information model
Parameters and equations	<p>HeatingBathinfo:</p> <p>parameters</p> <pre>real WBT = 51; //WaterBath Temperature</pre> <p>equations</p> <pre>WaterBathT=WBT;</pre> <p>HeatCoefficient:</p> <p>parameters</p> <pre>real A[4,2] = [0, 0 ; 1.001769793, 395 ; 2.012072435, 819 ; 4.033342296, 950];</pre> <p>variables</p> <pre>integer i, n; boolean found;</pre> <p>code</p> <pre>i = 1; n = rows(A); found = false; while (i <= n and not found) do if input < A[i,1] then found = true; if i == 1 then output = A[i,2]; else output = A[i-1,2] + (input - A[i-1,1]) * (A[i,2] - A[i-1,2]) / (A[i,1] - A[i-1,1]); end; else if i == n then found = true; output = A[i,2]; end; end; i = i + 1; end;</pre> <p>Se:</p> <p>variables</p> <pre>real flow;</pre> <p>equations</p> <pre>p.e = WBT; flow = p.f;</pre> <p>HeatTransfer:</p> <p>parameters</p> <pre>real CF=1; //Correction Factor</pre> <p>equations</p>


```

HeatTransferR=1/(U*CF*CoilInfo[1,1]);
FluidInfo:
parameters
    real Specificheatcapacity = 4200{J/kg.K}; //Specific heat capacity
    real Density = 1000{kg/m3}; //Fluid Density
equations
    FluidInfo=[Specificheatcapacity;Density];
PumpSpeed:
parameters
    //Pump with Hose Diameter 9.5mm
    real A[13,2] = [
        0,          0 ;
        10,         1.001769793 ;
        20,         2.012072435 ;
        30,         3.021148036 ;
        40,         4.033342296 ;
        50,         5.025125628 ;
        60,         6.009615385 ;
        70,         7.082152975 ;
        80,         8.099352052 ;
        90,         9.208103131 ;
        100,        10.12145749 ;
        110,        11.32075472 ;
        120,        12.66357113
    ];
variables
    integer i, n;
    boolean found;
code
    i = 1; n = rows(A); found = false;
    while (i <= n and not found) do
        if input < A[i,1] then
            found = true;
            if i == 1 then
                output = A[i,2];
            else
                output = A[i-1,2] + (input - A[i-1,1]) *
(A[i,2] - A[i-1,2]) / (A[i,1] - A[i-1,1]);
            end;
        else
            if i == n then
                found = true;
                output = A[i,2];
            end;
        end;
        i = i + 1;
    end;
end;

```

Model name	Heating
Parameters and equations	Se: variables real flow; equations p.e = WBT; flow = p.f; R (Heat transfer): equations p.e = HeatTransferR * p.f; R(water flow) variables real m,r; equations m=FluidInfo[2,1]*FluidS; r=1/(m*FluidInfo[1,1]); input1.e = r * input1.f; input1.f = output1.f; C: parameters real Tinit=20; variables real C; real Qinit; equations C=FluidInfo[2,1]*CoilInfo[2,1]*FluidInfo[1,1]; Qinit = C*Tinit; state = int(p.f,Qinit); p.e = state / C; HeatingBathinfo: parameters real WBT = 51;//WaterBath Temperature equations WaterBathT=WBT;

Model name	HeatHolding
Parameters and equations	Se: variables real flow; equations p.e = WBT; flow = p.f; R (Heat transfer): equations p.e = HeatTransferR * p.f; R(water flow) variables real m,r;

```

equations
    m=FluidInfo[2,1]*FluidS;
    r=1/(m*FluidInfo[1,1]);
    input1.e = r * input1.f;
    input1.f = output1.f;

C:
parameters
    real Tinit=20;
variables
    real C;
    real Qinit;
equations
    C=FluidInfo[2,1]*CoilInfo[2,1]*FluidInfo[1,1];
    Qinit = C*Tinit;
    state = int(p.f,Qinit);
    p.e = state / C;

Environment:
parameters
    real N = 6;
    real Volume = 0.02{ m3 };
    real ET = 20;//Environment Temperature
variables
    real HeatTransferArea;
    real VolumeUnit;
initialequations
    VolumeUnit=Volume/N;
equations
    WBInfo=[Volume;VolumeUnit];
    EnvironmentT=ET;

```

Model name	Cooling
------------	---------

Parameters and equations	Se: variables real flow; equations p.e = WBT; flow = p.f; R (Heat transfer): equations p.e = HeatTransferR * p.f; R(water flow) variables real m,r; equations m=FluidInfo[2,1]*FluidS; r=1/(m*FluidInfo[1,1]); input1.e = r * input1.f; input1.f = output1.f;
---------------------------------	--

C:

parameters

real Tinit=20;

variables

real C;

real Qinit;

equations

C=FluidInfo[2,1]*CoilInfo[2,1]*FluidInfo[1,1];

Qinit = C*Tinit;

state = int(p.f,Qinit);

p.e = state / C;

Environment:

parameters

//Coil Information

real N = 6;//Number of elements of Coil

real Volume = 0.02 {m3};

real WBT = 0;//WaterBath Temperature

variables

real HeatTransferArea;

real VolumeUnit;

initialequations

VolumeUnit=Volume /N;

equations

WBInfo=[Volume;VolumeUnit];

WaterBathT=WBT;

Waste heat recovery model

Model name	Diesel engine
Parameters and equations	<pre> Engine_parameters parameters real EnginePowerMCR = 3600; // Effective engine power at 100% MCR in kW real RPMMCR = 720{rpm}; // RPM at 100% MCR real SFCMCR = 200{g/kWh}; // Specific fuel consumption at 100% MCR in g/kWh real Meff = 0.85; // Mechanical efficiency real I_motor = 5.4; // Rotational inertia for rotating mass real HeatValue = 46.04; // Lower heating value for fuel in MJ/kg real Cycle = 2; // 2-stroke=1, 4-stroke=2 equations Engineinfo = [EnginePowerMCR; RPMMCR; SFCMCR; Meff; I_motor; HeatValue; Cycle]; Mse: variables real hidden Tt, ms_s,; equations // Fuel injected per cycle ms_s = s * Engineinfo[1,1] * Engineinfo[3,1] * (1 - 3/3600.0) / (Engineinfo[2,1] * (60.0 * Engineinfo[7,1])); // Calculate the theoretical torque on the shaft Tt = ms_s * Engineinfo[6,1] * 1e6 / (2 * pi * Engineinfo[7,1]); p.e = Tt; omega = p.f; E = Tt * omega; R(water flow) R(Heat): variables real Fuelc, x, dTi; real Qheat; equations // calculate the specific fuel consumption // Engine Ratio x = sPe / (Engineinfo[1,1] * 1000); // sPe: EnginePower signal / EnginePowerMCR Engine Ratio Fuelc = Engineinfo[3,1] + SFCcalculated; // Calculate the loss in torque relative to the theoretical torque for indicated torque produced dTi = s * (1 - 1 / (Engineinfo[4,1] * Engineinfo[6,1] * Fuelc / 3600.0)); // s for Torque signal p.e = dTi; Qheat = p.f * dTi * 0.6; pThermal.f = Qheat; EngineRatio = x; R(Mechanical): equations p.e = s * (1 - Engineinfo[4,1]); real N = 6; // Number of elements of Coil </pre>

I(Mechanical):

variables

real RPM;

equations

state = int(p.e);

p.f = state / Engineinfo[5,1];

RPM=p.f*30/pi;

R(Mechanical):

equations

p.e = s*(1-Engineinfo[4,1]);

Governor:

parameters

real K = 1.0 { }; // Proportional gain

real Td = 0.5 {s}; // Derivative time constant: Td > 0

real N = 10 { }; // Derivative gain limitation.

real Ti = 1 {s}; // Integral time constant: Ti > 0

real b = 1.0 { }; // Proportional setpoint weighting parameter: 0 <= b <= 1

real c = 1.0 { }; // Derivative setpoint weighting parameter: 0 <= c <= 1

real Ta = 1.0 {s}; // Tracking time constant: Ta > 0

real minimum = 0 { }; // Minimum controller output

real maximum = 1 { }; // Maximum controller output

variables

real error,PB_high,PB_low;

real hidden uP,uI,uD,uDstate,ideal_output;

equations

error = SP - MV;

uP = K * (b * SP - MV);

uI = int (K * error / Ti - (ideal_output - output) / Ta);

uDstate = int (uD * N / Td);

uD = K * (c * SP - MV) * N - uDstate;

ideal_output = uP + uI + uD;

output = limit (ideal_output, minimum, maximum);

PB_low = b * SP + (uI + uD - maximum)/K;

PB_high = b * SP + (uI + uD - minimum)/K;

SFCcurve:

parameters

real A[10,2] = [

0, 0;

0.25, 25;

0.3, 20;

0.4, 12;

0.5, 5;

0.6, 2.5;

0.7, 1.5;

0.8, 2;

1.0, 5;

1.2, 2;]

Model name Economizer**Parameters and equations****ExhaustMassFlow:**

```

real A[4,2] = [
    0,          0 ;
    0.5,        6.3 ;
    0.75,       9.0 ;
    1.0,       11.6 ];

```

ExhaustTemperature:

```

real A[4,2] = [
    0,          0 ;
    0.5,       385 ;
    0.75,      351 ;
    1.0,       343 ];

```

ExhaustInformation

vparameters

```

real Specificheatcapacity = 1122; //Specific heat capacity
real Waterflow = 500;
real Tinitial = 60; //Initial Temperature in the Heat Exchanger

```

variables

```

real gasdensity;
real GasVolumeFlow;

```

equations

```

gasdensity = 1.293*273/(273+gasT)*1.015; //kg/m^3
GasVolumeFlow=GasMassFlow/gasdensity;
GasInfo=[Specificheatcapacity;gasdensity;GasVolumeFlow;Tinitial];

```

C(Exhaust):

variables

```

real V,c;
real Qinit;

```

equations

```

c=waterinfo[1,1]*HEinfo*waterinfo[2,1];
Qinit=c*waterinfo[4,1];
state=int(p.f,Qinit);
p.e = state / c;

```

R(Exhaust):

variables

```

real m,r;
real HeatPower;

```

equations

```

m=waterinfo[2,1]*waterinfo[3,1]+1e-10;
r=1/(m*waterinfo[1,1]);
input1.e = r * output1.f;
input1.f = output1.f;
HeatPower = input1.f; //For plotting

```

equations

```

WBInfo=[Volume;VolumeUnit];
WaterBathT=WBt;

```

R(Heat Transfer):

equations

```

        p.e = r * p.f;
R (Cooling side):
variables
    real m,r;
    real HeatPower;
equations
    m=waterinfo[2,1]*waterinfo[3,1]+1e-10;
    r=1/(m*waterinfo[1,1]);

    input1.e = r * output1.f;
    input1.f = output1.f;
    HeatPower=input1.f;// For plotting
equations
    p.e = r * p.f;
C (Cooling side):
variables
    real m,r;
    real HeatPower;
equations
    m=waterinfo[2,1]*waterinfo[3,1]+1e-10;
    r=1/(m*waterinfo[1,1]);

    input1.e = r * output1.f;
    input1.f = output1.f;
    HeatPower=input1.f;// For plotting
equations
    p.e = r * p.f;

```

Model name Heating2
Parameters and equations CoilFludInfo (Exhaust gas heat):

```

parameters
    real N = 12;//Number of elements
    real Area = 389.7 {m^2};
    real LiquidVolume = 550 {dm^3};
variables
    real V;
    real Vu;
    real HeatTransferArea;
    real VolumeUnit;
initialequations
    Vu=LiquidVolume/(1000*2*N);
    HeatTransferArea=Area;
equations
    VolumeUnit=Vu;
    CoilInfo=[HeatTransferArea;VolumeUnit];
C (Exhaust gas heat):
parameters
    real Tinit=20;
variables

```



```

        real C;
        real Qinit;
    equations
        C=FluidInfo[2,1]*CoilInfo[2,1]*FluidInfo[1,1];
        Qinit = C*Tinit;
        state = int(p.f,Qinit);
        p.e = state / C;

```

R (Exhaust gas heat)

```

    variables
        real m,r;
    equations
        m=FluidInfo[2,1]*FluidS;
        r=1/(m*FluidInfo[1,1]);
        input1.e = r * input1.f;
        input1.f = output1.f;

```

HeatingTransfer

```

    parameters
        real CF=1;//CorrectionFactor
    variables
        real U;
    equations
        U=9.2*3600*VolumeFlow+200;
        HeatTransferR=1/(U*CF*CoilInfo[1,1]);

```

R (Heat transfer):

```

    equations
        p.e = HeatTransferR * p.f;

```

CoilFluidInfo (Engine heat)

```

    parameters
        real N = 12;
        real Area = 389.7 {m^2};
        real LiquidVolume = 405.99 {dm^3};
    variables
        real V;
        real Vu;
        real HeatTransferArea;
        real VolumeUnit;
    initialequations
        Vu=LiquidVolume/(1000*2*N);
        HeatTransferArea=Area;
    equations
        VolumeUnit=Vu;
        CoilInfo=[HeatTransferArea;VolumeUnit];

```

R(Engine heat):

```

    variables
        real m,r;
        real HeatPower;
    equations
        m=waterinfo[2,1]*waterinfo[3,1]+1e-10;

```

```

        r=1/(m*waterinfo[1,1]);
        input1.e = r * output1.f;
        input1.f = output1.f;
CoilFluidInfo (Cooling Side)
parameters
    real N = 12;//Number of elements
    real Area = 389.7 {m^2};
    real LiquidVolume = 405.99 {dm^3};
variables
    real V;
    real Vu;
    real HeatTransferArea;
    real VolumeUnit;
initialequations
    Vu=LiquidVolume/(1000*2*N);
    HeatTransferArea=Area;
equations
    VolumeUnit=Vu;
    CoilInfo=[HeatTransferArea;VolumeUnit];
R(Cooling Side):
variables
    real m,r;
    real HeatPower;
equations
    m=FluidInfo[2,1]*FluidS;
    r=1/(m*FluidInfo[1,1]);
    input1.e = r * input1.f;
    input1.f = output1.f;
    HeatPower = input1.f;// For plotting;
C (Cooling side):
parameters
    real Tinit=20;
variables
    real C;
    real Qinit;
equations
    C=FluidInfo[2,1]*CoilInfo[2,1]*FluidInfo[1,1];
    Qinit = C*Tinit;
    state = int(p.f,Qinit);
    p.e = state / C;

```

Model name GearBox**Parameters GearBoxParameter****and equations** parameters

```

    real r_GearBoxloss=0.02;
    real i_Gearinertia=0.09;
    real T=0.05; //Thickness of gear
    real D=0.25; //Diameter of gear

```

```

        real G=8393;//Modulus of elasticity
        real t=0.015;//material damping ratio of steel
        real k=2000000000000;//stiffness youngs modulus=200GPa
        real m=0.2;//Mass of gear
        real GearRatio=5;
    equations
        output=[r_GearBoxloss;i_Gearinertia;T;D;G;t;k;m];
        GearR=1/GearRatio;
R (Resistance):
    equations
        p.e = GearParameter[1,1] * p.f;
I (Inertia)
    variables
        real state;
    equations
        state = int(p.e);
        p.f = state / GearParameter[2,1];
R(Material damping)
    variables
        real r;
    equations
        r=GearParameter[6,1]*2*sqrt(GearParameter[7,1]*GearParameter[8,1]);
        p.e = r*p.f;
C:
    variables
        real state;
        real C_gearflexibility;
    equations
        C_gearflexibility=32*GearParameter[3,1]/(3.14*GearParameter[4,1]^4*GearParameter[5,1]);
        state = int(p.f);
        p.e = state / C_gearflexibility;;

```

APPENDIX B EXPERIMENT DATA

WaterBath T	50		Water Deepth	13.8mm				Simulation Result		
Pump Speed	Volume Flow(ml/s)	T1	T2	T2-T1	Qw	T_Average	Area	U	T	Devication
10	1.02E-06	16.9	48.8	31.8	1.36E+02	9.6165101	0.04523	313.1564	47.81	-0.99
20	2.04E-06	16.4	47.7	31.3	2.68E+02	11.672062	0.04523	507.0084	46.59	-1.11
30	3.04E-06	16.2	46.1	29.8	3.81E+02	13.845899	0.04523	609.3522	44.95	-1.15
40	4.03E-06	16.2	44.2	28	4.74E+02	15.885598	0.04523	660.0021	43.07	-1.13
50	5.02E-06	16.5	42.5	26	5.49E+02	17.372219	0.04523	698.3478	41.47	-1.03
60	6.02E-06	16.4	40.9	24	6.20E+02	18.755957	0.04523	730.698	39.94	-0.96
70	7.04E-06	16.4	39.5	23.1	6.83E+02	19.859849	0.04523	760.1171	38.68	-0.82
80	8.07E-06	16.5	38.3	21.8	7.39E+02	20.723288	0.04523	788.6227	37.49	-0.81
90	9.14E-06	16.3	37.2	20.9	8.02E+02	21.589734	0.04523	821.5197	36.54	-0.66
100	1.02E-05	16.2	35.9	19.7	8.47E+02	22.532672	0.04523	831.5323	35.32	-0.58
110	1.14E-05	16.3	35	18.7	8.94E+02	23.102174	0.04523	856.2327	34.62	-0.38
120	1.26E-05	16.2	34.5	18.3	9.68E+02	23.472951	0.04523	911.7314	34.3	-0.2

WaterBath T	85		Water Deepth		13.8mm				Simulation Result		Divication
Pump Speed	Volume Flow(m³/s)	T1	T2	T2-T1	WaterBath T	Qw	T_Average	Area	U	T	
10	1.01632E-06	15.6	82.5	66.9	85	2.86E+02	20.12879943	0.04523	3.14E+02	82.16	0.34
20	2.03545E-06	15.2	81.5	66.3	85	5.67E+02	22.15264176	0.04523	5.66E+02	81.2	0.3
30	3.03781E-06	14.7	78.2	63.5	85	8.10E+02	27.18497425	0.04523	6.59E+02	78.1	0.1
40	4.03119E-06	14.5	74.8	60.3	83.4	1.02E+03	28.97793003	0.04523	7.79E+02	74.78	0.02
50	5.02339E-06	14.8	71.5	56.7	83	1.20E+03	31.85218734	0.04523	8.31E+02	71.76	-0.26
60	6.02218E-06	14.9	68.6	53.7	82.5	1.36E+03	33.95040152	0.04523	8.85E+02	69.11	-0.51
70	7.03538E-06	14.6	65.3	50.7	81.9	1.50E+03	36.22055856	0.04523	9.15E+02	65.84	-0.54
80	8.07076E-06	14.5	62.2	47.7	81.2	1.62E+03	37.98478458	0.04523	9.41E+02	62.96	-0.76
90	9.13612E-06							0.04523			0
100	1.02393E-05							0.04523			0
110	1.1388E-05							0.04523			0
120	1.259E-05							0.04523			0

Heating Temperature- Experiment 2.2

Pump Speed/Output T	10	20	40
50	50.5	51	53
60	61.5	62.5	64.5
70		72	74.5

Holding Hose Length(m) with 8mm diameter

Pump/T-hod	10	20	40
30	0.607	1.215	2.431
60	1.214	2.431	
120	2.431		

Experiment 2.2 Result

Number	Target heating Temperature	Pump Speed	Volume flow	Heating Process Time	Holding Time	Input Coil	Out of heating Coil	Out of Holding Coil
1	70	40	4.03334	10.8	30	20.5	69.6	67.6
2	70	20	2.01207	21.67	60	20.5	70.3	68.1
3	60	40	4.03334	10.8	30	20.5	60.6	59.2
4	60	20	2.01207	21.67	60	20.5	60.7	58.9
5	60	10	1.00177	43.39	120	20.5	60.6	57.5
6	50	40	4.03334	10.8	30	20.5	50.3	48.8
7	50	20	2.01207	21.67	60	20.5	50.3	49
8	50	10	1.00177	43.39	120	20.5	50.2	48
9	Untreated	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Heating Temperature- Experiment 2.5			
Pump Speed/Output T	10	20	40
50	50.8	51	
55	56.2	57	59
60	61.2	63.7	66

Experiment 2.5 Result								
Number	Target heating Temperature	Pump Speed	Volume flow	Heating Process Time	Holding Time	Input Coil	Out of heating Coil	Out of Holding Coil
1	60	40	4.03334	10.8	30	8	59.9	58.8
2	60	20	2.01207	21.67	60	8	60.8	58.6
3	60	10	1.00177	43.39	120	8	60.3	57.2
4	55	40	4.03334	10.8	30	8	54.8	54.3
5	55	20	2.01207	21.67	60	8	55.5	54.2
6	55	10	1.00177	43.39	120	8	55.2	53
7	50	10	1.00177	43.39	60	8	50.3	49
8	50	20	2.01207	21.67	120	8	50.2	48
9	Untreated1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10	Untreated2	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Volume flow with Hose diameter: 9.5mm

Hose diameter	10mm	Length	22.1cm	Average Time(s)	Volume flow(ml/s)
Pump Speed	100ml	200ml	300ml		
10	101.93	97.63	99.91	99.82333333	1.001769793
20	49.58	49.77	49.75	49.7	2.012072435
30	32.89	33.33	33.08	33.1	3.021148036
40	24.8	24.92	24.66	24.79333333	4.033342296
50	19.79	19.99	19.92	19.9	5.025125628
60	16.6	16.78	16.54	16.64	6.009615385
70	14.22	14.1	14.04	14.12	7.082152975
80	12.43	12.35	12.26	12.34666667	8.099352052
90	10.61	10.87	11.1	10.86	9.208103131
100	9.96	9.73	9.95	9.88	10.12145749
110	8.99	8.82	8.69	8.833333333	11.32075472
120	8.06	7.79	7.84	7.896666667	12.66357113

Volume flow with Hose diameter: 7.9mm

Hose diameter	10mm	Length	22.1cm	Average Time(s)	Volume flow(ml/s)
Pump Speed	100ml	200ml	300ml		
10	168.76	169.62	171.95	170.11	0.587854917
20	85.14	83.43	86.7	85.09	1.175226231
30	57.21	56.34	57.12	56.89	1.757778168
40	43.09	42.33	42.18	42.53333333	2.351097179
50	34.68	33.57	33.95	34.06666667	2.935420744
60	28.18	28.32	28.41	28.30333333	3.53315275
70	24.37	24.48	24.03	24.29333333	4.116355653
80	20.79	21.08	21.14	21.00333333	4.761149024
90	18.55	18.78	18.73	18.68666667	5.351409204
100	16.71	16.48	16.79	16.66	6.00240096
110	14.98	15.36	15.09	15.14333333	6.603565926
120	13.58	13.99	14.1	13.89	7.199424046

Waste Heat Recovery experiment data

Waste heat recovery experiment(Parallel flow)					
	Htin	Htout	Ltin	Ltout	Waterbath Out
PumpS/Temperature	T1	T2	T3	T4	T5
8	52	36.4	22.8	36.7	65
10	52.7	37	22.9	37	64.9
15	53.7	37.8	22.9	37.7	65.1
31	55	38.3	22.8	38.6	65
60	55.1	38.8	22.5	38.3	64.9
120	55.3	38.2	20.1	36.5	65.1

Waste heat recovery experiment(Counter flow)					
	Htin	Htout	Ltin	Ltout	Waterbath Out
PumpS/Temperature	T1	T2	T3	T4	T5
8	53.3	35.6	24.7	41.1	64.9
10	53.7	36.5	25.1	41	65.1

15	54.6	36.9	25.3	42.1	65.1
31	55.3	40	25.9	41.3	65
60	55.3	40.8	26.3	40.9	64.9
120	55.5	40.3	26.2	41.8	65.1

APPENDIX C SIMULATION DATA

Process	Element NO.	120S	60S	30S
Heating	H1	7	7	7
	H2	22.89	20.78	18.22
	H3	34.14	31.21	27.32
	H4	42.1	39.11	34.68
	H5	47.72	45.09	40.64
	H6	51.67	49.62	45.46
	H7	54.51	53.04	49.37
	H8	56.5	55.63	52.54
	H9	57.9	57.6	55.1
	H10	58.9	59.08	57.17
	H11	59.6	60.2	58.85
	H12	60.1	61.05	60.21
Holding	HO1	59.84	60.83	60.08
	HO2	59.59	60.61	59.95
	HO3	59.34	60.39	59.83
	HO4	59.09	60.17	59.7
	HO5	58.84	59.95	59.58
	HO6	58.6	59.74	59.45
	HO7	58.36	59.52	59.33
	HO8	58.11	59.31	59.2
	HO9	57.88	59.1	59.08
	HO10	57.63	58.89	58.96
	HO11	57.4	58.68	58.84
Cooling	C1	57.4	58.68	58.83
	C2	33.97	38.21	42.28
	C3	20.01	24.89	30.38
	C4	11.89	16.21	21.82
	C5	7.03	10.56	15.68
	C6	4.16	6.87	11.27
	C7	2.46	4.48	8.1
	C8	1.46	2.92	5.82
	C9	0.86	1.9	4.18
	C10	0.51	1.23	3
	C11	0.3	0.8	2.16
	C12	0.17	0.53	1.55

Process	Element NO.	120S	60S	30S
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Heating	H1	7	7	7
	H2	21.4	19.91	17.52
	H3	31.59	29.48	25.92
	H4	38.8	36.59	32.61
	H5	43.89	41.86	37.95
	H6	47.5	45.76	42.21
	H7	50.04	48.67	45.61
	H8	51.84	50.82	48.32
	H9	53.12	52.41	50.48
	H10	54.02	53.6	52.2
	H11	54.66	54.48	53.58
	H12	55.1	55.13	54.68
Holding	HO1	54.89	55	54.59
	HO2	54.67	54.87	54.52
	HO3	54.45	54.75	54.44
	HO4	54.23	54.62	54.36
	HO5	54.02	54.5	54.29
	HO6	53.8	54.37	54.21
	HO7	53.59	54.25	54.13
	HO8	53.38	54.12	54.06
	HO9	53.17	54	53.98
	HO10	52.96	53.88	53.9
	HO11	52.75	53.76	53.83
Cooling	C1	52.74	53.57	53.83
	C2	37.3	39.73	42.94
	C3	26.38	29.46	34.25
	C4	18.66	21.85	27.32
	C5	13.2	16.2	21.79
	C6	9.33	12.01	16.38
	C7	6.1	7.91	11.87
	C8	3.3	4.9	8.82
	C9	2.33	3.63	7.04
	C10	1.65	2.69	5.61
	C11	1.16	2	4.47

Process	Element NO.	120S	60S
Heating	H1	7	7
	H2	20.06	20.41
	H3	29.22	29.73
	H4	35.65	36.22
	H5	40.18	40.72
	H6	43.34	43.85
	H7	45.56	46.03

	H8	47.12	47.55
	H9	48.22	48.6
	H10	48.99	49.33
	H11	49.53	49.84
	H12	49.9	50.19
Holding	HO1	49.79	50
	HO2	49.69	49.81
	HO3	49.58	49.63
	HO4	49.47	49.44
	HO5	49.36	49.26
	HO6	49.25	49.07
	HO7	49.13	48.89
	HO8	49.01	48.71
	HO9	48.87	48.52
	HO10	48.72	48.34
	HO11	48.55	48.16
Cooling	C1	48.55	48.16
	C2	34.21	35.04
	C3	24.01	25.49
	C4	16.85	18.54
	C5	11.83	13.49
	C6	8.3	9.81
	C7	5.82	7.14
	C8	2.87	3.78
	C9	2.01	2.75
	C10	1.41	2
	C11	0.99	1.45

APPENDIX D MATLAB EQUATIONS

Programme name Heat Transfer Coefficient

```

Parameters      clc
and             clear
equations       %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                PumpS=input('What is the Pump Speed?');
                TcIN=input('What is the fluid T in Coil?');
                TcOUT=input('What is the fluid T out Coil?');
                syms ThIN ThOUT Tav Qc Qw U A;
                %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                %Pump Speed Calculation
                SpeedEx=[0 10 20 30 40 50 60 70 80 90 100 110 120];
                VolumeEx=[0 1.001769793 2.012072435 3.021148036 4.033342296
                5.025125628 6.009615385 7.082152975 8.099352052 9.208103131
                10.12145749 11.32075472 12.66357113];
                PSC=polyfit(SpeedEx,VolumeEx,3)
                VolumeFlow=PSC(1,1)*PumpS^3+PSC(1,2)*PumpS^2+PSC(1,3)*PumpS+PSC
                C(1,4);
                %Coil information
                InDiameter=0.006;
                OutDiameter=0.008;
                A=OutDiameter*3.14*1.8
                %Water Bath information
                WBT=50.8;
                ThIN=WBT;
                ThOUT=WBT;
                %Volume Flow m^3
                Vw=VolumeFlow*10^-6
                %Fluid information
                Density=1000;
                Cp=4200;
                %Calculation
                Qw=Vw*Density*Cp*(TcOUT-TcIN)
                Tav=((ThIN-TcIN)-(ThOUT-TcOUT))/(log((ThIN-TcIN)/(ThOUT-
                TcOUT)))
                U=Qw/(A*Tav)

```