BACHELOR THESIS (ME 141502)

INFLUENCE OF EXHAUST GAS TREATMENT SYSTEM TO THE POSSIBLE EXHAUST GAS RECOVERY

Christian Laksmono
NRP. 4212 101 015

Academic Supervisor

1. Prof. Dr.-Ing. M Rachow
2. MSC Steffen Loest

DOUBLE DEGREE PROGRAM OF
MARINE ENGINEERING DEPARTMENT
Faculty of Marine Technology
Institut Teknologi Sepuluh Nopember
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SKRIPSI (ME 141502)

PENGARUH DARI SISTEM PENGOLAHAN GAS BUANG TERHADAP KEMUNGKINAN DAUR ULANG DARI GAS BUANG

Christian Laksmono
NRP. 4212 101 015

Dosen Pembimbing

1. Prof. Dr.-Ing. M Rachow
2. MSC Steffen Loest

TEKNIK SISTEM PERKAPALAN
PROGRAM GELAR GANDA
Fakultas Teknologi Kelautan
Institut Teknologi Sepuluh Nopember
Surabaya
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LEMBAR PENGESAHAN

TITLE : INFLUENCE OF EXHAUST GAS TREATMENT SYSTEM TO THE POSSIBLE EXHAUST GAS RECOVERY

AIM : TO DEVELOP THE KNOWLEDGE ABOUT EXHAUST GAS TREATMENT SYSTEM AND TO FIND ITS CONNECTION WITH EXHAUST GAS HEAT RECOVERY TO DEVELOP THE FUTURE DESIGN

PEMBIMBING : PROF. DR.-ING. M. RACHOW
MSC STEFFEN LOEST

SURABAYA, 25 JULI 2016

MSC. STEFFEN LOEST

Warnemünde, 17.11.2015

Task for Bachelor-Thesis

Subject: **Influence by the use of exhaust gas treatment systems of possible exhaust gas heat recovery**

Student: Christian Laksmono

Supervising Professor : Prof. Dr.-Ing. Michael Rachow
Assistant Supervisor : MSC Steffen Loest
Date of issue : April 2016
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The exhaust gas emission limits become for shipping industry more stringent and compliance. There are a number of options to comply the limits; presented by different technical and operational solutions to meet the SO_x and NO_x emission limits. Most options taking a strong influence upon the exhaust gas temperature and possible heat recovery. In this bachelor thesis is to analyse the influence of different exhaust gas treatment systems, of heat recovery potential and of heat recovery systems.

The following aspects should be particularly considered**:**

1. Characterisation of different technical and operational systems to meet the SO_x and NO_x emission limits,
2. Detailed description of influence of different exhaust gas treatment systems regarding the heat recovery potential,
3. Appointment of exhaust gas heat recovery potential in an example,
4. Evaluation of results.

The supervising Professor reserves the rights to extend or to narrow down the scope of the task during processing. Establishing contacts with other institutions and companies must be agreed with the supervisors. The publication of the work or parts of it requires the prior permission of

the supervisor. The work shall be prepared in accordance with the applicable guidelines of Hochschule Wismar for academic and scientific work. At least two consultations with the supervising Professor are required as part of the processing. The finished work is to be submitted in electronic form and in four printed copies in the organization office in Warnemünde.

Prof. Dr.-Ing. M. Rachow / MSC.Steffen Loest

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ABSTRACT

Bachelor Thesis with title of Influence of Exhaust Gas Treatment System to the Possible Exhaust Gas Recovery written by Christian Laksmono 4212101015 is the result of Environment Technology has been the major Breakthrough in 2010s, since the awareness of Global Warming increases rapidly. The Environment Technology is affecting whole Industry World with no exception to Marine World.

Diesel Engine is undeniably the most frequent used machinery over the world and this trend is also the same with Maritime World. The usage of Diesel Engine will be resulting emission gas such as Sulphur and Nitrogen Oxide, which is highly dangerous for current Environment Condition. Both pollution types can be categorized as the acid material which very harmful to the environment and therefore MARPOL announces the requirement regarding the concentration of Sulphur and Nitrogen Oxide in order to maintain the quality of environment. It could be said that the appliance of this rule is supported by the public wholly, since these pollutions will not only slowly damage environment but also human body by causing acid rain and respiratory disorders.

In order to fulfill the requirement of MARPOL The writer is trying to find the connection between EGTS and WHRS, and calculate the losses which are caused by application of EGTS. The calculation covers Chemical and Physical Calculation. From these connection and calculation, the writer gives analyzes how to use the Scrubber System with the possibility of WHRS including the suggestion how to improve the design of the EGTS in the future.

Keyword : EGTS , Exhaust Gas Treatment System , WHRS , Waste Heat Recovery System , Scrubber Losses , Heat Loss , Marpol , Environtment Technology , Scrubber

ABSTRAK

Bachelor Thesis dengan judul Pengaruh dari Sistem Pengolahan Gas Buang Terhadap Kemungkinan Daur Ulang dari Exhaust Gas ditulis oleh Christian Laksmono 4212101015 merupakan hasil dari Teknologi Hijau yang menjadi Trend sejak tahun 2010 , dimulai dengan kewaspadaan terhadap Global Warming yang meningkat secara pesat. Teknologi Hijau berdampak pada Industri Teknologi tanpa terkecuali Teknologi Kelautan.

Diesel Engine tidak dapat disangkal sebagai system permesinan yang paling banyak digunak di dunia dan trend ini juga berlaku di Teknologi Kelautan. Pengunaan Diesel Engine ini sendiri mengakibatkan Gas Emisi seperti Sulfur dan Nitrogen Oxide yang sangat berbahaya terhadap kondisi lingkungan. Kedua polutan ini dapat dikategorikan sebagai *acid material* yang sangat berbahaya sehingga MARPOL mengeluarkan peraturan mengenai kedua substansi ini. Dan dikeluarkannya peraturan ini didukung secara penuh oleh public , karena polutan ini tidak hanya berpengaruh pada lingkungan melainkan juga terhadap tubuh manusia dengan mengakibat gangguan pernapasan.

Dengan tujuan untuk memenuhi peraturan MARPOL Penulis mencoba mencari koneksi antara EGTS dengan WHRS serta menghitung *losses* yang diakibatkan oleh aplikasi dari EGTS. Perhitungan melingukpi perhitungan secara fisika dan kimia. Dari koneksi ini penulis akan memberikan analisa bagaimana untuk menggunakan EGTS dengan kemungkinan untuk *Heat* Recovery serta peluang untuk mengembangkan design EGTS kedepannya.

Keyword : EGTS , Exhaust Gas Treatment System , WHRS , Waste Heat Recovery System , Scrubber Losses , Heat Loss , Marpol , Environtment Technology , Scrubber

APPROVAL FORM

Influence of Exhaust Gas Treatment System to the Possible Exhaust Gas Heat Recovery

BACHELOR THESIS

Submitted to Comply One of the Requirements to Obtain
Bachelor of Engineering Degree
On
Laboratory of Marine and Machinery System (MMS)
S-1 Program Department of Marine Engineering
Faculty of Marine Technology
Institut Teknologi Sepuluh Nopember

Prepared By :
CHRISTIAN LAKSMONO
NRP. 4212 101 015

Approved By Chief Department :

Dr.Eng. M. Badrus Zaman, S.T., M.T.
NIP. 1977 0802 2008 01 1007

Surabaya
July, 2016

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Prepared By :
CHRISTIAN LAKSMONO
NRP. 4212 101 015

Approved By
Hochschule Wismar Representative in Indonesia :

Dr.Ing. Wolfgang Busse

Surabaya
July, 2016

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PREFACE

Technology is undoubtedly the major part of our lives in present, it is never demanding to be part of our life or even to be developed, but the existence of it giving such a huge presence to humanity to develop their world to be more advance ,and to be part of the current revolution then you must the part of the technology development itself. Putting much passion and love to Technology and Sea at the same time, this desire pushing me to learn Marine Engineering and working this thesis is the part to chase it

This following thesis is a combination between environment technology and marine engineering, by correlating between pollution prevention and exhaust gas which results Exhaust Gas Treatment System, and I put my consent to its thermodynamic consideration regarding influence between each other.

In order to finish my Thesis, I am working under the guidance of Prof. Dr-Ing Michael Rachow and MSC Steffen Loest who are sharing their advance knowledge and giving me a lot of advice to make this work better. In order to get the further data, I am collecting data from Hochschule Wismar Laboratory and I am really thankful to Hartmut Schmidt and Benjamin Muller who are my laboratory guides, and also Christo who is working and sharing data with me about the work in the laboratory. Lastly, I am very grateful to God and my parent who give me this precious chance to work my thesis in Rostock,

Germany and also Hochschule Wismar with ITS institution and Ir. Dwi Priyanta MSE. Ph.D to make this happen.

Rostock, June 2016

Christian Laksmono

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NOMENCLATURES

A	Area of Surface
^oC	Celsius
CARB	California Air Resources Board
cp	Specific Heat
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Σ	Total Sum up
E	Energy
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EG	Exhaust Gas
EGR	Exhaust Gas Recirculation
EGTS	Exhaust Gas Treatment System
EU	European Union
EPA	United States Environmental Protection Agency (EPA)
FO	Fuel Oil
GHE	Wet Gas Stoich
GHT	Total Wet Exhaust Gas
GSE	Dry Gas Stoich
GST	Total Dry Exhaust Gas
h	Overall Heat Transmission Coefficient
H	Enthalpy
$H_2 O$	Water
$H_2 SO_3$	Sulfurous Acid
$H_2 SO_4$	Sulfurous Acid
HC	Hydrocarbon
H/E	Heat Exchanger
HHV	Higher Heating Value
HSW	Hochschule Wismar
HT	High Temperature (cooling system)

IMO	International Maritime Organization
ITS	Institut Teknologi Sepuluh Nopember
J	Joule
k	Thermal Conduction Value
m	meter
MARPOL	Marine Pollution
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
$NaHSO_3$	Sodium Bisulfite
$NaHSO_4$	Sodium Bisulfate
NaOH	Natrium Hydroxide
$Na_2\ CO_3$	Natrium Carbonate
$Na_2\ SO_3$	Natrium Sulfite
$Na_2\ SO_4$	Natrium Sulfate
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
O_2	Oxygen
Pb	Brake Power Output
PM	Particular Matter
PSV	Saturated Vapour Pressure
PV	Partial Vapour Pressure
Q	Heat Transfer / Losses
Q cond	Heat Released by Conduction
Q conv	Heat Released by Convection
Q total	Total heat Released / Work Loss Total
Q oil	Heat Released to Lubricating Oil
SECA	SOx Emission Control Area
SFOC	Specific Fuel Oil Consumption
SOx	Sulphur Oxide
$T\infty$	Temperature Surrounding

T_{sw}	Temperature of SeaWater
T_{gas}	Temperature of Exhaust Gas
W	Watt
WHRS	Waste Heat Recovery System
XL	Humidity Factor
λ	Air Equivalance Ratio

CHAPTER 1
INTRODUCTION

1.1 Introduction about the Background of EGTS use

Shipping is one of the global industry and harmful emissions created from shipping vessels are affecting many regions worldwide. As a consequence Marine Industry is now challenged to adopt a new technology from the stricter international, national and local regulations to reduce emission from the ships. The change is involved from internal combustion engine and boiler exhaust gases to be friendlier to human beings and ecosystem, and this is demanded by not only by social community but also the scientific community. Regulations introduced by International Maritime Organization (IMO) , European Union (EU) and United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB) to reduce global emission by applying rules on maritime world. These rules and regulations will force the marine industry to make difficult adjustments. However the benefits of having better air quality are worth the struggles of it to maintain better future for us all.

Critical amongst these regulations are the measures to reduce the sulfur oxide (SOx) emissions inherent with the relatively high sulfur content of marine fuels. Ship designers, owners and operators have three general routes to achieve SOx regulatory compliance:

- Use low sulfur residual or distillate marine fuels in existing machinery,
- Install new machinery (or convert existing machinery where possible) designed to operate on an inherently low sulfur alternative fuel, such as liquefied natural gas (LNG), or
- Install an exhaust gas treatment system (EGTS) after treatment system.[1]

This statutory has been produced to reach the proper requirements applicable to SOx Exhaust Gas Treatment Systems (EGTS), or more known as scrubbers to provide an overview of available technologies. Marine air pollution regulations require the use of low sulfur fuel and the sulfate portion of the particulate matter (PM) emissions. The use of EGTS technology is called as an alternative of operating with low sulfur fuels. While EGTS systems have limited marine references at present, they are a proven existing technology with extensive experience and numerous applications to inert gas systems on tankers; they are considered a practical alternative for meeting SOx emission regulations.

Scrubbers can be effective to fulfill the regulations requirement which is demand the usage of fuel with 1 percent or 0.5 percent sulfur content; however the capability of certain scrubbers to provide required SOx emissions to 0.1 is more uncertain. With the consent to fulfill the regulatory requirements for emissions of nitrogen oxides (NOx), a typical scrubber provides only negligible reduction in NOx emissions and would not be normally considered as a method to achieve compliance with the NOx emission requirements. There are a number of primary (engine) and secondary (after treatment) techniques for reducing NOx emissions. One of those primary engine techniques currently being developed for marine applications is the use of exhaust gas recirculation (EGR), which involves the recirculation of a portion of the exhaust gases, typically 20 to 40 percent, back into the combustion chamber. For marine applications

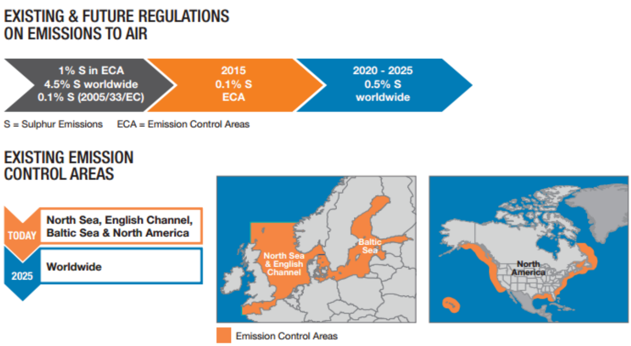

Figure 1 Existing & Future Regulation on Emissions to Air [2]

Regulatory Background, IMO Regulations Following development of the regulatory text by IMO's Marine Environment Protection

Committee (MEPC), an International Conference of Parties to the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the protocol of 1978 (MARPOL Convention), adopted the 1997 Protocol to the MARPOL Convention which added a new Annex VI on Regulations for the Prevention of Air Pollution from Ships. This Annex entered into force after acquiring the requisite number of signatories and tonnage on 19 May 2005. To reduce the harmful effects of SOx emissions on human health and the environment, Regulation 14 to the new Annex introduced a worldwide limit on the sulfur content of marine fuels of 4.5 percent and a limit within SOx emission control areas (SECA) of 1.5 percent. The Baltic Sea was the inaugural SECA adopted with the Annex and was followed, in accordance with the criteria for designation given under Appendix III to the Annex, by entry into force of the North Sea/ English Channel on 22 November 2007 through the adoption of IMO Resolution MEPC.132 (53).

In October 2008, the 58th IMO MEPC session adopted significant changes to Annex VI under Resolution MEPC.176(58). This introduced a reduction in the global sulfur fuel limit to 3.5 percent from 1 January 2012 with a further global reduction to 0.5 percent from 1 January 2020. The implementation date of 2020 is to be reviewed in 2018 to assess the availability of fuel oil to meet the 0.5 percent limit.

This review will determine whether the implementation date is to be extended to 2025 at the latest. The original Regulation 14 also mandated the monitoring of the sulfur content of residual fuel oils in accordance with the subsequently developed guidelines under IMO Resolutions MEPC.82 (43), MEPC.183(59) and MEPC.192(61); the average global fuel oil sulfur contents reported to MEPC 62 were 2.61 percent for residual and 0.15 percent for distillate fuel oils. The distillate results were obtained from a total of 26,189 samples corresponding to 2,396,849 tons (see Figure 2). The revised Annex VI also introduced a tiered reduction to the sulfur content of fuels for use in Emission Control Areas (ECA) to 1.0 percent from I July 2010 and more significantly, 0.1 percent from 1 January 2015 (see Table 1).

In addition to the IMO monitoring of fuel availability a number of other studies have been undertaken to assess the impacts of the regulatory requirements and the availability of low sulfur residual and distillate fuels for the 2015 and 2020 implementation dates. Although there is a degree of uncertainty the general consensus is that there will be sufficient quantities of low sulfur fuel available by 2015 for use in ECAs, however the picture at 2020 is far more uncertain. A more detailed summary is included under Appendix III to this Advisory. The revised Annex VI also included a revision to the terminology and regulations associated with the coastal air emission control areas with the revision from SECAs to ECAs. This added the provision to designate the areas as SOx, NOx and PM Emission Control Areas. However, at present IMO does not define PM limit criteria but PM is significantly reduced through the reduction of the sulfate portion of the PM, by the use of low sulfur fuels or other technological means such as EGC systems.[3]

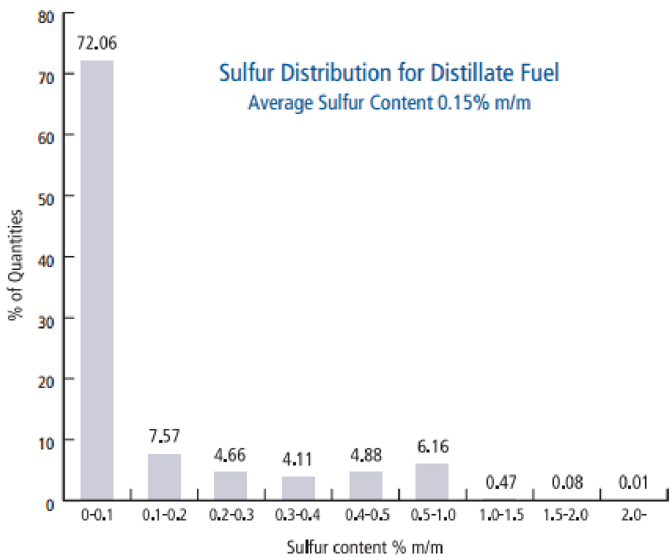

Figure 2 IMO Sulfur Monitoring Program[4]

1.2 Introduction about the Waste Heat Recovery System

The interest of reducing ship operating cost by adapting IMO EEDI rules calls for measures that ensure optimal utilization of the fuel used for main engines on board ships. Main engine exhaust gas energy is by far the most attractive among the waste heat sources of a ship because of the heat flow and temperature. It is possible to generate an electrical output of up to 11% of the main engine power by utilizing exhaust gas energy by comprising both steam and power turbines, and combined it with utilizing scavenge air energy for exhaust boiler feed-water heating.

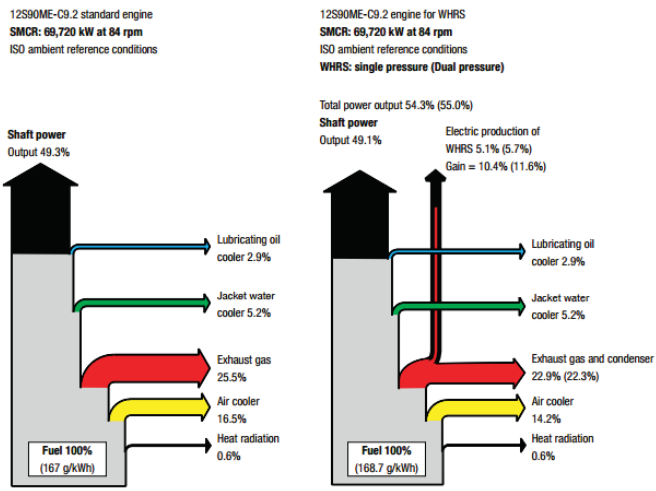

Figure 3 Heat balance for large-bore MAN B&W engine types without and with WHRS

Following the trend of a required higher overall ship efficiency since the first oil crisis in 1973, the efficiency of main engines has increased, and today the fuel energy efficiency is about 50%. This high efficiency has, among other things, led to low SFOC values, but also a correspondingly lower exhaust gas temperature after the turbochargers. Even though a main engine fuel energy efficiency of 50% is relatively high, the primary objective for the ship-owner is still to lower ship operational costs further, as the total fuel consumption of the ship is still the main target. This may lead to a further reduction of CO2 emissions – a task, which is getting even more important with the new IMO EEDI rules in place from 2013. The primary source of waste heat of a main engine is the exhaust gas heat dissipation, which accounts for about half of the total waste heat, i.e. about 25% of the total fuel energy.

In the standard high-efficiency engine version, the exhaust gas temperature is relatively low after the turbocharger, and just high enough for producing the necessary steam for the heating purposes of the ship by means of a standard exhaust gas fired boiler of the smoke tube design. However, the MAN B&W two-stroke ME main engine tuned for WHRS will increase the possibilities of producing electricity from the exhaust gas. The result will be an improvement in total efficiency but a slight reduction of the efficiency of the main engine will be seen. Fig.3 shows a comparison of engine heat balances, with and without WHRS. The figure shows that for the engine in combination with WHRS the total efficiency will increase to about 55%. The IMO EEDI formula allows for considering adding WHRS into the ship analyze EEDI effects and EEDI settings. As an even lower CO2 emission level can be achieved by installing a waste heat recovery system the EEDI, which is a measure for CO2 emissions, will also be lowered.[5]

CHAPTER 2
STATEMENT OF PROBLEMS

2.1 Influence of EGTS on Waste Heat Recovery System

The results of combustion process in diesel engine is Released in the form of Exhaust Gas. Inside of the Exhaust Gas consist of *Nitrogen Oxides(NOx), Sulfur Oxide (SOx), Hydrocarbon (HC), Carbon Monoxide(CO), and Particulates Matter (PM).* The impact of non-treated Exhaust gas can be shown by corrosion around exhaust gas tunnel which is caused by SOx . Not only SOx will impact to the Exhaust Gas System it is also impacting on environment. For example, Acid rain which is happened because of the reaction between SOx and H20. These cases will lead to the mandatory rules for the Exhaust Gas Treatment System.

The process through the Exhaust Gas to filter NOx and SOx substances inside of it , leads through Energy Losses in the process. Meanwhile, the process of NOx scrubbing is done on high temperature , which not convert to much heat to be released , on the other hand the scrubbing process of SOx is done by pouring Sea-Water on Open Loop System or Treat Water on Closed Loop System ,and this is done on Low temperature around 30-45 degree Celsius. This kind of treatment will lead to temperature drop, and the temperature drop is equal to energy release from the exhaust gas.

2.2 Hypothesis

a. The different EGTS installation will result different Exhaust Gas Temperature.
b. There will be the best installation of EGTS regarding WHRS capability.
c. Scrubber will result disadvantage in WHRS

2.3 Research Limitation

a. Characterization of different technical & operation systems to meet the SOx and NOx emission Limit
b. Influence of each EGTS installation regarding Heat Recovery Potential
c. Calculation of a Complete process Post ME until Post EGTS and conclusion
d. The use of Thermodynamic Calculation and Chemical Calculation to calculate losses from process.
e. The engine data which is used is MAN 6L 23/30 four stroke diesel engine 900kW of Hochschule Wismar in Warnemunde,Rostock.

2.4 Research Objectives

a. Calculate Losses through EGTS process.
b. Compare the Exhaust Gas Losses from each designs to find the most efficiency to WHRS capability
c. Determine the best Exhaust Gas Treatment Systems in correlation to the Heat Recovery Potential.
d. Analyze & Calculate the complete results of Comparison and Calculation to find the best solution and suggestion to improve the EGTS to reach WHRS efficiency.

2.5 Research Benefits

a. Understanding the technical data of scrubber due to SOx reduction.
b. Knowing the installation system of scrubber aboard ship to reduce SOx including scrubber's structure and processes.
c. Determine the basic Chemical and Thermodynamic Losses from EGTS usage.
d. Understand how to improve the EGTS installation to improve the capability to meet WHRS requirement.

CHAPTER 3
STUDY LITERATURE

In thermodynamics, we considered the amount of heat transfer as a system undergoes a process from one equilibrium state to another. Thermodynamics gives no indication of how long the process takes. In heat transfer, we are more concerned about the rate of heat transfer. The basic requirement for heat transfer is the presence of a temperature difference. The temperature difference is the driving force for heat transfer, just as voltage difference for electrical current. The total amount of heat transfer Q during a time interval can be determined from:

$$Q = \int_{0}^{\Delta t} Q^{\bullet} dt \qquad (kJ)$$

....(1)

The rate of heat transfer per unit area is called heat flux, and the average heat flux on a surface is expressed as

$$q^{\bullet} = \frac{Q^{\bullet}}{A} \quad \left(W / m^{2}\right)$$

(2)

3.1. Thermal Resistance Network

Consider steady, one-dimensional heat flow through two plane walls in series which are exposed to convection on both sides, see Fig. 2. Under steady state condition:

rate of heat convection into the wall	=	rate of heat conduction through wall 1	=	rate of heat conduction through wall 2	=	rate of heat convection from the wall

From the following statement we can formulize that into :

$$
\begin{aligned}
&Q^{\bullet} = h_1 A\left(T_{\infty,1} - T_1\right) = k_1 A\frac{T_1 - T_2}{L_1} = k_2 A\frac{T_2 - T_3}{L_2} = h_2 A\left(T_2 - T_{\infty,2}\right) \\
&Q^{\bullet} = \frac{T_{\infty,1} - T_1}{1/h_1 A} = \frac{T_1 - T_2}{L/k_1 A} = \frac{T_2 - T_3}{L/k_2 A} = \frac{T_2 - T_{\infty,2}}{1/h_2 A} \\
&Q^{\bullet} = \frac{T_{\infty,1} - T_1}{R_{conv,1}} = \frac{T_1 - T_2}{R_{wall,1}} = \frac{T_2 - T_3}{R_{wall,2}} = \frac{T_3 - T_{\infty,2}}{R_{conv,2}} \\
&Q^{\bullet} = \frac{T_{\infty,1} - T_{\infty,2}}{R_{total}} \\
&R_{total} = R_{conv,1} + R_{wall,1} + R_{wall,2} + R_{conv,2}
\end{aligned}
\qquad (3)
$$

Note that A is constant area for a plane wall. Also note that the thermal resistances are in series and equivalent resistance is determined by simply adding thermal resistances.[6]

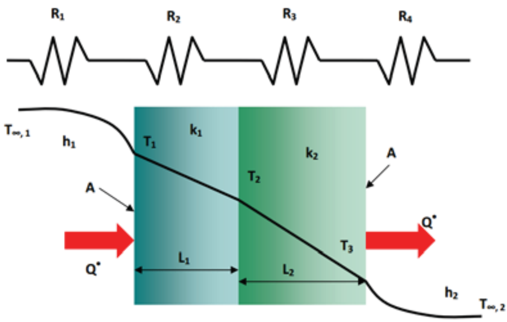

Figure 4 Thermal resistance network.

3.2. The Calculation Example of Multilayer Cylindrical Thermal Resistance Network

Steam at $T\infty,1$ = 320 °C flows in a cast iron pipe [k = 80 W/ m°C] whose inner and outer diameter are D1 = 5 cm and D2 = 5.5 cm, respectively. The pipe is covered with a 3-cm-thick glass wool insulation [k = 0.05 W/ m°C].

Heat is lost to the surroundings at $T\infty,2$ = 5°C by natural convection and radiation, with a combined heat transfer coefficient of h2 = 18 $W/m^2.°C$. Taking the heat transfer coefficient inside the pipe to be h1 = 60 W/m^2K, determine the rate of heat loss from the steam per unit length of the pipe. Also determine the temperature drop across the pipe shell and the insulation. (Assumption: Steady state and one – dimensional heat transfer).

Solution:

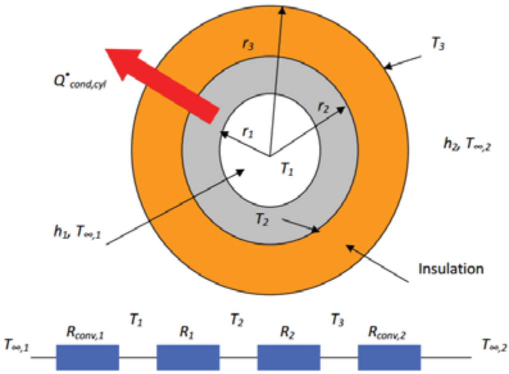

Figure 5 Multilayer Cylindrical Thermal Resistance

Taking L = 1 m, the areas of the surfaces exposed to convection are:

$$A1 = 2\pi r1L = 0.157\ m2$$
$$A2 = 2\pi r2L = 0.361\ m2$$

$$R_{conv,1} = \frac{1}{h_1 A_1} = \frac{1}{(60\ W/m^2.^\circ C)(0.157 m^2)} = 0.106\ ^\circ C/W$$
$$R_1 = R_{pipe} = \frac{\ln(r_2/r_1)}{2\pi k_1 L} = 0.0002^\circ C/W$$
$$R_2 = R_{insulation} = \frac{\ln(r_3/r_2)}{2\pi k_2 L} = 2.35^\circ C/W$$
$$R_{conv,2} = \frac{1}{h_2 A_2} = 0.154\ ^\circ C/W$$
$$R_{total} = R_{conv,1} + R_1 + R_2 + R_{conv,2} = 2.61^\circ C/W \quad (4)$$

The steady-state rate of heat loss from the steam becomes

$$Q^\bullet = \frac{T_{\infty,1} - T_{\infty,2}}{R_{total}} = 120.7\ W \qquad \text{(per m pipe length)} \quad (5)$$

The total heat loss for a given length can be determined by multiplying the above quantity by the pipe length. The temperature drop across the pipe and the insulation area:

$$\Delta T_{pipe} = Q^\bullet R_{pipe} = (120.7\ W)(0.0002\ ^\circ C/W) = 0.02^\circ C$$
$$\Delta T_{insulation} = Q^\bullet R_{insulation} = (120.7\ W)(2.35\ ^\circ C/W) = 284^\circ C \quad (6)$$

Note that the temperature difference (thermal resistance) across the pipe is too small relative to other resistances and can be ignored. [7]

3.3. Calculation Regarding Radiation

Radiant heat loss occurs as a result of highly energized molecules transmitting heat by way of waves or particles. For significant heat loss to occur from radiation, the hotter surface must be well above ambient temperature -- much higher than what is observed in typical heat trace applications. Therefore, heat loss from radiation can be ignored.

In practical low-to-medium temperature applications, convection and radiation account for about 10 percent of the overall heat loss of a system. By adding 10 percent, the general formula for calculating the heat loss of a system via conduction, convection and radiation can be calculated. [8]

3.4. Rockwool Insulation Thickness

Required insulation thicknesses If the three insulation systems are compared, taking into consideration similar heat losses, clear advantages are seen with regard to the insulation thicknesses with systems using Rockwool 850 pipe sections and Rockwool Duraflex load-bearing mats. These do not use spacers, in contrast to insulation systems made using wired mats. The table below shows the required insulation thicknesses taking into account the boundary conditions [9] :

Table 1 Rockwool Insulation Thickness

Nominal diameter Ø DN	NPS (inch)	Pipe diameter mm	Minimum insulation thickness		
			Pipe sections	Load bearing mats	Wired mats
			Rockwool 850	Rockwool Duraflex	ProRox WM 70
50	2	60	30	n.a.	n.a.
80	3	89	30	n.a.	n.a.
100	4	108	40	n.a.	n.a.
150	6	159	60	n.a.	n.a.
200	8	219	70	100	120
250	10	273	90	130	150
300	12	324	100	140 (2*70)	180 (2*90)
350	14	356	110	160 (2*80)	200 (2*100)

Multiple layer insulation (shaded cells) — n.a. = not applicable

3.5. NOx Scrubber Working System

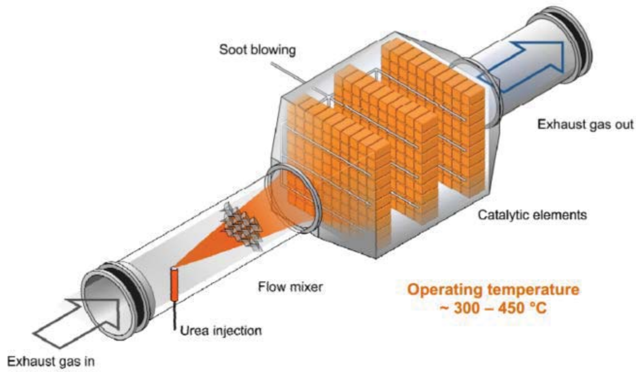

Figure 6 NOx Scrubber System by Wartsila

Nitrogen oxides (NOX) are reduced into nitrogen (N2) and water vapor (H2O) using Ammonia or urea at a suitable temperature on the surface of the catalyst. With minimum recommended temperature in the SCR compared to fuel Sulphur content.

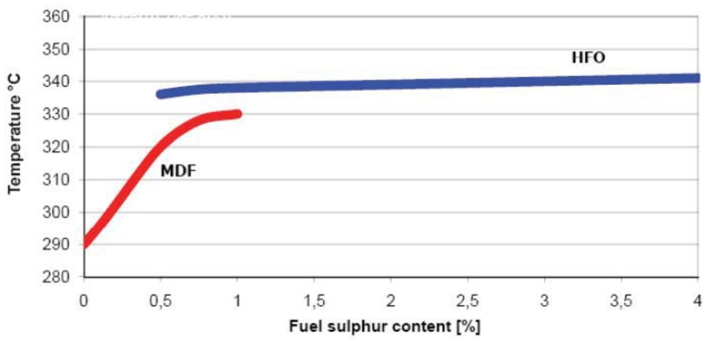

Figure 7 Recommended Temperature for SCR [10]

Those chemical products which is used NH3 and Oxygen to react NO into N2

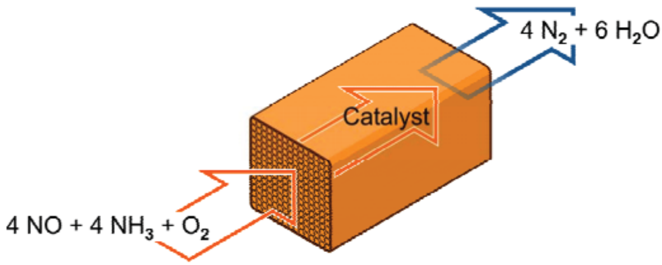

Figure 8 NOx with Catalyst Reduction

3.6. SOx Scrubber System

A scrubber is a device that installed in the exhaust system after the engine or boiler that treats the exhaust gas with a variety of substances including sea water, chemically treated fresh water or dry substances, so as to remove most of the SOx from the exhaust and reduce PM to some extent. After scrubbing, the cleaned exhaust is emitted into the atmosphere. All scrubber technologies create a waste stream containing the substance used for the cleaning process plus the SOx and PM removed from the exhaust. SOx (SO2 plus SO3) gases are water soluble. Once dissolved, these gases form strong acids that react with the natural alkalinity of the seawater, or the alkalinity derived from the added substances (normally sodium hydroxide), forming soluble sodium sulfate salt, which is a natural salt in the seas. In addition, the PM in the exhaust will become entrapped in the washwater, adding to the sludge generated by a scrubber. With dry scrubbers calcium hydroxide (Ca(OH)2), or hydrated lime as it is more commonly known, reacts with the SOx and solid calcium sulfate (CaSO4), or gypsum as it is more commonly known, is the product of the reaction. The waste stream and generated sludge has to be processed as per the IMO guidelines before discharge overboard, where allowed, or stored and discharged to shore as a waste substance.

Engine Exhaust Gas Chemistry:
$S + O_2 \rightarrow SO_2 \sim 95\%$
$SO_2 + ½O_2 \rightarrow SO_3 \sim 5\%$

SOx Reactions in a Scrubber:
$SO_2 + H_2O \rightarrow H_2SO_3$ *(Sulfurous Acid)*
$SO_3 + H_2O \rightarrow H_2SO_4$ *(Sulfuric Acid)*

Sulfurous gases in water are in a state of rapid oxidation: sulfur dioxide (SO_2) oxidizes to sulfur trioxide (SO_3), which dissolves in water to form sulfuric acid (H_2SO_4). Also, upon dissolution in water, SO_2 forms the hydrate $SO_2 + H_2O$ or sulfurous acid H_2SO_3, which dissociates rapidly to form the bisulfate ion HSO_3, which in turn, is oxidized to sulfate. There are two basic concepts commonly proposed for shipboard application of EGC systems, the dry scrubber-type and the wet scrubber-type. The basic principles for each concept are described further in this section [11].

3.7. Open Loop System

An open loop-type scrubber uses sea water as the medium for cleaning or scrubbing the exhaust as shown in Figure 10. Sea water is normally supplied by a dedicated pump. CO_2 dissolves in seawater forming carbonic acid, bicarbonate or carbonate ions depending on the pH. The positive companion ion can be calcium (Ca^{2+}) or sodium (Na^+) – here the sodium carbonate salt is used as an example. When the carbonate/bicarbonate ion reacts with an acid CO_2 is released.

$Na_2CO_3 + H_2SO_3 \rightarrow Na_2SO_3 + H_2O + CO_2$ *(Sodium Sulfite)*
$Na_2SO_3 + ½O_2 \rightarrow Na_2SO_4$ *(Sodium Sulfate)*
$Na_2CO_3 + H_2SO_4 \rightarrow Na_2SO_4 + H_2O + CO_2$ *(Sodium Sulfate)*

Each EGC system manufacturer has their own techniques for how the scrubber mixes the exhaust gas and the water. As previously mentioned an open loop scrubber is only effective if the source water is alkaline. However, some river water is ‘hard’ water with significant alkalinity, in some cases higher than seawater, so open loop scrubbers can also work effectively in some port and river areas, but it is necessary to know the alkalinity of the water before this can be determined.

Therefore, the effectiveness of an open loop scrubber very much depends on the chemistry of the water the vessel is operating in. This should be considered at the design and selection stage or when deploying a vessel to new areas. If the water is not alkaline (pH is too low), the scrubber will not meet the required performance level and the operator would have to use low sulfur fuel to be in compliance with the applicable SOx emission regulations.

As required by the 2009 Guidelines, scrubber manufacturers must state the operational limits in terms of maximum fuel sulfur content for operation to be in compliance with the Annex VI Regulation 14 requirements. Open loop scrubbers have larger water flow rates than closed loop scrubbers because there is less control over water alkalinity and more water is needed to make the scrubbing process effective then lower alkalinity water is used.

After the basic scrubbing process takes place in the main scrubber tower, the exhaust mixture normally passes through a demister or water droplet separator to remove the water particles from the gas, which reduces the potential for steam generation as the exhaust exists into the atmosphere. While a steam plume is harmless, it creates the appearance of exhaust smoke being emitted, and should be avoided. Many systems incorporate, or have the option to fit, a re-heater after the EGC system unit.

The water mixture generated during the scrubbing process falls to a wet sump at the bottom of the scrubber. This water, called washwater, is removed from the scrubber sump by gravity or by a pump, after passing through a deaerator in some systems, to a hydrocyclone or separator to remove the residuals from the washwater. The removed residuals are discharged to a dedicated residue tank on board. MARPOL Annex VI Regulation 16, Paragraph 2.6 prohibits incineration of sludge generated from a scrubber; it must be disposed of at suitable reception facilities ashore.

The collected residue will contain PM, ash, heavy metals, etc. removed from the fuel together with insoluble calcium sulfate, and silt entrained in the washwater drawn from estuaries, rivers, or harbor waters. Where the source of the washwater has a large amount of silt, this silt can make up the dominant portion of the sludge volume. Sludge generated from substances in the incoming water, such as silt, is an issue only with open loop-type scrubbers. Once the residuals are cleaned from the washwater it can be discharged overboard or retained on board where discharge of such water is restricted. In most cases, the discharge washwater pH can be adjusted by diluting the acidic substances in the washwater by increasing through-put when using open loop systems or by diluting it with sea water cooling water. However, other local and national restrictions may apply that limit wash water discharge.[12]

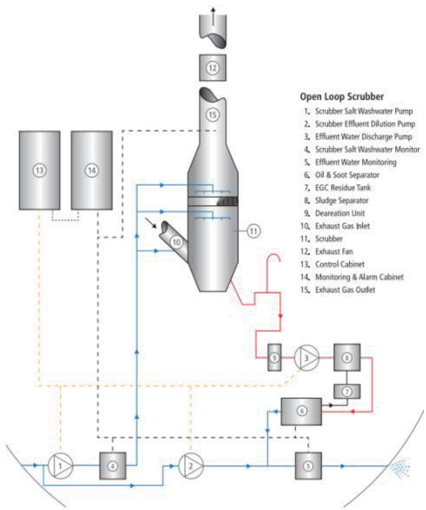

Figure 9 Open Loop Scrubber

3.8. Closed Loop Scrubber

In a closed loop-type scrubber, treated water is circulated through the scrubber to keep the scrubbing process independent of the chemistry of the waters the vessel is sailing in, plus there is little or no water discharged overboard from the scrubbing process, reducing the need for processing the washwater to make it suitable for discharge. Sodium hydroxide as a chemical additive is typically used in marine EGC systems to control the water alkalinity which can also be produced by electrolysis of seawater (see Figure 10).

The closed loop scrubber internals are similar to those of an open loop scrubber, and the chemical processes to remove the SOx missions are similar. The major difference between the two systems is that rather than going overboard, most of the circulating washwater is processed after it leaves the scrubber to make it suitable for recirculation as the scrubber washwater medium. The washwater can be fresh or salt water depending on the scrubber design. In this treatment process, the residues are removed from the water, and the water is dosed again with caustic soda to restore its alkalinity.

Manufacturers claim a closed loop scrubber requires about half or less of the washwater flow than an open loop scrubber to achieve the same scrubbing efficiency. The reason for this is that higher levels of alkalinity are ensured by the direct control of the alkalinity level using the caustic soda injection process. In fresh water scrubbers, SO2 combines with a salt and consequently does not react with the natural bicarbonate of sea water. There is no release of CO2.

$2NaOH + SO_2 \rightarrow Na_2SO_3 + H_2O$ *(Sodium Sulfite)*
$Na_2SO_3 + SO_2 + H_2O \rightarrow 2NaHSO_3$ *(Sodium Hydrogen Sulfite)*
$NaOH + H_2SO_4 \rightarrow NaHSO_4 + H_2O$ *(Sodium Hydrogen Sulfate)*
$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$ *(Sodium Sulfate)*

In a closed loop-type system, the dirty washwater exiting the scrubber goes to a process or circulating tank. A limited quantity of washwater from the bottom of the process tank, where the residuals have collected, is extracted using a low suction, and it goes to a hydrocyclone or separator, similar to an open loop system, where the residuals are removed or for some systems the extracted water can go to a bleed-off treatment unit (BOTU).From any of the processes, the cleaned bleed off water is discharged overboard or to a holding tank, depending on the ship's location and local regulations. The removed residual sludge goes to a residue tank for disposal ashore. Make up water is added to the process tank to replace the washwater lost in the particulate treatment process, bleed off and evaporation during the scrubbing process. A pump circulates the scrubbing water from the process tank back to the scrubber. The water passes through a sea water cooler before re-injection in the scrubber. A dosing unit adds caustic soda back to the scrubbing water, either in the processing tank or to the water as it leaves the tank, with the amount varied depending on the alkalinity requirements for the water.[13]

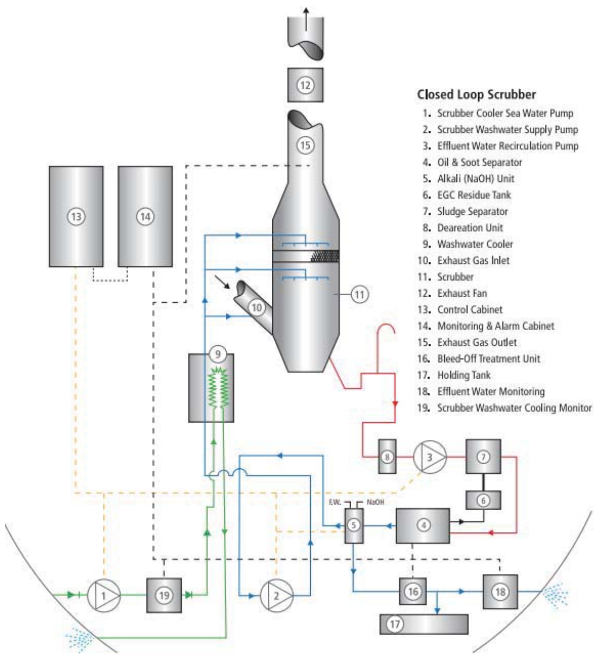

Figure 10 Closed Loop Scrubber System

3.9. The Coefficient data of Heat transfer Coefficient

Lambda (λ) Value / Thermal Conduction

Table 2 Thermal Conduction Value[14]

Materials	Lambda Value λ
Steel	50 W/m.K
Concrete	1.6 W/m.K
Glass	1.1 W/m.K
Wood	0.12 W/m.K
Rockwool	0.003 W/m.K

3.10. Overall Heat Transmission Coefficient

Table 3 Overall Heat Transmission Coefficient[15]

Fluid	Transmission Surface	Fluid	Overall Heat Transmission Coefficient	
			(Btu/ft^2 hr ^oF)	*(W/m^2 K)*
Water	Cast Iron	Air or Gas	1.4	7.9
Water	Mild Steel	Air or Gas	2.0	11.3
Water	Copper	Air or Gas	2.3	13.1
Water	Cast Iron	Water	40 - 50	230 - 280
Water	Mild Steel	Water	60 - 70	340 - 400
Water	Copper	Water	60 - 80	340 - 455
Air	Cast Iron	Air	1.0	5.7
Air	Mild Steel	Air	1.4	7.9
Steam	Cast Iron	Air	2.0	11.3
Steam	Mild Steel	Air	2.5	14.2
Steam	Copper	Air	3.0	17
Steam	Cast Iron	Water	160	910
Steam	Mild Steel	Water	185	1050
Steam	Copper	Water	205	1160
Steam	Stainless Steel	Water	120	680

3.11. Chemical Losses Calculation

Enthalpy, H

In a sample of methane, CH_4, How much energy do its molecules contain? The first thing that needs to know is the amount of methane present. From the chemist's side, so the answer is 1 mole (16 g). Energy is measured in joules, J, so by begin thinking where to start measuring from. There seems to be no starting point; can methane molecules ever have no energy contained within them? Indeed, it is *impossible* to know the total amount of energy stored in these molecules. Whatever its value, the total amount of energy in a given amount of a substance (sometimes called the Heat energy content) is known as the enthalpy, denoted H. Methane is a fuel, so how to get energy from it? The answer is to react it with oxygen.

$$\mathbf{CH_4(g) + 2O_2(g) \quad \text{®} \quad CO_2(g) + 2H_2O(l)}$$

The above chemical equation shows that 2 moles (64 g) of oxygen molecules are required to burn 1 mole of methane. Again, it is impossible to know the total enthalpy (heat energy content) of the oxygen. Likewise, it is unknown the total heat energy content of 1 mole of CO_2 and 2 moles of H_2O (the products).

Now imagine that 'molar enthalpy values' is found for elements and compounds in a chemical data book. This would make a possibility to work out the amount of energy given out when methane reacts with oxygen to form carbon dioxide and water, that is, an overall change in enthalpy, DH, when the above reaction takes place. The following equations represent such a calculation.

$$\mathbf{\Delta H = (H_{CO2} + 2H_{H2O}) - (H_{CH4} + 2H_{O2})}$$

In general,

$$\Delta H = \Sigma H_{products} - \Sigma H_{reactants} \ (7)$$

But remember, this is theoretical; it is not possible to determine the absolute value of the enthalpy of a chemical element or compound. However, DH values for chemical reactions can be obtained. They can be measured experimentally, or calculated using Hess's Law (see later), or worked out in other ways.

Exothermic and Endothermic Reaction

When chemical reactions take place they are often accompanied by *heat changes*. The system (the reactants which form products) may give out heat to the surroundings, causing them to warm up. In this case the reactants have *more* stored energy (greater total enthalpy) than the products. Such chemical reactions are said to be exothermic. The system may take heat from the surroundings, causing them to cool down. In this case the reactants have *less* stored energy (less total enthalpy) than the products. Such chemical reactions are said to be endothermic.

Exothermic reactions give out energy to the surroundings. Endothermic reactions take energy from the surroundings.

It is possible to measure changes in heat energy that accompany chemical reactions. Most reactions take place in vessels that are open to the atmosphere, that is, they take place at constant pressure (volume may vary). The special name given to a change in heat energy content measured at constant pressure is enthalpy change. This change in enthalpy is denoted by DH. The value of DH (often expressed in kJ, or kJ mol^{-1} when appropriate) is given a negative sign for exothermic reactions and a positive sign for endothermic reactions, indicating whether the system loses or gains energy as a result of the reaction.

The value of DH is given a negative sign for an exothermic reaction.

The value of DH is given a positive sign for an endothermic reaction.

Thermochemical data for chemical reactions can be found in chemical data books.

$CH_{4(g)} + 2O_{2(g)}$ ® $CO_{2(g)} + 2\ H_2O_{(l)}$ DH°$_{298}$ = - 890.3 kJ mol^{-1}
½$H_{2(g)}$ + ½$I_{2(s)}$ ® HI(g) DH°$_{298}$ = + 26.5 kJ mol^{-1}

Note the following changes:

$CO_{2(g)} + 2\ H_2O_{(l)}$ ® $CH_{4(g)} + 2O_{2(g)}$ DH°$_{298}$ = + 890.3 kJ
$H_{2(g)} + I_{2(s)}$ ® 2HI(g) DH°$_{298}$ = + 53.0 kJ [16]

3.12. Calculating Sulphur Content inside the Fuel

Data Required :

1 – Analysis of Diesel oil : % C and % H2
If the analysis is unknown, the following typical ratio may be used: % C = 87.0 % % H2 = 12.4 %
2 – Analysis of Sulphur content of Diesel oil : % S
3 – Excess of air in the exhaust gases: % Excess
4 – Average analysis of Oxygen in exhaust gases: % O2
5 – Reference level of Oxygen for presentation of emissions data : % O2

<u>CALCULATION 1</u> :
Calculation of stoichiometric air necessary for combustion of 1 Kg of Diesel oil, in accordance with analysis (% C , % H2 , % S):

(a) Oxygen for C = (%C/100) x 22.4 / 12 m3
(b) Oxygen for H2 = (%H2/100) x 22.4 / 4 m3
(c) Oxygen for S = (%S/100) x 22.4 / 32 m3
(d) Total Oxygen = (a) + (b) + (c) = O2
Dry stoichiometric air required = (d) O2 / 0.21 = Air Nm3 / Kg Diesel oil

CALCULATION 2 :

Exhaust Gases from combustion Volume of gases formed in combustion:

(a') $CO_2 = (\%C/100) \times 22.4 / 12$ N m3

(b') $H_2O = (\%H_2/100) \times 22.4 / 2$ N m3

(c') $SO_2 = (\%S/100) \times 22.4 / 32$ N m3

(d') N_2 = stoichiometric Air x 0.79 N m3

CALCULATION 3 :

Theoretical emission of SO_2 with exhaust gases

ST = maximum emission of SO_2 = % S x 10,000 x 64 / 32 = % S x 20,000 = mg S / Kg Diesel oil

Concentration of maximum theoretical SO_2 in gases, relative to % O_2 measured:

A) Based on wet gases: SO_2 (mg/Nm3) = ST / GHT

B) Based on dry gases: SO_2 (mg/Nm3) = ST / GST

Concentration of maximum theoretical SO_2 in gases, relative to Reference % O_2:

A) Based on wet gases: SO_2 (mg/Nm3) = (A) x (21 - %O_2 Ref.) / (21 - % O_2 measured)

B) Based on dry gases: SO_2 (mg/Nm3) = (B) x (21 - %O_2 Ref.) / (21 - %O_2 measured)

NOTES :

1. The emissions of SO_2 calculated must be normally refer to dry gases.
2. The emissions calculated are the maximum theoretically possible with the data of % S and % Excess air applied. In practice, the actual emissions are somewhat lower due to the fact that part of the SO_2 is converted into Sulphates (basically of calcium) and part into SO_3 . The calculation thus represents the maximum emission of Sulphur in the form of SO_2 .
3. The emissions data refer to the Reference % O_2, in accordance with the legislation in force in each Autonomous Community, for the type of combustion plant utilized.

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CHAPTER 4
CALCULATION

4.1. Heat Loss through Pipe

Diameter of the Pipe = 35cm
Thickness of the Pipe Steel = 3 mm
Thickness of the Rockwool = 110 mm
Thickness of the Outer Steel Cover = 1 mm

The method of calculation here is to calculate how much heat loss is happened during the transmission from inside the pipe to the pipe steel which is thermodynamically equal to the loss from the pipe steel to the Insulation substances which also equal to the loss from Insulation to the Outer Steel Cover and Equal to the total Losses from the Whole System. The thermodynamic calculation which I used in this calculation can be described as

rate of heat convection into the wall	=	rate of heat conduction through wall 1	=	rate of heat conduction through insulation	=	rate of heat conduction through wall 3	=	rate of heat convection from the wall

Taking the assumption that the system is Steady-state and one-dimensional heat transfer,

Taking current Length is equal to 1 meter the areas of the surfaces which is exposed to the convection are

$A1 = 2\pi r1L = 1.099\ m^2$ (Inner Pipe)
$A3 = 2\pi r3L = 1.81492\ m^{2\,(}$Outer Pipe)

Based on the data which is required, the thickness of Rockwool will be 110 mm for a 0.35 diameter-pipe, with Overall Heat transfer coefficient in the pipe = 8 W/m^2K equal to the Heat Transfer Coefficient outside the pipe = 8 $W/\ m^2K$ because the substances which is in contact is closer to the air specification rather than steam specification, for the full table can be found on the table. Taking the Heat transfer coefficient in pipe is equal to 50 W/mK and for the Rockwool substances is equal to 0.033 W/m.K the data can be found on the table 2.

$$Rconv,1 = \frac{1}{h1.A1} = \frac{1}{8\ x\ 1.099} = 0.2274\ {}^{C}/_{W}$$

$$Rcond,1 = Rinnerpipe = \frac{\ln\left(\frac{r2}{r1}\right)}{2\pi ksteel.L} = \frac{0.01699}{2\pi\ x\ 50} = 5.4\ x\ 10^{-5}\ {}^{C}/_{W}$$

$$Rcond,2 = Rinsulation = \frac{\ln(\frac{r3}{r2})}{2\pi kinsulation.L} = \frac{0.4811}{2\pi\ x\ 0.033} = 2.321\ {}^{C}/_{W}$$

$$Rcond,3 = Rinnerpipe = \frac{\ln(\frac{r4}{r3})}{2\pi ksteel.L} = \frac{0.00346}{2\pi\ x\ 50} = 1.1\ x\ 10^{-5}\ {}^{C}/_{W}$$

$$Rconv,3 = \frac{1}{h3.A3} = \frac{1}{8\ x\ 1.8149} = 0.1382\ {}^{C}/_{W}$$

$$Rtotal = Rconv1 + Rcond1 + Rcond2 + Rcond3 + Rconv3 = 2.6876\ {}^{C}/_{W}$$

The Steady-State Rate of Heat loss from the steam becomes:

$$Q = \frac{T\infty1 - T\infty2}{Rtotal} = \frac{255}{2.6876} = 94.88\ J/s$$

The total heat loss for a given length can be determined by multiplying the above quantity by the pipe length. The temperature drop across the pipe and the insulation are

$$\Delta Tinnerpipe = \ Q \ x \ Rinnerpipe = 21.58 \ Celcius$$

$$\Delta Tinsulation = \ Q \ x \ Rinsulation = 220.296 \ Celcius$$

$$\Delta Touterpipe = \ Q \ x \ Routerpipe = 13.1159 \ Celcius$$

This is the result of the calculation of 1 length meter pipe , but following up this calculation there's a problem with the method which is used since there'll be a temperature drop from the inlet for each time and it's can scientifically be described as

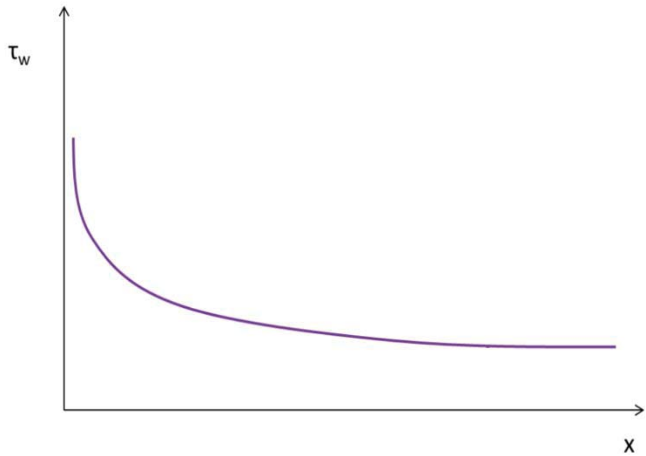


Figure 11 Temperature Drop on Pipe

Regarding this phenomena it's not wise to calculate the losses from each 1 meter as it is known the total length of the pipe is 5280mm, so the best approach is to calculate losses from each 10cm and then calculating the temperature losses from each

10cm and subtract it from the current temperature, and repeat this process until 5280 / 100 = 52,8 times which can be rounded up to 53 times. The calculation of this process will be done by program which I made to calculate data for each 10cm length. The Program Data can be seen in the reference, meanwhile the result of the process will be presented as a table.

In the following results of the program there are 5indicators which can be examined, the indicators can be explained as:

a) Qn (n= 1-43) = The Work losses from the n-1 meter to n meter (Example Q3 = The Work losses from the 20 meter to 30 meter)
b) En (n= 1-43) = The temperature losses from the n-1 meter to n meter (Example E3 = The Temperature losses from 20 meter to 30 meter)
c) Q total = To track the Total Work Losses from the 0 meter until that point
d) E total = To track the Total Temperature Losses from the 0 meter until that point
e) Current Temperature = To check the temperature on the pipe right now

The data which is represented on the next page are the result of the pipe losses calculation using the same method above with only differences the length which is measured is per-10cm and the current temperature is subtracted with the losses from each 10cm loss. The complete program algorithm can be found at appendix.

```
Data 41
   Q41 =        4.70 Qtotal=  200.43277
   E41 =        0.54 Etotal=   23.09660
 Current Temperature=  314.90040 Celcius

    314.36 temperarture inside pipe
Data 42
   Q42 =        4.69 Qtotal=  205.12516
   E42 =        0.54 Etotal=   23.63732
 Current Temperature=  314.36268 Celcius

    313.82 temperarture inside pipe
Data 43
   Q43 =        4.68 Qtotal=  209.80846
   E43 =        0.54 Etotal=   24.17699
 Current Temperature=  313.82301 Celcius
```

Figure 12 Results of Pipe Losses Calculation using Pascal Program (Data 41 – 43)

To calculate the exact data for the 5280 mm we can use the mathematic approach by calculating the difference from Data 52 - Data 53.And the graph results of the following calculation can be described in the graph as

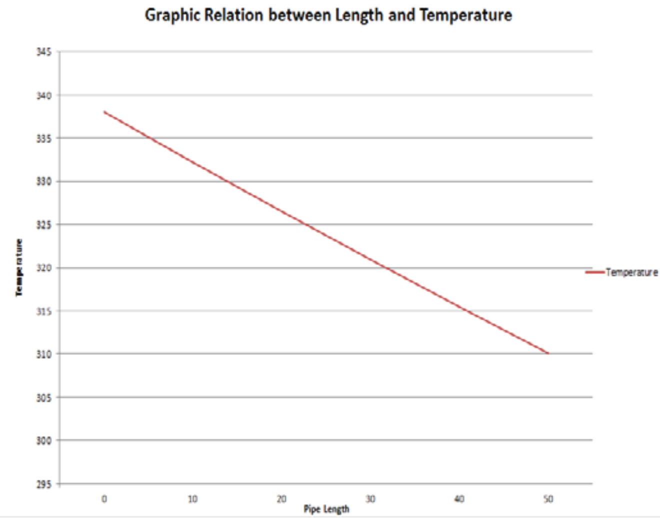


Figure 13 Graphic Relation between Length and Temperature

Losses on Data 52

Total Work Losses= 251.55221 Watt, Temp Losses= 28.98728

Losses on Data 53

Total Work Losses= 256.14561 Watt, Temp Losses= 29.51659

The graphic fail to represent the condition of the piping , assumedly because the losses isn't high enough to trigger that anomaly therefore we have the linearic function even though we are calculating it for each 10 cm.

Total Losses until Data 52.8 :

Qtotal52 + (Qtotal 53- Qtotal 52)*0.8 = **255.23 J/s**

Total Temperature Losses until Data 52.8 :

Etotal52 + (Etotal 53- Etotal 52)*0.8 = **29.41 C**

Current Temperature on 5280mm :

Current Temp 52 – (Etotal 53 – Etotal 52.8) = **308.59 C**

It can be concluded from the work flow from the pipe through the whole process the total **Temperature losses = 29.41 and Work Losses = 255.23 J/s.**

Taking Radiation into conclusion which is possible to be happen, 10 percent consideration is take to the Work Losses since the temperature losses in radiation will be very small and it can be unconsidered , so the new **Work Losses with$_{10\%}$ Radiation = 280.75 J/s**

4.2. Heat loss through Chemical Process in the Scrubber

$SO_2 + CaCO_3 = CaSO_3 + CO_2$

SO_2 = -296,83 kJ/mol

CO_2 = -393,5 kJ/mol
$CaCO_3$ = -1206,9 kJ/mol
$CaSO_3$ = -1158.968 kJ/mol

$\Delta H = \Sigma H_{products} - \Sigma H_{reactants}$ (8)

= (-1158.962 – 393.5) – (-1206.9 – 296.8) kJ/mol
= -48.72 kJ/mol

Mass(m) = mol (n) x Molarmass (M) (9)

Molar Mass of SO_2 = 64.066 g/mol

Based on Sulphur Content Calculation :
ST = total maximum SO2 emitted = 0.3 x 20,000 = 6,000 mg / Kg Diesel oil
n = m/ M = 6 gram / 64.066 g/mol (per 1 kg diesel Oil)
n = 0.093 mol (per 1 kg diesel Oil)
ΔH = -48.72 kJ / mol x 0.093 mol = -4.522 kJ (per 1 kg diesel Oil)

To compare there are more than 1 type of catalyst which is used to remove the SOx concentration using scrubber system. The following substances are usually used to remove SOx from the water:

<u>Hydrated Lime :</u>
$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$

<u>Magnesium Hydroxide</u>
$Mg(OH)_2 + SO_2 \rightarrow MgSO_3 + H_2O$

<u>Caustic :</u>
$2NaOH(aq) + SO_2 \rightarrow Na_2SO_3 + H_2O$

<u>Sea Water</u>
$SO_2 + H_2O + \frac{1}{2} O_2 \rightarrow SO_4^{2-} + 2H^+$

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2$$

Therefore we have 5 substances which will be able to remove the SOx and using the same method the results of the calculation will come as

Table 4 Scrubber Chemical Reaction Enthalpy

Reaction	Enthalpy Formation		Enthalpy
Hydrated Lime :	Product	Reactants	(kJ/mol)
$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$	-1283	-1444.798	-161.798
Magnesium Hydroxide			
$Mg(OH)_2 + SO_2 \rightarrow MgSO_3 + H_2O$	-1221.49	-1570.74	-349.25
Caustic :			
$2NaOH(aq) + SO_2 \rightarrow Na_2SO_3 + H_2O$	-1130.61	-1376.18	-245.57
Sea Water :			
$SO_2 + H_2O + ½ O_2 \rightarrow SO_4^{2-} + 2H^+$	-582.66	-909.27	-313.95
$HCO_3^- + H^+ \rightarrow H_2O + CO_2$	-691.99	-679.33	
Calcium Carbonate			
$SO_2 + CaCO_3 = CaSO_3 + CO_2$	-1503.73	-1552.468	-48.738

Taking the consideration that

Based on Sulphur Content Calculation:

ST = total maximum SO2 emitted = 0.3 x 20,000 = 6,000 mg / Kg Diesel oil

n = m/ M = 6 gram / 64.066 g/mol (per 1 kg diesel Oil)
n = 0.093 mol (per 1 kg diesel Oil)

We would get the total Losses for each 1 kilogram of Fuel

Table 5 Sulphur Reactant Chemical Reaction Comparison

Table of Comparison					
	Ca(OH)2	Mg(OH) 2	2NaOH(aq)	Sea Water :	CaCO3
Enthalpy	-161.798	-349.25	-245.57	-313.95	-48.738
Losses (kJ/kg DO)	-15.047214	-32.48025	-22.83801	-29.19735	-4.532634
Comparison	3.319750503	7.1658665	5.0385736	6.441585621	1
Percentage	331.98%	716.59%	503.86%	644.16%	100.00%

Using the same method, since there is only 1 catalyst which is used after the NOx Scrubber (SCR) which is ammonia, but there are several reactions which is available, and different reactions resulting different Enthalpy. Those processes can be listed as:

1. $6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O$ - *Pure anhydrous ammonia*
2. $4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$ - *Aqueous ammonia*
3. $6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$ - *Nitrogen Dioxide Reactant*
4. $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$ - *Nitrogen Dioxide Reactant (2)*
5. $NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$ - *Fastest Nitrogen Dioxide Reactant.*[17]

Table 6 NOx Scrubber Enthalpy Calculation

Reaction	Enthalpy Formation		Enthalpy
Pure anhydrous ammonia	Product	Reactants	(kJ/mol)
$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O$	357.06	-1714.98	-2072.04
Aqueous ammonia			
$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$	176.56	-1714.98	-1891.54
Nitrogen Dioxide Reactant			
$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$	-169.8	-3429.96	-3260.16
Nitrogen Dioxide Reactant (2)			
$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$	-118.08	-1714.98	-1596.9
Fastest Nitrogen Dioxide Reactant			
$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$	31.21	-857.49	-888.7

Using the Data which is acquired

Table 7 NO concentration in the Engine

J	CHEMICAL LOSSES OF EXHAUST GAS						
J.1	**NO gases**						
1	NO gases compostition in EG	=	920	ppm (mg / kg EG)			
2	NO mass flow rates	=	5257.878	gr / hour			
3	NO molecular weight	=	30.01	gr / mol			
4	NO enthalpy	=	90.4	kJ / mol	=	3.0123	kJ / gr
5	Heat losses due to NO gases	=	4.400	kJ / s			
J.2	**NO2 gases**						
1	NO2 gases composition on EG	=	61.4397	ppm (mg / kg EG)			
2	NO2 mass flow rates	=	351.133	gr / hour			
3	NO2 molecular weight	=	46.01	gr/mol			
4	NO2 enthalpy	=	33.9	kJ / mol	=	0.7368	kJ / gr
5	Heat losses due to NO2 gases	=	0.0719	kJ / s			

Therefore we can calculate the mol for NO and NO_2 and there for we will have 2 compound in the catalyst for NO and 2 compound for NO_2 and 1 compound which can react which directly react with both NO and $NO_{2.}$ Using the Combination we can get 5 different types of NOx Scrubbing system.

Table 8 Calculation Table for NOx Scrubber (SCR)

Table of Comparison					
	Pure Amonia	Aqueous	Nitro 1	Nitro 2	Fast Nitro
Enthalpy	-2072.04	-1891.54	-3260.16	-1596.9	-888.7
Losses	-63.5213862	-57.987897	-4.3527848	-2.13209231	-28.430928
Combination	Pure + Nitro1	Pure+Nitro2	Aqu + Nitro1	Aqu + Nitro2	Fast Nitro
Losses (kJ/kg DO)	-67.874171	-65.653479	-62.340682	-60.1199897	-28.430928
Comparison	2.387335744	2.3092274	2.19270654	2.114598206	1
Percentage	238.73%	230.92%	219.27%	211.46%	100.00%

4.3. Heat Loss through Scrubber System Piping

Using the same method as how to calculate the losses from the pipe system, we can applied the same formula and method to determine the Work Losses and Temperature Losses from the scrubber system, meanwhile the calculation of the scrubber system is done without using the pascal program because the uncertainty of the temperature on the surface of the Scrubber system therefore we only use the scientific calculation to calculate how much the estimation of the heat losses through the process. The weakness of this calculation type is the accuracy of the data. Data of Scrubber Venturi which is used is :

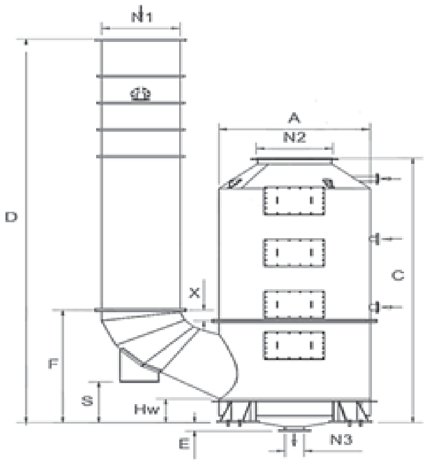


Figure 14 Venturi Diagram

With the following data as the detail information of the Venturi System [18]

Table 9 Scrubber Venturi Data

Dimension	Description	Nominal
A	Vessel diameter (mm)	1350
B	Overall length (mm)	2240
B1	Overall width (mm)	1580
C	Outlet height (mm)	4460
D	Inlet height (mm)	5200
E	Drain below base (mm)	120
F	Scrubber inlet height (mm)	1660
X	Difference between bottom part and inlet (mm)	0
S	Distance between support (mm)	745
N1	Inlet nominal bore (mm)	600
N2	Oulet nominal bore (mm)	600
N3	Drain nominal bore (mm)	200

The results of the total heat loss from the Scrubber system is equal to 40.962 Celsius with the remaining Exhaust Gas temperature of 267.63 Celsius (From 308.43 Celsius – Data on table 5) and the Losses in total is equal to 2328.1 Watt. The complete calculation can be seen on the Venturi Calculation Excel for Calculation using Conduction and Convection A+B, C.

4.4. Energy and Temperature Losses in Scrubber System

To calculate the Losses which is happened in Scrubber, the approach of the calculation will be done by using the Energy and Temperature Balance from the system itself. It is almost impossible to calculate the contact between the water droplets with exhaust gas and then calculating the losses from each droplet and sum it up to get the real results. This approach is physically friendly, and we can see the movement of the energy balance by using this approach.

To describe the energy balance of the system, this graph will be used to illustrate it:

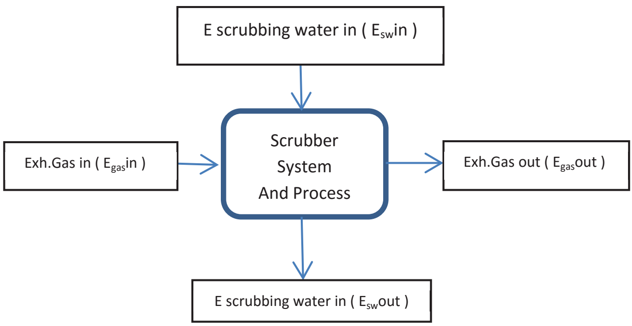


Figure 15 Scrubber Energy Balance

From the Following figure we can make a Formula which is :

$$E_{gas}in + E_{sw}in = E_{gas}out + E_{sw}out + E_{pipinglosses} \quad (10)$$

$$E = cp. \Delta T. M_{flowrates} \quad (11)$$

Taking the Data from previous equation current Temperature is 267.47 after reduced from piping losses and scrubber system piping losses as well. Adding the data for Sea Water inlet temperature $T_{sw}in = X^{o}C$ where the X is equal to $14^{o}C$ for the closed loop system and $20^{o}C$ for the open loop system. From both the equation we will get the temperature of the $T_{gas}out$ and $T_{sw}out$.

From the Following data that we have we can calculate as we already know the specific heat of exhaust gas and sea water which is 1,047 kJ/kg.K and 4.182 kJ/kg.K. And mass flowrate taking from the same 900kW Engine we know that the Mass flow rate is 1.64 for exhaust gas. The only problem to completing this calculation is the data of Mass flow rate Water which is unknown, and without any supported data we can't calculate this except we make a range of consideration. In order to calculate this, the kind of consideration which is used is the ratio of Mass flow rate water and Mass flow rate Gas which is know the Mass flow rate Water usually higher than the mass flow of the Exhaust Gas. That consideration is represented in a table as:

Table 10 Sea Water Mass Flow Rate Ratio

Table	Mass Flow Rate Water
Mass flow rate Water / Mass flow Rate Gas	
1	1.64
2	3.28
3	4.92
4	6.56
5	8.2
6	9.84

And from the Energy Formula we can calculate Energy input which is coming from the Exhaust Gas and Sea Water, and the data is separated into two since we have different temperature for both Open Loop and Closed Loop System

Table 11 Inlet Energy Calculation

Mass Flow Rate Water	E water Open Loop	E in (gas + open loop)	E water Closed Loop	E in (gas + Closed loop)
1.64	2009.53	2937.56	1975.24	2903.27
3.28	4019.07	4947.10	3950.48	4878.51
4.92	6028.60	6956.63	5925.73	6853.75
6.56	8038.14	8966.16	7900.97	8829.00
8.20	10047.67	10975.70	9876.21	10804.24
9.84	12057.21	12985.23	11851.45	12779.48

After we got the inlet data, the next step is to calculate the Outlet Energy to determine how much the temperature on Exhaust Gas temperature to calculate the Work Losses. Taking the following known data from most of the common voyages which is using scrubbing system we can assume that $T_{gas}out = T_{sw}out + 5^{o}\ _{Celcius}$, by combining the formula above and the assumption we will got :

$$Einlet – Elosses = m.cp.(T_{gas}out - 5^{o}\ _{Celcius}) + m.cp.(T_{gas}out\ )$$

And by submitting the variable we can get the Tgas out formula as:

$$T_{gas}out: ((E\ in\ -\ Elosses) + 5\ x\ M_{flowrates-water}\ x\ cp_{water}\ ) / (M_{flowrates-water}\ x\ cp_{water}) + M_{flowrates-gas}\ x\ cp_{gas})$$

which produces results as :

Table 12 Exhaust Gas Out Calculation

T gas out Open Loop (in Celcius)	T gas out Closed Loop (in Celcius)	Mass flow rate Water / Mass flow Rate Gas
41.71	37.72	1.00
34.29	29.84	2.00
31.43	26.81	3.00
29.92	25.21	4.00
28.98	24.22	5.00
28.34	23.54	6.00

From the following data we will be able to calculate the Total Losses from the system which happen on Exhaust Gas by taking Environment as Consideration (20 degree Celcius).

$$\text{Exhaust Gas Losses} = E_{gas\text{-}in} - E_{gas\text{-}out} - E_{heat\text{-}loss}$$

In order to calculate this system it's needed the new heat coefficient for the new temperature since different temperature giving different specific heat and the difference can be determined by using this following table:

Table 13 Exhaust Gas Properties

Physical Properties of Air (p = 101.13 kPa)

T temperature, K; **ρ** density, kg/m^3; **h** specific enthalpy, kJ/kg; **s** specific entropy, kJ/(kg·K); C_p specific heat at constant pressure, kJ/(kg·K); **μ** viscosity, 10^{-4} Pa·s; **k** thermal conductivity, W/(m·K)

T	ρ	h	s	C_p	μ	k
260	1.340	260.0	6.727	1.006	0.165	0.0231
280	1.245	280.2	6.802	1.006	0.175	0.0247
300	1.161	300.3	6.871	1.007	0.185	0.0263
350	0.995	350.7	7.026	1.009	0.208	0.0301
400	0.871	401.2	7.161	1.014	0.230	0.0336
450	0.774	452.1	7.282	1.021	0.251	0.0371
500	0.696	503.4	7.389	1.030	0.270	0.0404
600	0.580	607.5	7.579	1.051	0.306	0.0466
800	0.435	822.5	7.888	1.099	0.370	0.0577
1000	0.348	1046.8	8.138	1.141	0.424	0.0681
1200	0.290	1278	8.349	1.175	0.473	0.0783
1400	0.249	1515	8.531	1.207	0.527	0.0927

To determine the cp , it can be used the following approach formula :

(Tx– T1) / (T2 – Tx) = (Cp x – Cp 1) / (Cp 2 – Cp x) (12)

and the following result of that approach is :

Table 14 New Specific Heat

Mass flow rate Water / Mass flow Rate Gas	Open Loop	Closed Loop
1	0.978171	0.977772
2	0.977429	0.976984
3	0.977143	0.976681
4	0.976992	0.976521
5	0.976898	0.976422
6	0.976834	0.976354

By having all the data which is necessary we can calculate the losses from the scrubbing system which is represented in the table:

Table 15 Losses Calculation Results

Losses Scrubber System		
Open Loop System	Closed Loop System	Mass flow rate Water / Mass flow Rate Gas
392.42	396.51	1.00
402.02	409.15	2.00
406.61	414.01	3.00
409.03	416.58	4.00
410.53	418.17	5.00
411.56	419.25	6.00

APPENDIX

Appendix1: Pascal Program for Piping Losses Calculation (with details)

Appendix 2: Pascal Program Results (Page 1)

Appendix 3: Pascal Program Results (Page 2)

Appendix 4: Pascal Program Temperature Losses Table

Appendix 5: SOx Scrubber Design Data

Appendix 6: SOx Scrubber Design Calculation (Normal Steel)

Appendix 7: SOx Scrubber Design Calculation (Carbon Steel)

Appendix 8: Summary of Calculation (Carbon Steel) + Comparison with Normal Steel

Appendix 9: Summary of Calculation (Normal Steel) + Scrubbing Losses

Appendix 10: Losses in form of Graphics

Appendix1: Pascal Program for Piping Losses Calculation (with details)

begin

writeln('Insert Measurement in Meter'); *write the the following text*

write(' Insert Diameter of the Pipe '); readln(d1); *Input for pipe diameter*

write(' Insert Thickness of the Pipe '); readln(t2); *Input for pipe thickness*

write(' Insert Thickness of the Insulation '); readln(t3);

Input for insulation

write(' Insert Thickness of the Steel Cover '); readln(t4);

Input for steel thickness

ksteel:=50; *Coefficient of steel thermal conductivity (Lambda)*

kinsul:=0.033; *Coefficient of insulation conductivity (Lambda)*

writeln('k for steel is ',ksteel :10:2); *Writing Format for Lambda*

writeln('k for instulation is ',kinsul :10 : 3); *Writing Format for Lambda*

hin:=7.9; *Overall heat transfer Coefficient inside the pipe*

hout:=7.9; *Overall heat transfer Coefficient outside the pipe*

writeln('h in',hin:10:2); Statement for the Overall Heat Transmission Coefficient

writeln('h out',hout:10:2); Statement for the Overall Heat Transmission Coefficient

d2:= d1+(2*t2); Diameter 2 = Diameter 1 + (2 x Thickness pipe inside)

d3:= d2+(2*t3); Diameter 3 = Diameter 2 + (2 x Thickness insulation)

d4:= d3+(2*t4); Diameter 2 = Diameter 3 + (2 x Thickness pipe outside)

a:=ln(d2/d1); a is logarithmic natural of d2 divided with d1

b:=ln(d3/d2); b is logarithmic natural of d3 divided with d2

c:=ln(d4/d3); c is logarithmic natural of d4 divided with d3

writeln(a:10:6); statement to write the ln (d2/d1)

writeln(b:10:6); statement to write the ln (d3/d2)

writeln(c:10:6); statement to write the ln (d4/d3)

write('ME Room Temperature Celcius : ');

readln(Eroom); Input data for Engine Room Temperature

write('Exhaust Gas Output : ');

readln(Eout); Input data for Exhaust Gas after Turbocharger

writeln('Convection Calculation'); statement of convection calculation

conv1:=1/(hin * 3.14 * d1 *1);

conv3:=1/(hout * 3.14 * d3 *1);

Convection formula = 1 / (heat transfer coefficient * phi * diameter of the following diameter * 1 (length of 1 meter)

writeln(conv1:10:3);

writeln(conv3:10:3);

Decimal writing for Convection

writeln('Conduction Calcualtion'); statement of conduction calculation

cond1:=a/(2*3.14*ksteel*1);

cond2:=b/(2*3.14*kinsul*1);

cond3:=c/(2*3.14*ksteel*1);

Conduction formula = logarithmic natural / (2* phi * thermal conduction material * 1 (length of 1 meter)

writeln(cond1:10:3);

writeln(cond2:10:3);

writeln(cond3:10:3);

Decimal writing for Conduction

R1:= conv1 + cond1 ; Total Resistance in Inner Pipe (Conduction + Convection)

R2:= cond2; Total Resistance in Insulation (Conduction)

R3:= conv3 + cond3 ; Total Resistance in Outer Pipe (Conduction + Convection)

Rtot:=conv1+conv3+cond1+cond2+cond3; Total Resistance in the System

writeln('Rtot = ',Rtot:10:2); Decimal Writing for Rtotal

Qtot:=(Eout-Eroom)/Rtot; Qtotal = Losses Total = (Exhaust After T.C. Temperature – Engine Room Temperature) / Rtotal

writeln('Qtot = ',Qtot:10:2); Decimal Writing for Q total

writeln('Losses Through Pipe: ', (Qtot*cond1):10:6 ,' Celcius');

Loses in Inner Pipe = Qtotal * Conduction 1 , and decimal statement

writeln('Losses Through Insulation: ', (Qtot*cond2):10:2 ,' Celcius');

Loses in Insulation = Qtotal * Conduction 2 , and decimal statement

writeln('Losses Through Pipe Cover: ', (Qtot*cond3):10:6 ,' Celcius');

Loses in Outer Pipe = Qtotal * Conduction 3 , and decimal statement

readln;

write('Temperature Surface in Celcius : ') ;readln(tempc);

Input data for Temperature Surface of Pipe

write('Insert Pipe Length in centimeter: '); readln(pipel);

Input data for Pipe Length , based on system

pipeten := (pipel div 10) + 1;

Pipeten = Indicator for Pipelength per 10 meter

Pipel = Pipelength

Pipel div 10 + 1 , round up number of pipe length divided by 10

Losses1 := 0; Initial variable for Losses1 = 0 (accumulated temperature loss)

Qfor := 0; Initial variable for Qfor = 0 (Accumulated Work loss)

for z:= 1 to pipeten do (Loop cycle to calculate per 10 cm)

begin

tempb:= tempc + ((R3/RTot) * (Eout - Eroom));

tempa:= tempb + ((R2/(RTot-R3)) * (Eout - Tempc));

temp a & temp b = formula to calculate the temperature on the system using the thermodynamic calculation using the theory of Q1 = Q2 = Q3 = QT .

Q1:= (Eout - tempa) / (R1 * 10) ;

Q1 calculate the losses from the system and we only calculate the loss from inside the pipe , because that's the loss which directly affect the exhaust gas.

Qfor := Qfor + Q1;

Qfor = accumulated Work Loss

Loses1 := Q1 * R1 ;

Losses = Work Loss x Resistance (Conduction + Convection)

Losses1 := Losses1 + Loses1;

Losses1 = Accumulated Temperature Losses

Eout:= Eout - Loses1;

Eout = Current temperature per 10cm temperature losses in the system

writeln(Eout:10:2,' temperarture inside pipe');

Decimal writing of Current Temperature

writeln ('Data ',z);

write('   Q',z,' = ',Q1:10:2); Decimal writing of Work Loss

writeln(' Qtotal= ',Qfor:10:5); Decimal writing of Accumulated Work Loss

write('   E',z,' = ',Loses1:10:2); Decimal writing of Temperature Loss

writeln(' Etotal= ',Losses1:10:5); Decimal Writing of Accumulated Temperature Loss

writeln(' Current Temperature= ',Eout:10:5,' Celcius');

Decimal Writing of Current Temperature

readln;

end; End of the loop

readln;

end. End of the Program

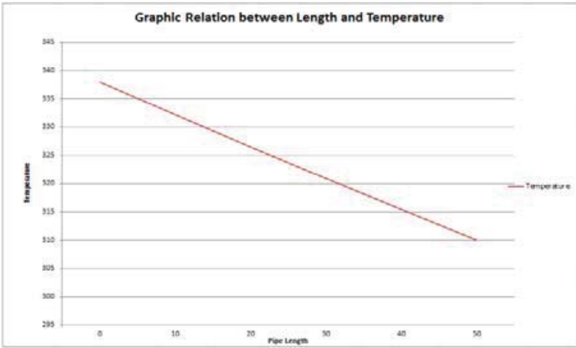
Appendix 2: Pascal Program Results (Page 1)

```
Data 1
  Q1 =       5.00 Qtotal=    5.00049
  E1 =       0.59 Etotal=    0.58544
 Current Temperature=  337.41456 Celcius

   336.83 temperarture inside pipe
Data 2
  Q2 =       5.07 Qtotal=   10.15114
  E2 =       0.58 Etotal=    1.16975
 Current Temperature=  336.83025 Celcius

   336.25 temperarture inside pipe
Data 3
  Q3 =       5.06 Qtotal=   15.21198
  E3 =       0.58 Etotal=    1.75293
 Current Temperature=  336.24707 Celcius

   335.67 temperarture inside pipe
Data 4
  Q4 =       5.05 Qtotal=   20.26301
  E4 =       0.58 Etotal=    2.33498
 Current Temperature=  335.66502 Celcius

Data 5
  Q5 =       5.04 Qtotal=   25.30427
  E5 =       0.58 Etotal=    2.91590
 Current Temperature=  335.08410 Celcius

   334.50 temperarture inside pipe
Data 6
  Q6 =       5.03 Qtotal=   30.33576
  E6 =       0.58 Etotal=    3.49570
 Current Temperature=  334.50430 Celcius

   333.93 temperarture inside pipe
Data 7
  Q7 =       5.02 Qtotal=   35.35751
  E7 =       0.58 Etotal=    4.07437
 Current Temperature=  333.92563 Celcius

   333.35 temperarture inside pipe
Data 8
  Q8 =       5.01 Qtotal=   40.36954
  E8 =       0.58 Etotal=    4.65193
 Current Temperature=  333.34807 Celcius

Data 9
  Q9 =       5.00 Qtotal=   45.37186
  E9 =       0.58 Etotal=    5.22836
 Current Temperature=  332.77164 Celcius

   332.20 temperarture inside pipe
Data 10
  Q10 =      4.99 Qtotal=   50.36450
  E10 =      0.58 Etotal=    5.80368
 Current Temperature=  332.19632 Celcius

   331.62 temperarture inside pipe
Data 11
  Q11 =      4.98 Qtotal=   55.34747
  E11 =      0.57 Etotal=    6.37789
 Current Temperature=  331.62211 Celcius

   331.05 temperarture inside pipe
Data 12
  Q12 =      4.97 Qtotal=   60.32079
  E12 =      0.57 Etotal=    6.95098
 Current Temperature=  331.04902 Celcius

Data 13
  Q13 =      4.96 Qtotal=   65.28448
  E13 =      0.57 Etotal=    7.52297
 Current Temperature=  330.47703 Celcius

   329.91 temperarture inside pipe
Data 14
  Q14 =      4.95 Qtotal=   70.23856
  E14 =      0.57 Etotal=    8.09384
 Current Temperature=  329.90616 Celcius

   329.34 temperarture inside pipe
Data 15
  Q15 =      4.94 Qtotal=   75.18304
  E15 =      0.57 Etotal=    8.66362
 Current Temperature=  329.33638 Celcius

   328.77 temperarture inside pipe
Data 16
  Q16 =      4.93 Qtotal=   80.11795
  E16 =      0.57 Etotal=    9.23228
 Current Temperature=  328.76772 Celcius

Data 17
  Q17 =      4.93 Qtotal=   85.04331
  E17 =      0.57 Etotal=    9.79985
 Current Temperature=  328.20015 Celcius

   327.63 temperarture inside pipe
Data 18
  Q18 =      4.92 Qtotal=   89.95913
  E18 =      0.57 Etotal=   10.36632
 Current Temperature=  327.63368 Celcius

   327.07 temperarture inside pipe
Data 19
  Q19 =      4.91 Qtotal=   94.86543
  E19 =      0.57 Etotal=   10.93169
 Current Temperature=  327.06831 Celcius

   326.50 temperarture inside pipe
Data 20
  Q20 =      4.90 Qtotal=   99.76223
  E20 =      0.56 Etotal=   11.49597
 Current Temperature=  326.50403 Celcius

Data 21
  Q21 =      4.89 Qtotal=  104.64955
  E21 =      0.56 Etotal=   12.05915
 Current Temperature=  325.94085 Celcius

   325.38 temperarture inside pipe
Data 22
  Q22 =      4.88 Qtotal=  109.52741
  E22 =      0.56 Etotal=   12.62124
 Current Temperature=  325.37876 Celcius

   324.82 temperarture inside pipe
Data 23
  Q23 =      4.87 Qtotal=  114.39582
  E23 =      0.56 Etotal=   13.18225
 Current Temperature=  324.81775 Celcius

   324.26 temperarture inside pipe
Data 24
  Q24 =      4.86 Qtotal=  119.25480
  E24 =      0.56 Etotal=   13.74216
 Current Temperature=  324.25784 Celcius

Data 25
  Q25 =      4.85 Qtotal=  124.10438
  E25 =      0.56 Etotal=   14.30100
 Current Temperature=  323.69900 Celcius

   323.14 temperarture inside pipe
Data 26
  Q26 =      4.84 Qtotal=  128.94456
  E26 =      0.56 Etotal=   14.85875
 Current Temperature=  323.14125 Celcius

   322.58 temperarture inside pipe
Data 27
  Q27 =      4.83 Qtotal=  133.77537
  E27 =      0.56 Etotal=   15.41542
 Current Temperature=  322.58458 Celcius

   322.03 temperarture inside pipe
Data 28
  Q28 =      4.82 Qtotal=  138.59683
  E28 =      0.56 Etotal=   15.97102
 Current Temperature=  322.02898 Celcius

Data 29
  Q29 =      4.81 Qtotal=  143.40895
  E29 =      0.55 Etotal=   16.52554
 Current Temperature=  321.47446 Celcius

   320.92 temperarture inside pipe
Data 30
  Q30 =      4.80 Qtotal=  148.21176
  E30 =      0.55 Etotal=   17.07898
 Current Temperature=  320.92102 Celcius

   320.37 temperarture inside pipe
Data 31
  Q31 =      4.79 Qtotal=  153.00526
  E31 =      0.55 Etotal=   17.63135
 Current Temperature=  320.36865 Celcius

   319.82 temperarture inside pipe
Data 32
  Q32 =      4.78 Qtotal=  157.78949
  E32 =      0.55 Etotal=   18.18266
 Current Temperature=  319.81734 Celcius
```

Appendix 3: Pascal Program Results (Page 2)

```
Data 33
  Q33 =        4.77 Qtotal=  162.56445
  E33 =        0.55 Etotal=   18.73289
 Current Temperature=  319.26711 Celcius

    318.72 temperarture inside pipe
Data 34
  Q34 =        4.77 Qtotal=  167.33816
  E34 =        0.55 Etotal=   19.28206
 Current Temperature=  318.71794 Celcius

    318.17 temperarture inside pipe
Data 35
  Q35 =        4.76 Qtotal=  172.08665
  E35 =        0.55 Etotal=   19.83017
 Current Temperature=  318.16983 Celcius

    317.62 temperarture inside pipe
Data 36
  Q36 =        4.75 Qtotal=  176.83392
  E36 =        0.55 Etotal=   20.37722
 Current Temperature=  317.62278 Celcius

Data 37
  Q37 =        4.74 Qtotal=  181.57201
  E37 =        0.55 Etotal=   20.92320
 Current Temperature=  317.07680 Celcius

    316.53 temperarture inside pipe
Data 38
  Q38 =        4.73 Qtotal=  186.30091
  E38 =        0.54 Etotal=   21.46813
 Current Temperature=  316.53187 Celcius

    315.99 temperarture inside pipe
Data 39
  Q39 =        4.72 Qtotal=  191.02067
  E39 =        0.54 Etotal=   22.01201
 Current Temperature=  315.98799 Celcius

    315.45 temperarture inside pipe
Data 40
  Q40 =        4.71 Qtotal=  195.73128
  E40 =        0.54 Etotal=   22.55483
 Current Temperature=  315.44517 Celcius

Data 41
  Q41 =        4.70 Qtotal=  200.43277
  E41 =        0.54 Etotal=   23.09660
 Current Temperature=  314.90340 Celcius

    314.36 temperarture inside pipe
Data 42
  Q42 =        4.69 Qtotal=  205.12516
  E42 =        0.54 Etotal=   23.63732
 Current Temperature=  314.36268 Celcius

    313.82 temperarture inside pipe
Data 43
  Q43 =        4.68 Qtotal=  209.80846
  E43 =        0.54 Etotal=   24.17699
 Current Temperature=  313.82301 Celcius

    313.28 temperarture inside pipe
Data 44
  Q44 =        4.67 Qtotal=  214.48270
  E44 =        0.54 Etotal=   24.71562
 Current Temperature=  313.28438 Celcius

Data 45
  Q45 =        4.67 Qtotal=  219.14788
  E45 =        0.54 Etotal=   25.25321
 Current Temperature=  312.74679 Celcius

    312.21 temperarture inside pipe
Data 46
  Q46 =        4.66 Qtotal=  223.80403
  E46 =        0.54 Etotal=   25.78975
 Current Temperature=  312.21025 Celcius

    311.67 temperarture inside pipe
Data 47
  Q47 =        4.65 Qtotal=  228.45117
  E47 =        0.54 Etotal=   26.32526
 Current Temperature=  311.67474 Celcius

    311.14 temperarture inside pipe
Data 48
  Q48 =        4.64 Qtotal=  233.08930
  E48 =        0.53 Etotal=   26.85973
 Current Temperature=  311.14027 Celcius

Data 49
  Q49 =        4.63 Qtotal=  237.71846
  E49 =        0.53 Etotal=   27.39316
 Current Temperature=  310.60684 Celcius

    310.07 temperarture inside pipe
Data 50
  Q50 =        4.62 Qtotal=  242.33865
  E50 =        0.53 Etotal=   27.92556
 Current Temperature=  310.07444 Celcius

    309.54 temperarture inside pipe
Data 51
  Q51 =        4.61 Qtotal=  246.94989
  E51 =        0.53 Etotal=   28.45693
 Current Temperature=  309.54307 Celcius

    309.01 temperarture inside pipe
Data 52
  Q52 =        4.60 Qtotal=  251.55221
  E52 =        0.53 Etotal=   28.98728
 Current Temperature=  309.01272 Celcius

Data 53
  Q53 =        4.59 Qtotal=  256.14561
  E53 =        0.53 Etotal=   29.51659
 Current Temperature=  308.48341 Celcius
```

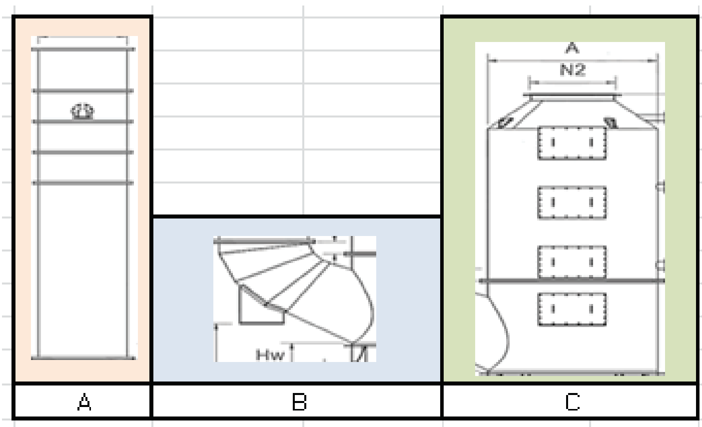
Appendix 4: Pascal Program Temperature Losses Table



Length	Temperature
0	338
1	337.41
2	336.83
3	336.24
4	335.67
5	335.1
6	334.5
7	333.92
8	333
9	332.77
10	332.2
11	331.62
12	331.05
13	330.5
14	329.9
15	329.3
16	328.7
17	328.2
18	327.63
19	327.06
20	326.5
21	325.94
22	325
23	324.8
24	324.2
25	323.7
26	323.14
27	322.58
28	322.03
29	321.47
30	320.92
31	320.36
32	319.81
33	319.26
34	318.71
35	318.16
36	317.62
37	317.07
38	316.53
39	315.98
40	315.44
41	314.9
42	314.36
43	313.82
44	313.28
45	312.7
46	312.21
47	311.67
48	311.14
49	310.6
50	310.07
51	309.54
52	309.01
53	308.48

Appendix 5: SOx Scrubber Design Data

Type	Data	Formula	mm	metre
A	Thickness		3	0.003
	Length	D - F	3540	3.54
B	Thickness		3	0.003
	Height	F-S	915	0.915
	Length	π D x 0.25	1436.55	1.43655
C	Thickness		3	0.003
	Length		4460	4.46
A+B	Length			4.97655



Appendix 6: SOx Scrubber Design Calculation (Normal Steel)

Diameter	1	60	cm	0.6	m	Hin	8	w/m.K		
	2	60.6	cm	0.606	m	H out	8	w/m.K		
	3	82.6	cm	0.826	m					
	4	82.8	cm	0.828	m	R conv 1	0.026699475			
						R conv 2	0			
Thickness	Steel 0-1	3	mm	0.003	m	R conv 3	0.019394292			
	Rockwool 1-2	110	mm	0.11	m					
	Steel 2-3	1	mm	0.001	m	R cond 1	7.10515E-06			
						R cond 2	0.335083852			
Ln	D4/D3	0.002418381	0.002418381			R cond 3	1.72687E-06			
	D3/D2	0.309714787								
	D2/D1	0.009950331				R total	0.381186451			
						Q	754.4601849	W	0.754460185	kJ/s
λ	steel	50	W/m.K							
	rockwool	0.033	W/m.K			Lose through Pipe		20.14905	Celcius	
						Lose Through Insualtion		252.8074		
2λ	steel	100	W/m.K			Lose through 2nd pipe		0.001303	Celcius	
	rockwool	0.066	W/m.K							
hs	12.1	W/m2.K								
Temperature E.Room		21	Celcius	294	Kelvin					
Exhaust Gas Temperature										
		308.59	Celcius	581.59	Kelvin					
						Calculation using Conduction and Convection				A + B

Diameter	1	135	cm	1.35	m	Hin	8	w/m.K		
	2	135.6	cm	1.356	m	H out	8	w/m.K		
	3	157.6	cm	1.576	m					
	4	157.8	cm	1.578	m	R conv 1	0.013223357			
						R conv 2	0			
Thickness	Steel 0-1	3	mm	0.003	m	R conv 3	0.010748709			
	Rockwool 1-2	110	mm	0.11	m					
	Steel 2-3	1	mm	0.001	m	R cond 1	2.84163E-06			
						R cond 2	0.14597409			
Ln	D4/D3	0.001268231	0.001268231			R cond 3	8.12666E-07			
	D3/D2	0.150350802								
	D2/D1	0.004434597				R total	0.16994981			
						Q	1573.646645	W	1.573646645	
λ	steel	50	W/m.K							
	rockwool	0.033	W/m.K			Lose through Pipe		20.81336	Celcius	
						Lose Through Insualtion		229.7116		
2λ	steel	100	W/m.K			Lose through 2nd pipe		0.001279	Celcius	
	rockwool	0.066	W/m.K							
						Current Temperature		267.6276		
hs	12.1	W/m2.K								
						Total Work loss		2328.107		
Temperature E.Room		21	Celcius	294	Kelvin	C				
Exhaust Gas Temperature						Total Losses A-C		40.96241		
		288.4409486	Celcius	561.440949	Kelvin					
						Calculation using Conduction and Convection				C

Appendix 7: SOx Scrubber Design Calculation (Carbon Steel)

Diameter	1	135	cm	1.35	m		Hin	8	w/m.K	
	2	135.6	cm	1.356	m		H out	8	w/m.K	
	3	157.6	cm	1.576	m					
	4	157.8	cm	1.578	m		R conv 1	0.013223357		
							R conv 2	0		
Thickness	Steel 0-1	3	mm	0.003	m		R conv 3	0.010740709		
	Rockwool 1-2	110	mm	0.11	m					
	Steel 2-3	1	mm	0.001	m		R cond 1	4.58328E-06		
							R cond 2	0.14597409		
Ln	D4/D3	0.001268231	0.001268231				R cond 3	1.31075E-06		
	D3/D2	0.150350802								
	D2/D1	0.004434597					R total	0.16995205		
							Q	1573.608258	W	1573608258
λ	steel	31	W/m.K							
	rockwool	0.033	W/m.K				Lose through Pipe		20.8156	Celcius
							Lose Through Insualtion		229.706	
2λ	steel	62	W/m.K				Lose through 2nd pipe		0.002063	Celcius
	rockwool	0.066	W/m.K							
							Current Temperature		267.6224	
hs	12.1	W/m2.K								
							Total Work loss		2328.058	
Temperature E.Room		21	Celcius	294	Kelvin		C			
Exhaust Gas Temperature							Total Losses A-C		40.96765	
		288.4379493	Celcius	561.437949	Kelvin	Calculation using Conduction and Convection				C

Diameter	1	60	cm	0.6	m		Hin	8	w/m.K	
	2	60.6	cm	0.606	m		H out	0	w/m.K	
	3	82.6	cm	0.826	m					
	4	82.8	cm	0.828	m		R conv 1	0.026699475		
							R conv 2	0		
Thickness	Steel 0-1	3	mm	0.003	m		R conv 3	0.019394292		
	Rockwool 1-2	110	mm	0.11	m					
	Steel 2-3	1	mm	0.001	m		R cond 1	1.14599E-05		
							R cond 2	0.335083852		
Ln	D4/D3	0.002418381	0.002418381				R cond 3	2.78528E-06		
	D3/D2	0.309714787								
	D2/D1	0.009950331					R total	0.381191864		
							Q	754.4494711	W	0.75444947
λ	steel	31	W/m.K							
	rockwool	0.033	W/m.K				Lose through Pipe		20.15205	Celcius
							Lose Through Insualtion		252.8038	
2λ	steel	62	W/m.K				Lose through 2nd pipe		0.002101	Celcius
	rockwool	0.066	W/m.K							
hs	12.1	W/m2.K								
Temperature E.Room		21	Celcius	294	Kelvin					
Exhaust Gas Temperature										
		308.59	Celcius	581.59	Kelvin	Calculation using Conduction and Convection				A + B

Diameter	1	35	cm	0.35	m		Hin	8	w/m.K	
	2	35.6	cm	0.356	m		H out	8	w/m.K	
	3	57.6	cm	0.576	m					
	4	57.8	cm	0.578	m		R conv 1	0.043083244		
							R conv 2	0		
Thickness	Steel 0-1	3	mm	0.003	m		R conv 3	0.026179054		
	Rockwool 1-2	110	mm	0.11	m					
	Steel 2-3	1	mm	0.001	m		R cond 1	1.6536E-05		
							R cond 2	0.439741335		
Ln	D4/D3	0.003466208	0.003466208				R cond 3	3.37209E-06		
	D3/D2	0.48117693								
	D2/D1	0.016997576					R total	0.509023541		
							Q	585.4346132	W	0.585434613
λ	steel	31	W/m.K							
	rockwool	0.033	W/m.K				Lose through Pipe		25.2321	Celcius
							Lose Through Insualtion		257.4398	
2λ	steel	62	W/m.K				Lose through 2nd pipe		15.3281	Celcius
	rockwool	0.066	W/m.K							
hs	12.1	W/m2.K								
Temperature E.Room		40	Celcius	313	Kelvin					
Exhaust Gas Temperature										
		338	Celcius	611	Kelvin	Calculation using Conduction and Convection				Pipe Losses

Appendix 8: Summary of Calculation (Carbon Steel) + Comparison with Normal Steel

Summary of Calculation (Best Losses)				
	Temperature		Work Losses	
Pipe Losses	**20.1521**	Celcius	**0.256**	kJ/s
NOx Chemical Losses			**28.43**	kJ/s
SOx Chemical Losses			**4.53**	kJ/s
Scrubber Piping Losses	**40.9676**	Celcius	**2.32805773**	kJ/s
Scrubber System Losses	**233.341**	Celcius	**392.415313**	kJ/s
Total	294.4603	Celcius	427.9593709	kJ/s

Summary of Calculation (Average Losses)				
	Temperature		Work Losses	
Pipe Losses	**20.1521**	Celcius	**0.256**	kJ/s
NOx Chemical Losses			**0**	kJ/s
SOx Chemical Losses			**0**	kJ/s
Scrubber Piping Losses	**40.9676**	Celcius	**2.32805773**	kJ/s
Scrubber System Losses	**235.562**	Celcius	**394.464551**	kJ/s
Total	296.6821	Celcius	397.0486085	kJ/s

Summary of Calculation (Maximus Losses)				
	Temperature		Work Losses	
Pipe Losses	**20.1521**	Celcius	**0.256**	kJ/s
NOx Chemical Losses			**0**	kJ/s
SOx Chemical Losses			**0**	kJ/s
Scrubber Piping Losses	**40.9676**	Celcius	**2.32805773**	kJ/s
Scrubber System Losses	**237.784**	Celcius	**396.513788**	kJ/s
Total	298.904	Celcius	399.0978461	kJ/s

Summary of Calculation (without EGTS)				
	Temperature		Work Losses	
Pipe Losses	**20.1521**	Celcius	**0.256**	kJ/s
Scrubber Piping Losses	**40.9676**	Celcius	**2.32805773**	kJ/s
Total	61.1197	Celcius	2.584057729	kJ/s

Differences :			
	Temperatire		Work Losses Comparison
Best Losses	9.252717	Celcius	1.000000115
Average Losses	9.252717	Celcius	1.195701456
Maximum Losses	9.252717	Celcius	1.240546739
without EGTS	9.252717	Celcius	1.000019001

Appendix 9: Summary of Calculation (Normal Steel) + Scrubbing Losses

Summary of Calculation (Best Losses)		
	Temperature	Work Losses
Pipe Losses	**29.41** Celcius	**0.26** kJ/s
NOx Chemical Losses		**28.43** kJ/s
SOx Chemical Losses		**4.53** kJ/s
Scrubber Piping Losses	**40.96** Celcius	**2.33** kJ/s
Scrubber System Losses	**228.78** Celcius	**449.55** kJ/s
Total	299.16 Celcius	485.10 kJ/s

Summary of Calculation (Average Losses)		
	Temperature	Work Losses
Pipe Losses	**29.41** Celcius	**0.26** kJ/s
NOx Chemical Losses		**56.88** kJ/s
SOx Chemical Losses		**20.82** kJ/s
Scrubber Piping Losses	**40.96** Celcius	**2.33** kJ/s
Scrubber System Losses	**231.01** Celcius	**451.61** kJ/s
Total	301.38 Celcius	531.90 kJ/s

Summary of Calculation (Maximus Losses)		
	Temperature	Work Losses
Pipe Losses	**29.41** Celcius	**0.26** kJ/s
NOx Chemical Losses		**63.52** kJ/s
SOx Chemical Losses		**32.48** kJ/s
Scrubber Piping Losses	**40.96** Celcius	**2.33** kJ/s
Scrubber System Losses	**233.23** Celcius	**453.66** kJ/s
Total	303.60 Celcius	552.25 kJ/s

Summary of Calculation (without EGTS)		
	Temperature	Work Losses
Pipe Losses	**29.41** Celcius	**0.26** kJ/s
Scrubber Piping Losses	**40.96** Celcius	**2.33** kJ/s
Total	70.37 Celcius	2.58 kJ/s

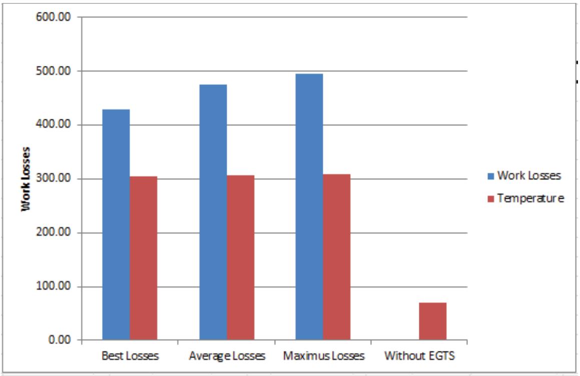
Summary Of Scrubbing Losses (Taking Ratio mFW / mSW = 2)

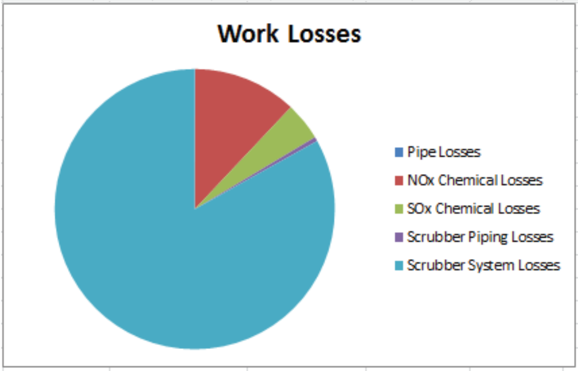
	Temperature	Temperature Losses	Work Losses
Open Loop System	34.29 Celcius	233.34 Celcius	392.42 kJ/s
Closed Loop System	29.84 Celcius	237.78 Celcius	396.51 kJ/s

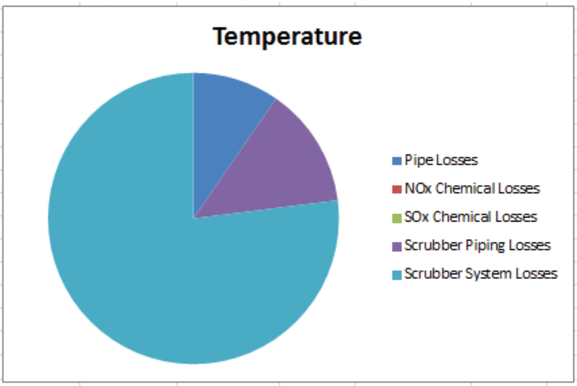
Losses Analysis

	Temperature	Work Losses
Best Losses	303.71 Celcius	427.96 kJ/s
Average Losses	305.93 Celcius	474.75 kJ/s
Maximus Losses	308.16 Celcius	495.10 kJ/s
Without EGTS	70.37 Celcius	2.58 kJ/s

Appendix 10: Losses in form of Graphics







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CHAPTER 5
TABLE AND ANALYSIS

After completing all the calculation through the system we can make the summary of the losses to analyze the improvement of the system and how to override the losses to get the better chance of WHRS.

Table 16 Summary of Calculation

Summary of Calculation (Best Losses)				
	Temperature		Work Losses	
Pipe Losses	**29.41**	Celcius	**0.26**	kJ/s
NOx Chemical Losses			**28.43**	kJ/s
SOx Chemical Losses			**4.53**	kJ/s
Scrubber Piping Losses	**40.96**	Celcius	**2.33**	kJ/s
Scrubber System Losses	**233.34**	Celcius	**392.42**	kJ/s
Total	303.71	Celcius	427.96	kJ/s

Summary of Calculation (Average Losses)				
	Temperature		Work Losses	
Pipe Losses	**29.41**	Celcius	**0.26**	kJ/s
NOx Chemical Losses			**56.88**	kJ/s
SOx Chemical Losses			**20.82**	kJ/s
Scrubber Piping Losses	**40.96**	Celcius	**2.33**	kJ/s
Scrubber System Losses	**235.56**	Celcius	**394.46**	kJ/s
Total	305.93	Celcius	474.75	kJ/s

Summary of Calculation (Maximus Losses)				
	Temperature		Work Losses	
Pipe Losses	**29.41**	Celcius	**0.26**	kJ/s
NOx Chemical Losses			**63.52**	kJ/s
SOx Chemical Losses			**32.48**	kJ/s
Scrubber Piping Losses	**40.96**	Celcius	**2.33**	kJ/s
Scrubber System Losses	**237.78**	Celcius	**396.51**	kJ/s
Total	308.16	Celcius	495.10	kJ/s

Summary of Calculation (without EGTS)				
	Temperature		Work Losses	
Pipe Losses	**29.41**	Celcius	**0.26**	kJ/s
Scrubber Piping Losses	**40.96**	Celcius	**2.33**	kJ/s
Total	70.37	Celcius	2.58	kJ/s

To determine the Best Losses, the variable that is used is the lowest losses on NOx and SOx scrubber chemical reaction, and the scrubber system losses indicating that the Closed-Loop system is using 20 degree Celsius as the constant temperature, even though using the closed loop system there's still possibility to maximizing the work of the cooling system so that we can reach the same temperature as the open loop system.

Following the Best Losses, we have the average Losses which the number Losses of NOx and SOx is the average losses of the various types of the calculated chemical products and the temperature and it is also applied to the Scrubber system Losses. Meanwhile the Maximum Losses applies all the highest possible number of losses from the data which is used to determine how many losses which is able to reach if there is no selection through the design process. The last one is the system without EGTS which will work as the patient zero, to understand how much loss that we get from the application of the EGTS.

In order to describe the losses which is resulted from every segments, the average losses represents the best data to do the comparison. The pie chart will be used to describe the contribution of each part.

5. Results and Analysis

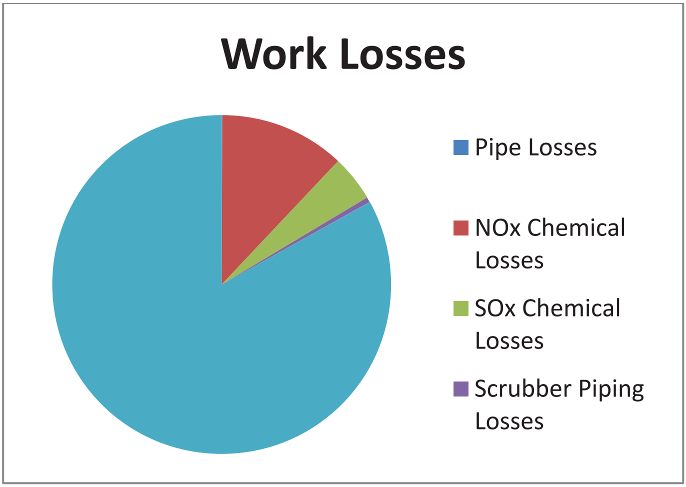

Figure 16 Average Work Losses Distribution

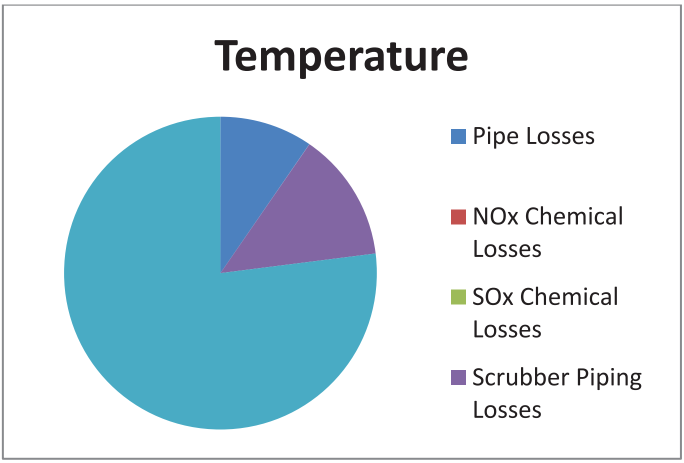

Figure 17 Average Temperature Losses Distribution

5.1. Improvement on EGTS to Maximize the Potential of WHRS

Analyzing the acquired data, these following points will be the next steps to increase the potential of Waste Heat Recovery System

5.1.1 Better heat-resist material inside the pipe

As it can be seen on the table and analysis Piping Losses accumulated from Scrubber Piping and Pipe Losses system the number of losses which is produced is up to 60%, and 45% due to Temperature Losses. Seeing from this formula:

$$Q = \frac{T\infty1 - T\infty2}{Rtotal} \; and \; Rcond = \frac{\ln(\frac{rn+1}{rn})}{2\pi k.L} \quad (13)$$

We can see the relation between the k of the material or can be called as Lambda λ , the higher the number of lambda will results a higher Losses , so in Order to reduce the losses we can select a Material with lower Heat conductivity rather than current common material. Let’s take Carbon Steel, max 1.5% C with 36 W/m.K, we will able to get following calculation:

Table 17 Carbon Steel Usage

Differences :			
	Temperatire		Work Losses Comparison
Best Losses	9.252717	Celcius	1.000000115
Average Losses	9.252717	Celcius	1.195701456
Maximum Losses	9.252717	Celcius	1.240546739
without EGTS	9.252717	Celcius	1.000019001

We can save up to 9 degree Celsius and save 0.19 less Work Losses from the steel only by changing the material, this mean the better the material is , more temperature that and Losses that we can save.

5.1.2 Shorter Pipe Length to Achieve less heat loss

$$Q = \frac{T\infty1 - T\infty2}{Rtotal} \; and \; Rcond = \frac{\ln(\frac{rn+1}{rn})}{2\pi k.L}$$

With less pipe usage, it's undeniable we can save a number of Heat and Temperature Losses by reducing significant number of pipe length , since pipe length is directly impact the Conduction Losses which will summed up to Heat Loss.

5.1.3 Putting Consideration on Chemical Products

Table of Comparison					
	Ca(OH)2	Mg(OH) 2	2NaOH(aq)	Sea Water :	CaCO3
Enthalpy	-161.798	-349.25	-245.57	-313.95	-48.738
Losses (kJ/kg DO)	-15.047214	-32.48025	-22.83801	-29.19735	-4.532634
Comparison	3.319750503	7.1658665	5.0385736	6.441585621	1
Percentage	331.98%	716.59%	503.86%	644.16%	100.00%

Table of Comparison					
	Pure Amonia	Aqueous	Nitro 1	Nitro 2	Fast Nitro
Enthalpy	-2072.04	-1891.54	-3260.16	-1596.9	-888.7
Losses	-63.5213862	-57.987897	-4.3527848	-2.13209231	-28.430928
Combination	Pure + Nitro1	Pure+Nitro2	Aqu + Nitro1	Aqu + Nitro2	Fast Nitro
Losses (kJ/kg DO)	-67.874171	-65.653479	-62.340682	-60.1199897	-28.430928
Comparison	2.387335744	2.3092274	2.19270654	2.114598206	1
Percentage	238.73%	230.92%	219.27%	211.46%	100.00%

Accumulating the Comparison from the Maximum Losses that we can get from chemical losses by multiplying Mg(OH)2 and Pure + Nitro1 we will get 16,54 higher than the losses from the Lowest losses (CaCO3 and Fast Nitro). Where 16.54 higher is equal to 57.74 kJ/kg Diesel Oil which is a significant number of losses , so putting attention on the chemical reaction will resulting significant number of Losses which is saved.

5.1.4 Using the Acid-Free Material on Scrubber Piping System

Taking the current regulation which has no requirement on temperature inlet of the scrubber system , if we have the acid-free material installed on the system than we can compromise the existence of acid rain on piping system since there will be no disadvantage if we have acid free material. Even though Acid free material will be cost more , but we can save more energy from the application of it.

The number of saved energy is come from the lower limitation of temperature before it entered. Currently , we only have 128,59 degree Celsius (308,59 – 180 = 128,59^{o}C) because the 180^{o}C regulation , and by this application we can deduct on the very low level , rough assumption 70 ^{o}C then we will have 238,59 ^{o}C to be used on the WHRS.

If Figure 3 represent the normal condition , then by having acid-free material we can gain 85.5% more , and mathematically calculated then we can have 11% + (11% x 85%) = 18.26% at maximum, without considering the other factor. This can be a huge impact on WHRS since if this possible, then we can take a conclusion if EGTS is very supporting the WHRS process , by eliminating Acid Rain Factor.

5.2. Conclusion of Whole Calculation

5.2.1. EGTS does not affect WHRS

Based on some voyage experiences it is concluded that Acid Rain happen on 160-180°C of Exhaust Gas with Sulphur Content inside of it. By removing the calculation of SOx Chemical Reaction, SOx Piping and System Losses it can be determined the number of losses post NOx Scrubber

Table 18 Calculation Post NOx Scrubber

Scrubber Analysis pre SOx Scrubber					
Summary of Calculation (Best Losses)					
		Temperature		Work Losses	
Pipe Losses		**29.41**	Celcius	**0.26**	kJ/s
NOx Chemical Losses				**28.43**	kJ/s
SOx Chemical Losses				**0.00**	kJ/s
Scrubber Piping Losses		**0.00**	Celcius	**0.00**	kJ/s
Scrubber System Losses		**0.00**	Celcius	**0.00**	kJ/s
	Total	29.41	Celcius	28.69	kJ/s
Summary of Calculation (Average Losses)					
		Temperature		Work Losses	
Pipe Losses		**29.41**	Celcius	**280.75**	kJ/s
NOx Chemical Losses				**56.88**	kJ/s
SOx Chemical Losses				**0.00**	kJ/s
Scrubber Piping Losses		**0.00**	Celcius	**0.00**	kJ/s
Scrubber System Losses		**0.00**	Celcius	**0.00**	kJ/s
	Total	29.41	Celcius	337.63	kJ/s
Summary of Calculation (Maximus Losses)					
		Temperature		Work Losses	
Pipe Losses		**29.41**	Celcius	**280.75**	kJ/s
NOx Chemical Losses				**63.52**	kJ/s
SOx Chemical Losses				**0.00**	kJ/s
Scrubber Piping Losses		**0.00**	Celcius	**0.00**	kJ/s
Scrubber System Losses		**0.00**	Celcius	**0.00**	kJ/s
	Total	29.41	Celcius	344.27	kJ/s
Summary of Calculation (without EGTS)					
		Temperature		Work Losses	
Pipe Losses		**29.41**	Celcius	**280.75**	kJ/s
Scrubber Piping Losses		**0.00**	Celcius	**0.00**	kJ/s
	Total	29.41	Celcius	280.75	kJ/s

From the Following table we can see the losses is 29,41^{o}C and taking that number from the exhaust gas post ME the current temperature will be 338^{o}C - 29,41^{o}C = 308.59^{o}C, this calculation is neglecting the NOx Scrubber piping and design system because the preheating system which is available before the NOx Scrubbing System, or the conditioning of it to reach the high temperature , and the system can be categorized as a small losses since there is only an abrupt system exist on it. By having 308,59^{o}C that mean we have 308,59 – 180 = 128,59^{o}C at best to be flowed in into the Waste heat recovery system which is equal a half of the system without EGTS.

But this disadvantage that is mentioned is working the same way with the rules from the MARPOL where a ship must have exhaust gas don to 160 – 180 degree Celsius to prevent Acid Rain on exhaust gas piping to prevent acid rain on the ship , and if there is no additional limitation which is given by the Scrubber manufacturer , then this disadvantages is working the same way with class rules as German Lloyd or American Bureau of Shipping , so it can be said that the same rules is applied whether on the system with EGTS or non-EGTS ship. But, if there's an additional requirement from Scrubber system as it is known that It can work on lower temperature it creates such a probability that the ship with EGTS has better WHRS potential or vice versa if the requirement of the temperature is asked higher from the system.

5.2.2. The Current Best Installation of WHRS on a ship

To install the WHRS in the ship with EGTS, there are 3 probabilities that can be happened, they are:

1) Installed after Main Engine Process , before the NOx and SOx Scrubber System
2) Installed after Whole EGTS systems, after SOx Scrubber System

3) Installed in between NOx and SOx Scrubber System

The detail of weaknesses and strengths from each type followed by a recommendation to install a scrubber system will be detailed on each point. And by comparing every single system we can reach a conclusion that the last design has the best advantages and only in this system the EGTS will not influencing the WHRS with a probability to unleash the higher potential of WHRS.

1) Post ME , Pre-EGTS

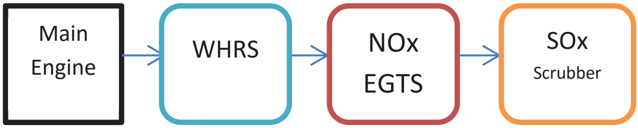

Figure 18 Installation WHRS (Design 1)

The main problem of this Systems is the requirement of NOx EGTS which is needed 300°Celcius to operate the scrubbing system , and by having Exhaust Gas temperature post ME as much as 338°C , it means we only can use 38°C to be used on WHRS systems. Even though it is possible to do this and install a pre-heating system before NOx EGTS it means that we will have to spend more money to apply the Pre-Heating system just in order to get a certain number of Exhaust gas and the rules of applying WHRS as a smart technology can be neglected , since if we are using the pre-heating system we will resulting a certain number of energy by the exhaust gas , and on the other hand we are taking energy again by using that pre-heating system on NOx scrubber to fulfill it requirement. By requiring 300°C in inlet temperature EGTS on this system is influencing the WHRS potential, so the installation of WHRS after the ME and before EGTS systems is highly not recommended.

2) Post ME and EGTS

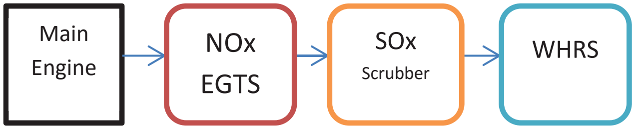

Figure 19 Installation WHRS (Design 2)

The main disadvantage of putting WHRS systems after EGTS systems is the SOx Scrubber process which is resulting the highest number of losses in Heat since there are 250°Celsius or more difference in Temperature between the coolant and the Exhaust Gas which resulting a burst in the number of Losses during the Process of Sulphur Solubilize, and we will only have 40°Celsius which is slightly higher than the installation before EGTS without pre-heating system. Even though it is possible but the very low number of temperature in the outlet making this idea not recommended and on this system EGTS will influencing the WHRS by the high number of losses during the scrubbing system in SOx Scrubber.

3) Post ME and Pre-EGTS

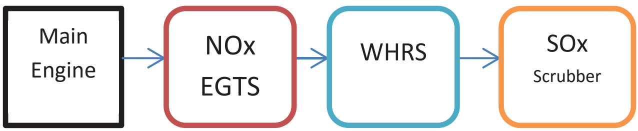

Figure 20 Installation WHRS (Design 3)

Compared to idea 1 and 2, this is undeniably the best design that we can expect since the NOx is required to be worked above 300°C and the fact that Exhaust Gas from MAN 6L 23/30 four stroke diesel engine on 87,3 load is 338°C which is met the basic requirement of NOx EGTS therefore no pre-Heating system is needed on it , and there is no temperature drop only work losses from the NOx

EGTS is happening therefore there is almost no impact of NOx EGTS to the condition of Exhaust Gas , therefore we have to meet the requirement of SOx Scrubber which is the temperature should be higher than the condition to meet Acid Rain which is the same with normal ship MARPOL rules, therefore we can take 94,71 degree Celsius or 2.5 higher than the other designs , and therefore this installation is the one which highly recommended for the voyage. And taking WHRS as the consideration, only on this design EGTS will have no influence on it, and by adding several installations it is possible that EGTS can unleash more potential of WHRS compared to the system without EGTS.

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APPENDIX

Appendix1: Pascal Program for Piping Losses Calculation (with details)

Appendix 2: Pascal Program Results (Page 1)

Appendix 3: Pascal Program Results (Page 2)

Appendix 4: Pascal Program Temperature Losses Table

Appendix 5: SOx Scrubber Design Data

Appendix 6: SOx Scrubber Design Calculation (Normal Steel)

Appendix 7: SOx Scrubber Design Calculation (Carbon Steel)

Appendix 8: Summary of Calculation (Carbon Steel) + Comparison with Normal Steel

Appendix 9: Summary of Calculation (Normal Steel) + Scrubbing Losses

Appendix 10: Losses in form of Graphics

BIODATA PENULIS

Nama : Christian Laksmono

Tempat/Tanggal Lahir :
Surabaya, 23 Desember 1994

Riwayat Pendidikan:

1998-2000	TK SANTA MARIA
2000-2006	SD SANTA MARIA
2006-2009	SMPK SANTA MARIA
2009-2012	SMAK SANTA MARIA
2012- …	INSTITUT TEKNOLOGI SEPULUH NOPEMBER
2012- …	HOCHSCHULE WISMAR

Aktivitas :
Tutor Olimpiade Matematika dan Komputer
Pengelola Workshop Air Conditioning & Refrigerant

Prestasi :
Juara 3 Lomba Komputer Petra Parade
Finalis Lomba Komputer UBAYA ILPC
Finalis Lomba Matematika UGM
Best Seminar Attendance Rottenberg