CHALMERS

Thermal insulation of catalysts for marine applications

Degree project in the Bachelor of Science in Mechanical Engineering

Fredrik Ejresjö

Department of Materials and Manufacturing Technology
Division of Advanced Non-destructive Testing
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2015 Examiner: Gert Persson Report No. 142/2015

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Abstract

Volvo Penta develops engines and propulsion systems for marine and industrial applications.
Stricter emission regulation for marine commercial diesel engines will be introduced during the period 2016-2021 in accordance with the International Maritime Organization Tier 3 (IMO3).
In order to meet the coming regulation, Volvo Penta has developed an engine concept with an exhaust after-treatment system (EATS) with selective catalytic reduction (SCR). The exhaust gas is running through the SCR and it gets very hot. For safety reasons, the maximum temperature of an exposed surfaces in a marine engine compartment is regulate by law.

The objective of the project is to determine the thermal regulations that applies to the EATS, investigate and evaluate different insulation methods and develop an insulation solution for the EATS.

The regulations were determined by contacting relevant authorities and organizations and by examine their rule-documents.
The result shows that the maximum surface temperature allowed for boats in international traffic is 220°C while the maximum temperature for some specific types of boats in national traffic is 60°C. In both cases the insulation material must be non-combustible with a non oil-absorbing surface and with a melting point above 925°C. The rules also states that measures shall be taken to eliminate any risk of injury caused by contact with materials at high temperature.

The surface temperatures of the uninsulated exhaust system and SCR were determined by examining the result from existing tests. The tests showed that the components can reach a surface temperature of over 500°C.

Several different insulation methods were investigated with focus on solutions currently used for marine exhaust systems. Insulation methods used for other hot engine components such as turbochargers were also investigated. The most common approach for insulation of marine exhaust systems were a blanket-type of insulation wrapped around the exhaust pipes, often covered by a protective metallic shield.

Concepts for insulation of the EATS were developed based on the researched insulation solutions. Basic heat transfer calculations were performed to determine the insulation thickness needed to meet the regulations. The heat loss from the exhaust pipe between the engine and SCR were estimated with calculations.
The concepts were evaluated and ranked with help of a selection matrix.

The winning concept is of simple construction. It uses a blanket-type of insulation, about 50 mm thick, which is wrapped around the exhaust system. It has an aluminum reinforced soft cover equipped with hooks. The blankets are held together with metallic wires. The blankets are highly customizable and easy to dismount and remount in case of service or modifications to the EATS. The heat loss from the exhaust pipe between the engine and the SCR is estimated to be up to 4°C.

Sammanfattning

Volvo Penta utvecklar motorer och framdrivningssystem för marina och industriella applikationer.
Striktare utsläppsregler för kommersiella marina dieselmotorer kommer att införas under perioden 2016-2021 i enlighet med International Maritime Organization Tier 3 (IMO3).
Volvo Penta har utvecklat ett motorkoncept med ett avgasefterbehandlings-system (EATS) med selektiv katalytisk reduktion (SCR). Avgassystemet blir mycket varmt. Av säkerhetsskäl är den högsta tillåtna temperaturen för synliga ytor i ett marint motorrum begränsad enligt lag.

Målet med projektet är att fastställa de bestämmelser som gäller för yttemperaturen, undersöka och utvärdera olika isoleringsmetoder och utveckla en isoleringslösning för EATS.

De gällande bestämmelserna fastställdes genom att kontakt berörda myndigheter och organisationer samt granska deras regeldokument.
Resultatet visar att den varmaste tillåtna yttemperaturen för båtar i internationell trafik är 220°C medan den maximala temperaturen för vissa typer av båtar i nationell trafik är 60°C. I båda fallen måste isoleringsmaterialet vara av icke-brännbart material, ha en smältpunkt över 925°C och ha en olje-avisande yta. Vidare säger reglerna att åtgärder bör vidtas för att undvika risk för personskador till följd av kontakt med material av hög temperatur.

Den oisolerade yttemperaturen hos avgassystemet och SCR fastställdes genom att studera befintliga tester som gjorts. Testerna visar att komponenterna kan få en yttemperatur på över 500°C.

Flera olika typer isolering undersöktes med fokus på de lösningar som används för marina avgassystem. Isoleringsmetoder för andra varma komponenter såsom turboladdare undersöktes också.
Det vanligaste tillvägagångssättet för isolering av marina avgassystem visade sig vara en isoleringsmatta som lindas runt avgassystemet. Det är också vanligt att isoleringen bekläds med en skyddande plåt.

Isoleringskoncept utvecklades baserat på de studerade isoleringslösningar. Grundläggande värmeöverföringsberäkningar utfördes för att bestämma den isoleringstjocklek som krävs för att uppfylla föreskrifterna. Avgasernas temperaturskillnad mellan motorn och SCR beräknades också.
Koncepten utvärderades och rangordnas med hjälp av en urvalsmatris.

Det vinnande konceptet är konstruerat på ett enkel sätt. Det använder en isoleringsmatta som är lindad runt avgassystemet. Isoleringstjockleken är ca 50 mm. Mattans yta har ett aluminiumförstärkt tyg utrustad med krokar. Mattan hålls fast med ståltråd. Lösningen är mycket anpassningsbar och lätt att demontera och montera vid behov av service eller modifiering av systemet. Värmeförlusten från avgasröret mellan motorn och SCR uppskattades vara upp till 4°C.

Nomenclature

CAD	Computer-Aided Design
EATS	Exhaust After-treatment System
ECA	Emission Control Area
IACS	International Association of Classification Societies
IMO	International Maritime Organization
IMO3	IMO Tier 3 emission standard.
IPS	Drive system with forward-facing propellers developed by Volvo Penta
LMTD	Logarithmic Mean Temperature Difference
NO_x	Generic term for the nitrogen oxides NO and NO_2
SCR	Selective Catalytic Reduction
SOLAS	Safety of Life at Sea
A_c	Cross-sectional area
A_s	Surface area
C_p	Specific heat coefficient
D_h	Hydraulic diameter
$\dot{m}$	Mass flow rate
$\dot{Q}$	Rate of heat conduction
T_∞	Surrounding temperature
T_s	Surface temperature
V_m	Mean flow velocity
ΔT_{lm}	Logarithmic mean temperature different
A	Area
h	Convection heat transfer coefficient
k	Thermal conductivity coefficient
L	Length
Nu	Nusselt number
Pr	Prandt number
r	Radius
R	Thermal resistance
Re	Reynold’s number
T	Temperature
ε	Emissivity of a surface
μ	Dynamic viscosity

ν	Kinematic viscosity
ρ	Density
σ	Stefan-Boltzmann constant

Preface

This report presents the final result of a degree project in the Bachelor of Science in Mechanical Engineering conducted at the Department of Materials and Manufacturing Technology at Chalmers University of Technology, Gothenburg, Sweden.

The objective of the project is to investigate and evaluate thermal insulation methods and develop an insulation solution for a marine exhaust after-treatment system in accordance with current safety regulations.

The project was performed during the period 9/3-12/6 2015.

Acknowledgements

I would like to thank Volvo Penta and my supervisor Dr Rolf Westlund for the opportunity to work with this project and for helpful guidance throughout the work process.

Also, a great thanks to the people at Volvo Penta for their patient help throughout the steps of the project.

I would like to offer my special thanks to Swedish Sea Rescue Society and staff at station Käringön for a wonderful visit and showcase of their rescue boat Ilse Sanne.

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1 Introduction

In this section the background and purpose of the project will be explained.

1.1 Background

Volvo Penta develops engines and propulsion systems for marine and industrial applications.
Their marine commercial engines are used for propulsion, power generation and auxiliary power.

Marine commercial engines have so far had relatively liberal emission regulations. It has been sufficient with combustions optimization to comply with the regulation.

Stricter emission regulation for marine commercial engines with power of 130 kW and above will be introduced during the period 2016-2021 in accordance with the International Maritime Organization (IMO).
The new IMO Tier 3 regulation applies to ships operating in specific Emission Control Areas (ECA). The NO_x emission requirement varies with the engine's rated speed. For Volvo Penta's engine range this means a demand on maximum 2 g/kWh NO_x emissions with fuel that contains maximum 1000 ppm sulfur.
Outside the ECA zones, Tier 2 regulation applies. That means emission restrictions of 7.2 g/kWh of NO_x.

In order to meet the coming regulation, Volvo Penta has developed an engine concept with low soot combustion and an exhaust after-treatment system (EATS) with selective catalytic reduction (SCR).

Since the exhaust gas is running through the SCR it can get very hot. It is not safe to have surfaces with very high temperatures in a marine engine compartment. Laws regulate the maximum temperature of engine and exhaust system surfaces.

Volvo Penta needs to develop a SCR system that meets all regulations for marine commercial engines. Surface temperature requirements from authorities, classification organizations, boat builders and users are therefore to be identified. This project will investigate different methods of thermal insulation for engine and EATS components. Design concepts of an insulated SCR system will be developed.

1.2 Objective

The initial part of the project is to determine the regulations of surface temperatures of the SCR system for use with marine diesel engines.
The objective of the project is to investigate different thermal insulation methods and evaluate or develop an insulation solution for the SCR system that best meets the specified requirements. The results of the project will be a design concept of an insulated SCR system that satisfies the current regulations.

The following questions will be resolved during the project:

- Which requirements do authorities, classification organizations, boat builders and users have for insulation of the SCR system?
- What is the maximum allowed surface temperature of exhaust systems for marine applications?
- Which methods for insulation are available?
- What is the best method and material for insulation of the SCR system?

1.3 Delimitations

- Only insulation methods for the SCR unit and the exhaust pipe after the turbine to the SCR are to be studied in this project.
- Only basic heat conduction calculations will be performed. No computer based modeling of heat flows through the SCR or engine compartment will be done.
- CAD-models of design concepts will not be derived
- The project will be carried out during the period 9/3-12/6 2015

2 Basic functions of engine components

This section explains some of the basic functions of the engine components with focus on EATS, air- and exhaust flow.

2.1 Engine overview

The focused engine is a 13 liter in-line 6 cylinder commercial marine diesel engine. It uses a single turbocharger with charge air cooler. It has a SCR system that substantially reduces NO_x emissions.

The D13 engine is offered with power levels from 300- 600 hp. All engines have the same hardware but different software in order to deliver the rated power.
The 600 hp (441kW) engine delivers 2399 Nm at 1400rpm. (MY14 IMO Tier 2 version)

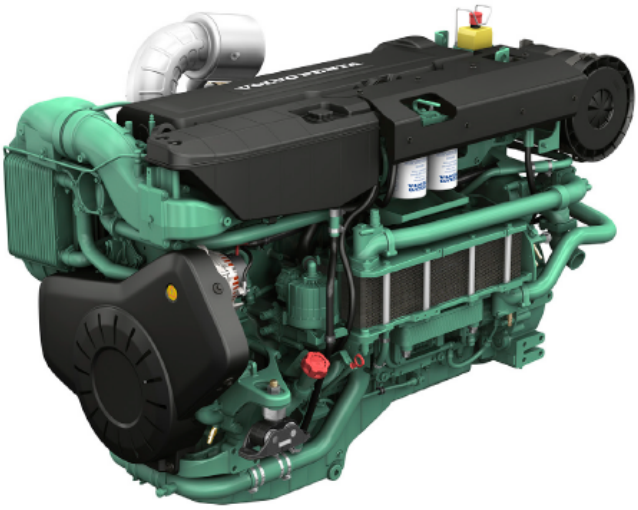

Figure 2-1 Volvo Penta D13-600 engine

Installations with twin engines are often used for propulsion. The engines are used in a wide range of different boats and ships. Some examples of boats and ships that use this engine are:

- Pilot boats
- Fishing boats
- Smaller cargo ships and tankers
- Passenger and car/cargo ferries

Figure 2-2 and 2-3 shows examples of boats that use the D13 engine.

Figure 2-2 Car/cargo ferry Ärlan uses twin D13-500 engines for propulsion

Figure 2-3 Pilot boat 745 uses twin Volvo Penta D13-600 engines for propulsion. © Bo Randstedt

2.2 Air and exhaust gas flow

The D13 engine uses a turbo charging system with a single turbocharger and a charge air cooler. Figure 2-4 shows an overview of the system's main components.

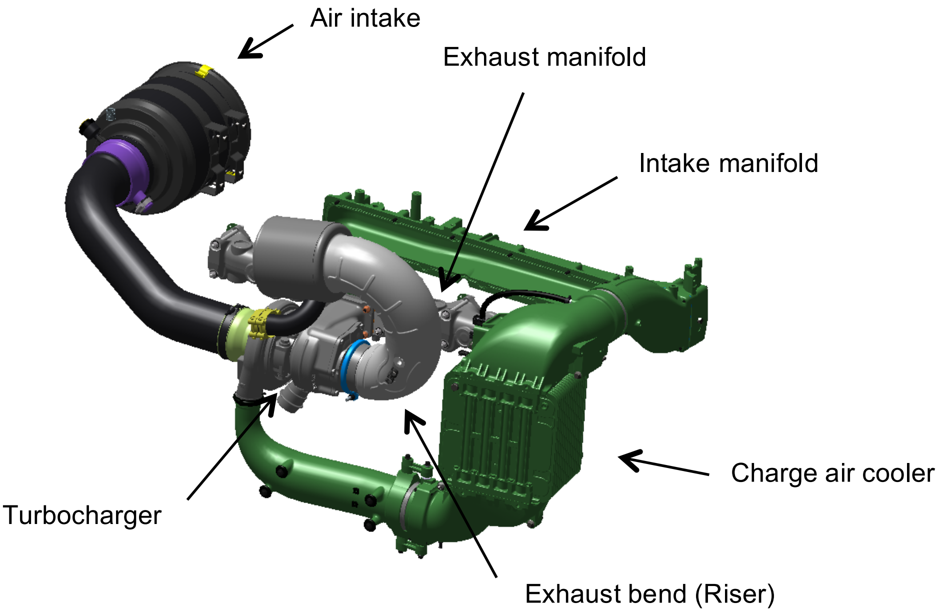

Figure 2-4 Air and exhaust system

2.2.1 Charge air system

Figure 2-5 shows the air's way to the combustion chamber and the components that it passes through.

The air intake system ensures that the air is supplied to the combustion chamber and meets the combustion process' requirements.
The density of the charge air has to be regulated. This is done by closely controlling the temperature and pressure of the air.
Clean intake air is required. The level of impurities such as dust and dirt must be kept at acceptable levels.

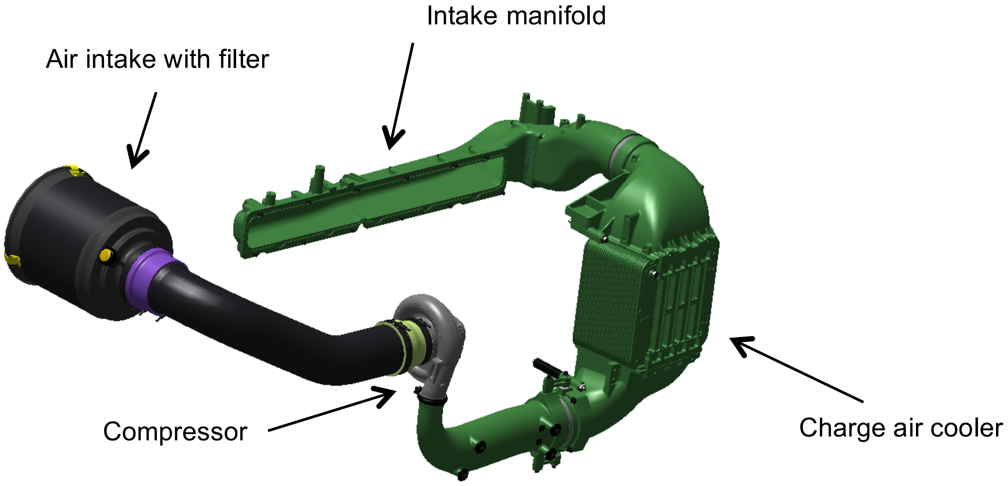

Figure 2-5 Air intake system

2.2.1.1 Air intake

The intake air is taken directly from the engines surroundings. A ventilation system is supplying the room with air from the outside the boat. The temperature and quality of the intake air varies with the ambient temperature of the environment the boat operates in.

A filter in the air intake ensures that impurities such as dust and dirt in the air are kept at an acceptable level.

2.2.1.2 Compressor, turbocharger

The turbocharger consists of two main components, a turbine and a compressor. The turbine drives the compressor that compresses the intake air in order to increase its density. Higher air density enables increased power rating. The temperature of the air increases with the compression process.

2.2.1.3 Charge air cooler

High combustion temperature affects the engine’s performance and emissions. A charge air cooler is used to control the compressed air’s temperature. The colder air also increases the air’s density further. The result is better combustion and increased engine performance.

2.2.1.4 Intake manifold

The intake manifold’s function is to distribute the air evenly to the cylinders.

2.2.2 Exhaust system

The figure below shows part of the exhaust system, including an exhaust bend and system for cooling the exhaust gas.

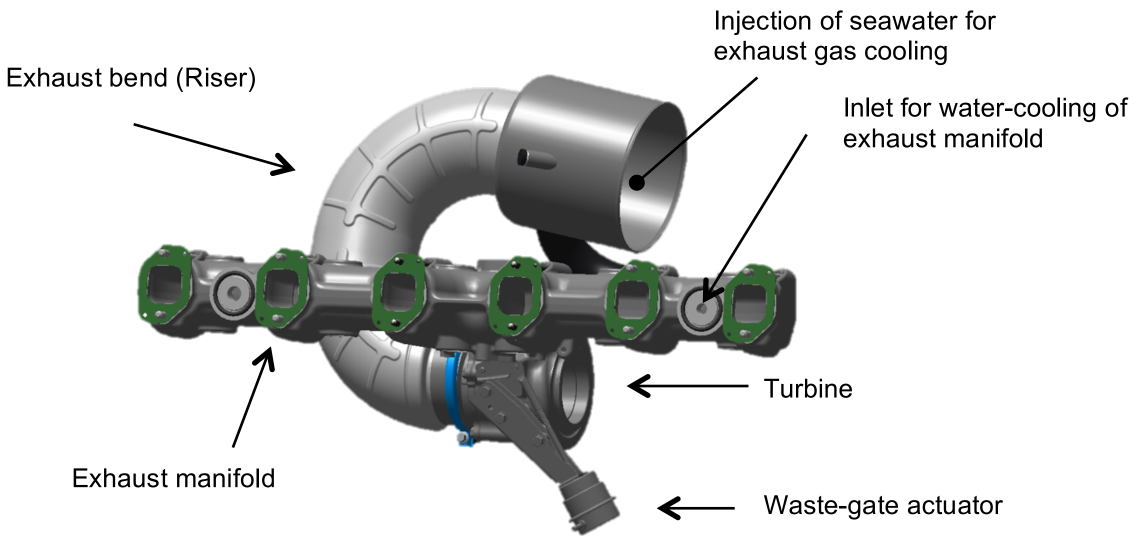

Figure 2-6 Exhaust system

2.2.2.1 Exhaust manifold

The exhaust manifold collects and leads the exhaust gas from the cylinders to the turbine. The manifold is water-cooled to reduce its temperature.

2.2.2.2 Turbine, turbocharger

Energy is extracted from the exhaust gas by the turbine and used to drive the compressor. A waste-gate valve is used to control the speed of the turbine and in turn the compression of the charge air. When the valve is open, some of the exhaust gas flow will bypass the turbine.
A waste-gate actuator is used for controlling the valve opening. A pressure line is connecting the intake manifold to the actuator. The waste-gate valve opens when a defined air pressure is met.

2.2.2.3 Exhaust pipe

The exhaust pipe will be very hot and needs to be insulated to minimize the risk for injuries or fire in the engine compartment.
A part of the exhaust pipe needs to be flexible in order not to transfer vibrations from the engine to the rest of the exhaust system. With the addition of a SCR system, the flexible connection needs to be positioned between the turbo outlet and SCR muffler.

2.2.2.4 Dry or wet exhaust system

Exhaust systems can be of either dry or wet design.
A dry system is just an exhaust pipe leading the exhaust gas out to the ambient.

A wet system will mix seawater with the exhaust gas, in order to reduce the exhaust gas temperature. The mixing occurs in the exhaust pipe after the gas has passed the SCR system. The mixture will then be released to the sea. This system is more complex but will lower the exhaust gas temperature significantly allowing simpler piping and enables use of materials with less thermal resistance. Wet exhaust systems are common with commercial applications.
As water is injected inside the exhaust pipe, it is crucial to prevent the water from entering the engine system. To minimize the risk for this, the SCR system should be positioned above the engine to act as a water trap.

2.2.2.5 IPS drive

Installations with Volvo Penta’s IPS inboard system are using a wet exhaust system. The exhaust gas is mixed with seawater after the turbo. It is then lead through the IPS drive and released in the sea behind the propellers.

Figure 2-7 shows engines without EATS installed with IPS drives.

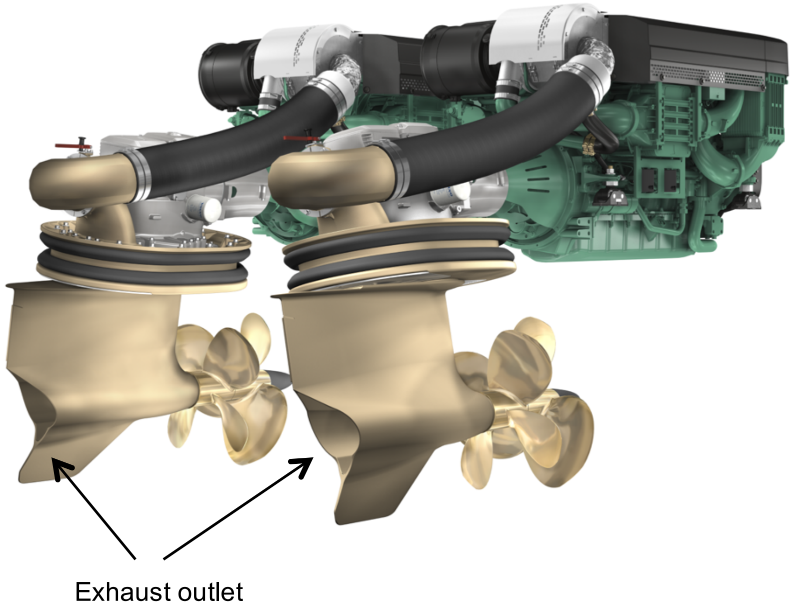

Figure 2-7 Twin Volvo Penta engines with IPS drive. © Volvo Penta Image Library

2.3 Diesel emissions

An ideal diesel combustion process would produce carbon dioxide (CO_2) and water vapor (H_2O). In reality the exhaust gas from the diesel process consist of CO_2, H_2O, unused engine charge air (O_2 and N_2) and pollutants.
Most pollutants are created from incomplete combustion of fuel, engine oil, sulfur compounds and fuel additives. Hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter (PM) are the most common pollutants.
The pollutants cause negative health and environmental effects.
The exhaust gas typically consists of less than 1% of pollutants, 2-12% of CO_2, 2-12% H_2O, 3-17% O_2 and N_2 for the rest.
The concentration of the gases varies with engine load. CO_2 and H_2O increases with engine load, while O_2 decreases with increasing engine load.
Engine exhaust emissions are typical regulated with limits for maximum levels of certain substances. The limit applies to some of the pollutants; typically NO_x, PM, HC and CO.

There's generally a trade-off between NO_x and PM emissions. The engine can either be optimized for low PM and fuel consumption with high NO_x emissions or vice versa. Typically low PM and fuel consumption are preferred and the NO_x emissions are lowered using an EATS. (DieselNet, 2015)

Commercial marine diesel engines that are subject to IMO3 have only two regulated limits. NO_x emissions must not exceed 2 g/kWh and the fuel must not contain more than 1000 ppm sulfur.

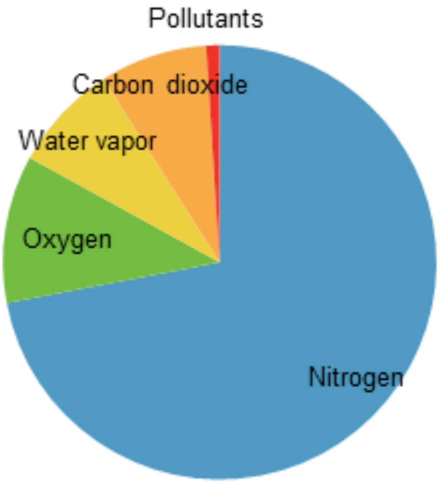

Figure 2-8 Example of exhaust gas composition

2.4 Selective catalytic reduction (SCR) system

A SCR system is used for reduction of NO_x emissions by letting NO_x react with ammonia. The ammonia, in form of Urea, is injected to the exhaust gas upstream of the SCR catalyst.

Figure 2-9 shows a D13 marine engine and the main components of the SCR system. Note that the SCR muffler and Urea tank are not connected to the engine, since the components positions are yet to be determined. Also, the exhaust bend with water-injection shown in the figure will have to be placed after the SCR system. The figure is meant to show the SCR systems size compared to the engine.

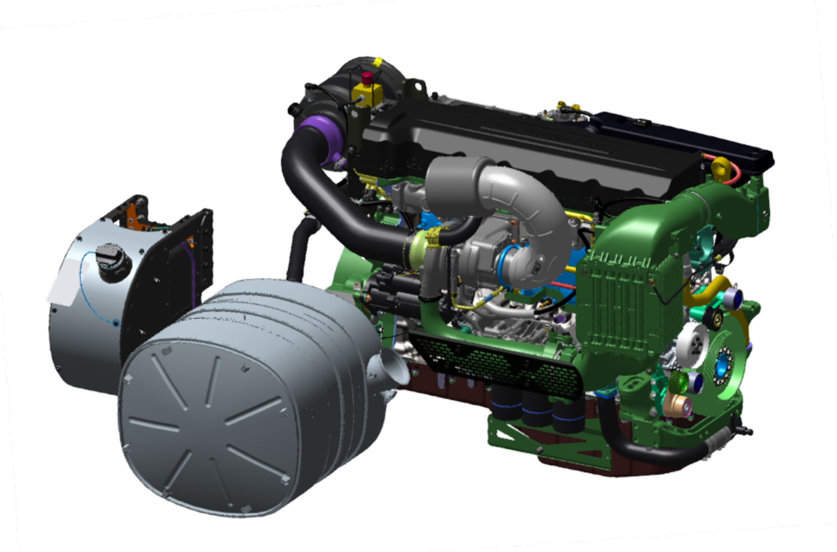

Figure 2-9 Engine together with urea tank and SCR muffler

2.4.1 Urea injection

Pure ammonia is toxic and troublesome to handle. Mobile SCR systems instead uses a water solution of Urea $CO(NH_2)_2$. Marine vessels typically use a solution with 40% Urea while on-road vehicles use a solution of 32.5% Urea.

Urea is injected in the exhaust pipe upstream of the SCR muffler and mixed with the hot exhaust gas. Due to the high temperature, the urea decomposes in two steps and forms ammonia (NH_3). Some of the ammonia is formed in the exhaust pipe and some at the catalyst surface.
Figure 2-10 shows the general layout for the SCR system.

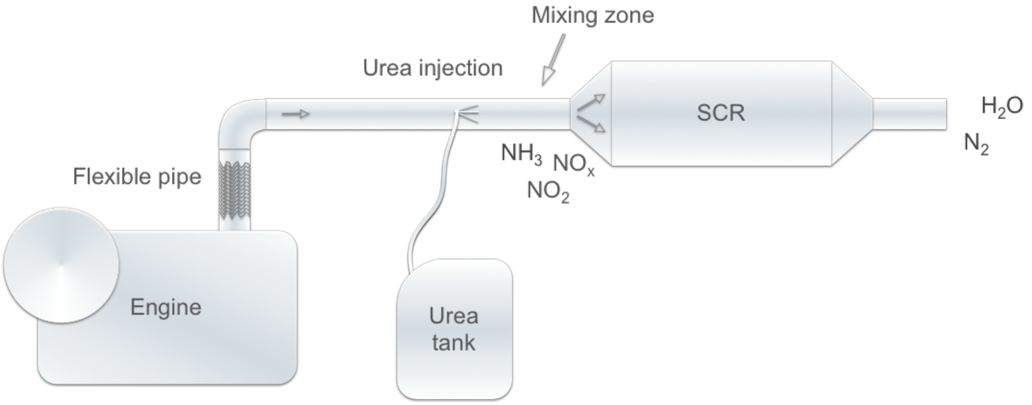

Figure 2-10 General layout of the SCR system

It is important that the right amount of urea is injected to ensure good NO_x conversion. Sensors on the exhaust pipe are continuously measuring NO_x level and temperatures for the exhaust flow. Based on that information the Urea control unit is calculating how much injection of urea is necessary. (DieselNet, 2015)

2.4.2 SCR muffler

The SCR unit features a ceramic monolithic substrate. Either the washcoat layer or the entire substrate consists of the catalytic material. Vanadium oxide is typical used as catalytic material for systems designed for use with diesel fuels containing sulfur.

When the SCR has a sufficient operational temperature, the chemical reactions occur at the surface of the catalyst. NO_x (NO and NO_2) reacts with ammonia (NH_3) and forms N_2 and H_2O.
Undesirable reactions may also occur that includes nonselective reactions with oxygen, which is abundant in the exhaust gas.

Depending on how much urea is injected in the system, not all of the resulting ammonia might be used for the reactions that convert NO_x. The unused ammonia will then follow the exhaust gas through the system resulting in “ammonia slip”. (DieselNet, 2015)

Figure 2-11 shows a typical design of catalytic converter.

Automotive EATS use an oxidation catalyst placed after the SCR to reduce the ammonia slip. However; an oxidation catalyst will be damaged by the sulfur components in marine diesel fuels and is therefore not used for marine applications.

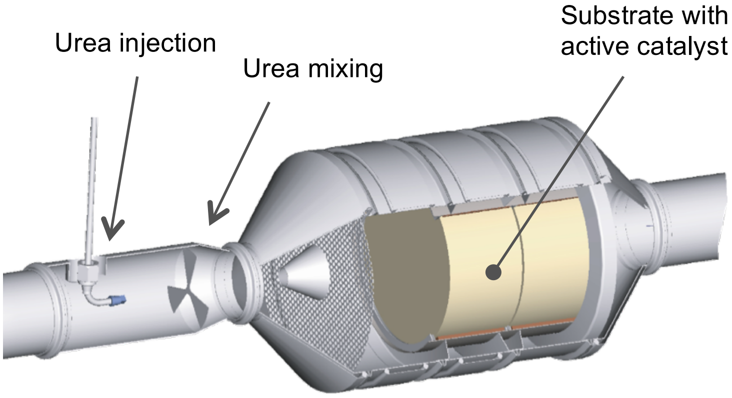

Figure 2-11 Cut-through of a catalytic converter. © Volvo Penta Image Library

The sulfur in marine fuels will result in an exhaust gas containing sulfur trioxides. At low exhaust temperatures, below 250°C, ammonium reacts with sulfur trioxides and forms ammonium sulfate. The formed compound is building up inside the SCR and covering the catalyst surface, preventing NO_x conversion to occur. The result is deactivation of the catalyst. (DieselNet, 2015)
To activate the catalyst again (regenerate), the temperature needs to be 350°C or above. (Andersson, 2013)
It is important to ensure good operating temperature for the SCR to minimize the risk of deactivation of the catalyst.

SCR systems can reduce NO_x emissions with more than 80%. The NO_x conversion depends on exhaust temperature and space velocity. Figure 2-13 shows NO_x conversion for an industrial SCR system at different temperatures and exhaust flows. It is clear that the exhaust gas need to be kept between 300-500°C in order to achieve the goal of a NO_x conversion rate above 80%.

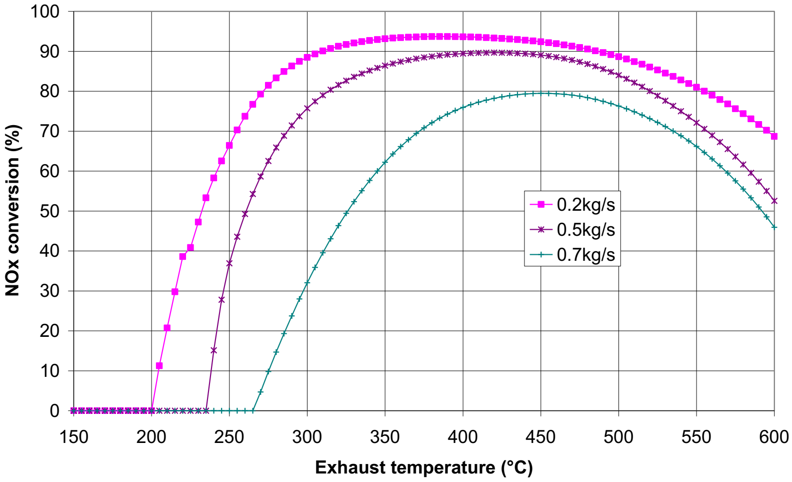

Figure 2-12 NO_x conversion at different flow rates and temperatures. © Volvo Penta

3 Basic theory of heat transfer

This section explains some of the basic theory of heat transfer through walls. The basics of heat exchanges are explained. A method for approximation of convection coefficients of fluids flowing in a pipe is described.

(Cengel & Turner, 2004) *is used as reference literature for the complete chapter.*

Heat is a form of energy that can transfer from one system to another as result of a difference in temperature. The energy transfers from the system with higher temperature to the system with lower temperature. When the systems temperature is equal, the energy transfer stops. Heat transfer is defined as the rate of energy transferred between systems.
There are three basic types of heat transfer; conduction, convection and radiation.

3.1 Conduction

Conduction is energy transfer in a solid, liquid or gas that occurs by interaction between particles in the substance.
The rate of heat conduction through a large plane wall is determined by Fourier's law of heat conduction as

$$\dot{Q}_{cond} = kA\frac{T_1-T_2}{\Delta x} = -kA\frac{dT}{dx} \quad [W] \qquad \text{(Eq. 3-1)}$$

where *k* is the thermal conductivity [W/mK] of the material, *A* is the area normal to the heat transfer direction, *dT* the temperature different and *dx* the thickness of the plane wall.
The negative sign means that heat transfer in positive x direction is positive.
The thermal conductivity coefficient of materials varies with temperature.

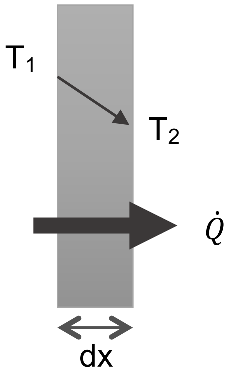

Figure 3-1 Heat transfer by conduction through a large plane wall

3.1.1 Steady and one-dimensional heat transfer

A steady state heat transfer means that the temperature does not vary with time. One dimensional heat transfer is when heat is transferred in only one direction. An example of a steady and one-dimensional heat transfer is through a plane wall with constant surface temperatures such as shown in figure 3-1.
The thermal conductivity of the wall is presumed to be constant for the temperature range.

For one-dimensional steady heat transfer, the rate of heat transfer into wall is equal to the rate of heat transfer out of it. That means $\dot{Q}$ through the wall is constant.

3.1.2 Heat conduction through a plane wall

Fourier's law of heat conductions describes the rate of heat transfer trough a plane wall. For steady one-dimensional heat transfer equation 3-1 is rearranged and expressed as

$$\int_{x=0}^{L} \dot{Q}_{cond,wall}\, dx = -\int_{T=T_1}^{T_2} kA\, dT \qquad \text{(Eq. 3-2)}$$

where L is the wall's thickness. Performing the integration and rearranging equation 3-2 gives the rate of heat conduction through the wall as

$$\dot{Q}_{cond,wall} = kA\frac{T_1-T_2}{L} \qquad \text{(Eq. 3-3)}$$

3.1.3 Heat conduction through cylindrical pipes

Heat transfer at steady and one-dimensional conditions trough a cylindrical pipe is defined by Fourier's law of heat conduction.

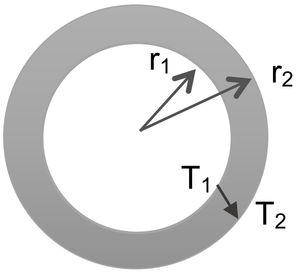

Figure 3-2 Heat transfer by conduction through a cylindrical pipe

Rearranging and integrating equation 3-1 with the pipe's boundaries (figure 3-2) gives

$$\int_{r=r_1}^{r_2} \frac{\dot{Q}_{cond,wall}}{A}\, dr = -\int_{T=T_1}^{T_2} k\, dT \qquad \text{(Eq. 3-4)}$$

where *A=2πrL* and is the pipe's surface area, *L* is the pipe's length.
Solving equation 3-4 gives the rate of heat transfer trough the pipe's wall.

$$\dot{Q}_{cond,cyl} = 2\pi Lk\frac{T_1-T_2}{\ln(r_2/r_1)} \qquad \text{(Eq. 3-5)}$$

3.2 Convection

Convection is heat transfer between a gas or liquid in motion and a nearby solid surface. The heat transfer is a combination of conduction and fluid motion. Convection can either be of forced or natural type. Forced convection is when a fluid is forced to flow over a surface by, for example, a fan or the wind. Natural convection is when the fluid's motion is driven by density changes due to temperature variations of a fluid.

The rate of convection heat transfer is given by Newton's law of cooling.

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \quad [W] \tag{Eq. 3-6}$$

where h is the convection heat transfer coefficient [W/m^{2}K], A_s is the solid's surface area, T_s is the solids surface temperature and T_∞ is the temperature of the fluid sufficiently far away from the solid's surface not to be influenced by its temperature.

3.3 Radiation

Energy emitted by matter in form of electromagnetic waves is called radiation. Energy transfer by radiation is not limited to the presence of an intervening medium. Radiation can be transferred in vacuum.

The rate of heat transfer by radiation from a surface, A_s , at an absolute temperature, T_s, in a room separated by a gas such as air and completely enclosed by a much larger area of temperature, T_{surr}, is given by

$$\dot{Q}_{rad} = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4) \quad [W] \tag{Eq. 3-7}$$

where ε is the surface's emissivity and σ is Stefan-Boltzmann constant.

Radiation heat transfer from a solid's surface to gas occurs parallel to convection if there is a bulk gas motion.

In these cases it is often convenient to combine the contribution of the radiation and convection heat transfer and define that as a combined heat transfer coefficient h_{com} [W/m^{2}K].

The total heat transfer from a solid's surface to the surroundings by convection and radiation can be expressed as

$$\dot{Q}_{com} = h_{com}A_s(T_s - T_\infty) \quad [W] \tag{Eq. 3-8}$$

Heat transfer by radiation is usually negligible with forced convection but should be considered with natural convection or conduction.

3.4 Thermal resistance

The concept of thermal resistance is often used with heat transfer calculations. The thermal resistance depends on geometry and thermal properties.

The rate of heat transfer trough a plane wall is determined by equation 3-3. With the thermal resistance defined as

$$R_{cond,wall} = \frac{L}{kA} \quad [°C/W] \tag{Eq. 3-9}$$

Equation 3-3 can be expressed as

$$\dot{Q}_{cond,wall} = \frac{T_1 - T_2}{R_{cond,wall}} \tag{Eq. 3-10}$$

In the same way, the thermal resistance for cylindrical pipes can be expressed as

$$R_{cond,cyl} = \frac{\ln(r_2/r_1)}{2\pi Lk} \qquad \text{(Eq. 3-11)}$$

Similarly, heat transfer by convection can be expressed with the thermal resistance concept based on equation 3-8 as

$$R_{conv} = \frac{1}{hA_s} \qquad \text{(Eq. 3-12)}$$

Equation 3-12 also applies when the combined heat transfer coefficient of convection and radiation are used.

Network of thermal resistance can be used for calculation of problems with heat transfer through multiple mediums with different heat conduction and convection coefficients.

Consider a plane wall with warmer air on one side than the other. (Figure 3-3) The heat transfer is driven by the temperature gradient through the wall. The heat transfer includes convection to the surrounding air from the surface of the wall on respective side.

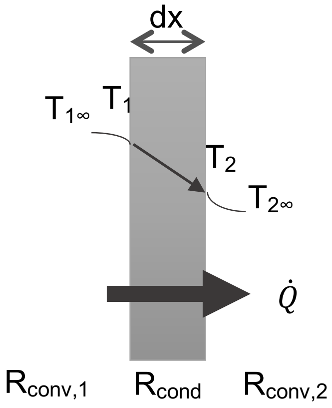

Figure 3-3 Heat transfer through multiple mediums

With the rate of heat transfer constant through the media, the total thermal resistance can be expressed as.

$$R_{total} = R_{conv,1} + R_{cond} + R_{conv,2} = \frac{1}{h_1 A_s} + \frac{L}{kA} + \frac{1}{h_2 A_s} \qquad \text{(Eq. 3-13)}$$

Since the rate of heat transfer is constant through the media, the overall rate of heat transfer can be expressed as

$$\dot{Q} = \frac{\Delta T}{R_{total}} = \frac{T_{1\infty} - T_{2\infty}}{R_{total}} = \frac{T_{1\infty} - T_1}{R_{conv,1}} = \frac{T_1 - T_2}{R_{cond}} = \frac{T_2 - T_{2\infty}}{R_{conv,2}} \qquad \text{(Eq. 3-14)}$$

3.5 Heat exchangers

Heat exchangers are devices that transfer heat between two media of different temperatures while keeping the mediums separated.
In a double walled heat exchanger the fluids are separated by a thin pipe wall. The heat exchange is driven by the temperature difference of the fluids. The rate of heat transfer is controlled by the fluids temperature difference and flow velocity.
Several assumptions are made to simplify the analysis of heat exchangers.
The mass flow rate is considered constant and a steady-flow state is assumed. The fluid properties are assumed to be constant through the temperature range. The heat exchanger is presumed to be fully insulated to the surroundings resulting in heat transfer only between the fluids.

The behavior of the fluids' temperatures in a double walled, parallel flow heat exchanger is shown in figure 3-4.

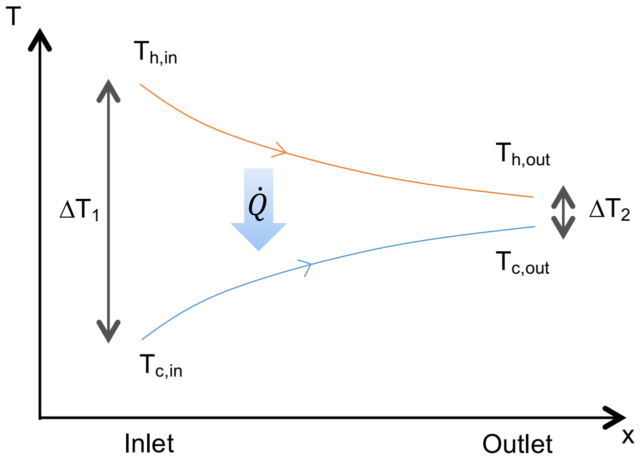

Figure 3-4 Temperature behavior of the two fluids in a heat exchanger

The first law of thermodynamics requires the rate of heat transfer from the hot and the cold fluid to be equal. The rate of heat transfer for each fluid in the heat exchanger is expressed as

$$\dot{Q} = \dot{m} C_p \Delta T \tag{Eq. 3-15}$$

where $\dot{m}$ is the fluids mass flow rate, C_p the specific heat coefficient and ΔT the temperature different of the fluid at the inlet and outlet.

3.5.1 Logarithmic mean temperature difference

The rate of heat transfer at a specific location depends on the size of the temperature difference between the fluids at that location. For analysis of heat exchangers it is suitable to use an equivalent mean temperature difference that can be applied for the entire heat exchanger. A method for determine the mean temperature difference is the Logarithmic Mean Temperature Difference (LMTD).
It is defined as

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \qquad \text{(Eq. 3-16)}$$

Where ΔT_1 and ΔT_2 are defined as the temperature difference between the two fluids at the inlet and outlet of the heat exchanger. (Figure 3-4)

The rate of heat transfer for the entire heat exchanger with the use of LMTD is expressed as

$$\dot{Q} = \frac{\Delta T_{lm}}{R_{total}} \qquad \text{(Eq. 3-17)}$$

where R_{total} is the thermal resistance through the pipe's wall.

3.6 Estimation of heat convection coefficient

The Nusselt number is a dimensionless convection heat transfer coefficient and is defined as

$$Nu = \frac{hD_h}{k} \qquad \text{(Eq. 3-18)}$$

where D_h is the hydraulic diameter. For cylindrical pipes the hydraulic diameter is equal to the pipes diameter.

For fully developed turbulent flow in smooth cylindrical pipes the Nusselt number can be estimated by the Colburn equation which is a fairly simple estimation which may give an error of up to 25%. The Colburn equation is defined as

$$Nu = 0.023 Re^{0.8} Pr^{1/3} \qquad \begin{pmatrix} 0.7 \le Pr \le 160 \\ Re > 4000 \end{pmatrix} \qquad \text{(Eq. 3-19)}$$

Re is Reynold's number which is a dimensionless number correlating with the viscous behavior of a Newtonian fluid. It is defined as the ration between the inertial forces and the viscous forces in the fluid. The Reynolds number can be used to determine if a flow is laminar of turbulent.

$$Re = \frac{\rho V_m D_h}{\mu} = \frac{V_m D_h}{\nu} \qquad \text{(Eq. 3-20)}$$

where ρ is the density, μ is the dynamic viscosity, ν is the Kinematic viscosity, D_h the hydraulic diameter and V_m the mean flow velocity defined as

$$V_m = \frac{\dot{m}}{\rho A_c} \qquad \text{(Eq. 3-21)}$$

where A_c is the cross-sectional area of the pipe's opening.

Pr is the Prandtl number, a dimensionless number that is formulated as the ratio between molecular diffusivity of momentum and molecular diffusivity of heat.
The Prandtl number is defined as

$$Pr = \frac{\mu C_p}{k} \qquad \text{(Eq. 3-22)}$$

The heat convection factor can be estimated if the fluid properties, mass flow rate and pipe geometry are known.
Combining equation 3-18 and 3-19 and solving for *h* gives the convection coefficient as

$$h = \frac{0.023 k Re^{0.8} Pr^{1/3}}{D_h} \qquad \text{(Eq. 3-23)}$$

4 Method

In this section the general work process for the project and the method to reach an insulation solution for the EATS will be explained and motivated.

The project can be divided in to several steps illustrated by the figure 4-1.

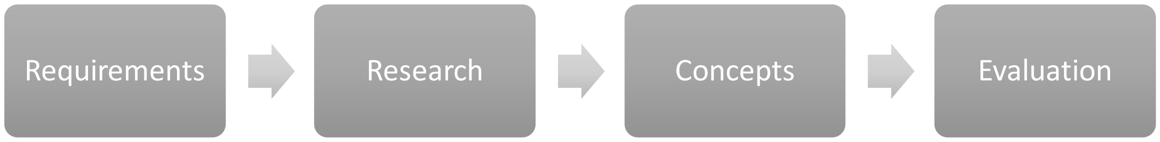

Figure 4-1 The project's substeps

Requirements
Applicable regulations for marine exhaust and EATS will be examined.
Requirements and opinions regarding engine installations with EATS will be collected from some of Volvo Penta's customers.
Surface temperatures of EATS at the current state without any insulation will be determined.

Research
Research of insulations methods and materials are then performed to create an understanding of what alternatives are possible.

Concept development
Concepts for insulation of SCR system are generated. Basic heat conduction calculations are performed as part of the development process of the concepts.

Evaluation
The concepts are compared to each other, analyzed and the best concept is selected. The selection process is systematically conducted with project development method such as Pugh's concept selection.

4.1 Requirements

The first step is to identify the relevant legislations and study their requirements.
A starting point for this was to use Volvo Penta's department of Law and Regulations to get some guidance on where to start the investigation.
Information regarding design and requirements of the EATS was also collected from people with knowledge at Volvo Penta and during interviews with customers.
Furthermore, field trips were done for studying existing installations of Volvo Penta's engines, including some with third party SCR systems. Additional opinions regarding the engine installation was collected from customers during the field trips.

4.1.1 Laws and regulations

All engines used in ships must meet certain safety regulations. The regulations is compiled and monitored by several authorities and organizations.

Government authorities in most countries with shipping have authorized classifications societies to control and monitor that laws and regulations are met. The 12 main classification societies are members of International Association of Classification Societies (IACS), which is an organization for maritime safety and regulations.

The classifications societies most important to Volvo Penta are:

- American Bureau of Shipping (ABS)
- Bureau Veritas (BV)
- China Classification Society (CCS)
- Det Norske Veritas (DNV)
- Germanischer Lloyd (GL)
- Korean Register of Shipping (KRS)
- Lloyd's Register of Shipping (LRS)
- Nippon Kaiji Kyokai (NKK)
- Polski Rejestr Statkow (PRS)
- Registro Italiano Navale (RINA)
- Russian Maritime Register of Shipping (RMRS)

Other important authorities and regulations are the Swedish Transport Agency, SOLAS (Safety of life at sea) and the Machinery Directive.

4.1.1.1 Classification societies

The Department of Laws and Regulations at Volvo Penta has written a guideline based on the classification societies rules that summarize the regulations that are relevant for its engines and components. The guideline is meant to help engineers to keep track of current regulations that need to be met.

Regulations that apply to the exhaust pipe and EATS are:

- Where the temperature on external surfaces in the intake- and exhaust systems are exceeding 220°C the systems shall be well insulated.
- Insulation shall be made of non-combustible material with non oil-absorbing surface
- If not fixed insulation material is used the insulation material should be covered by sheets of metallic material or equivalent. This requirement is applicable also for connections, flanged joints and elastic compensators. The exhaust system ought to be water-cooled (water-jacketed).
- Exhaust pipes from several engines are not to be connected, but are to have separate outlets, unless precautions are taken to prevent the return of exhaust gases to a stopped engine.
- Exhaust pipe compensators are to be of an approved type. Some societies, i.e BV, require Type Approved compensators.
- The materials used in exhaust gas cleaning components and systems shall be made of materials with a melting point above 925°C.

(Volvo Penta, 2015)

The complete set of rules can be found at DNV's webpage. (DNV, 2015)

4.1.1.2 SOLAS

The following is said about protection of high temperature surfaces:

- Surfaces with temperatures above 220°C which may be impinged as a result of a fuel system failure shall be properly insulated.
- Precautions shall be taken to prevent any oil that may escape under pressure from any pump, filter or heater from coming into contact with heated surfaces.

(SOLAS, 2005)

4.1.1.3 The Machinery Directive

The Machinery Directive specifies the essential health and safety requirements applying to all machinery released within the EU.

The following is said about machinery with high surface temperatures:

- Measures shall be taken to eliminate any risk of injury caused by contact or within a close proximity to machinery parts or materials at high or very low temperature.

(Arbetsmiljöverket, 2014)

4.1.1.4 Swedish Transportation Agency

In addition to the rules from the classification societies stated before, the agency have additional regulations and guidelines that applies machinery and electrical installations at a national level. The regulation includes requirements from surface temperatures of marine exhaust systems.

- Exhaust pipes with surface temperatures exceeding 60°C shall be insulated or provided with protection against contact with exposed parts.

- The exhaust pipe shall be arranged to prevent surrounding materials to exceed temperatures of 60°C.

(Swedish Transportation Agency, 2014)

4.1.2 Feedback from customers

It is important for Volvo Penta to get feedback on new engine technology from its customers. Especially when the new equipment will occupy additional space in the engine compartment compared to the present technology.

Feedback from some customers of Volvo Penta engines is summarized below.

4.1.2.1 Swedish Sea Rescue Society (SSRS)

Their main concern was how much additional space the system occupies. The space in the engine compartment is very limited, especially with smaller boats. It is critical to design a SCR system that to takes up as little space as possible.
They had no additional surface temperature requirements beyond those required by SOLAS and DNV.
They use boats with composite hull and wet exhaust system. That requires the exhaust pipe connected to the hull not to exceed an operational temperature of 70-90°C. (Pettersson P.-E. , 2015)

4.1.2.2 Styrsöbolaget

Their main concern was the reliability of the system. It’s critical to have operational engines even if the SCR system would fail.
Their ships are applicable to Swedish Transport Agency’s rules. That means all exposed surfaces on the system with a temperature exceeding 60°C must be insulated. (Pettersson R. , 2015)

4.1.3 Engine installations

Volvo Penta does not have control over how customers install their engine. Installations will be different depending on the ship and its engine compartment design.
The main concern for positioning of the SCR system is to keep the length of the exhaust pipe to a minimum in order to reduce heat loss.

Otherwise the SCR muffler can be positioned relatively free in the engine compartment. The rotation of the SCR muffler is somewhat restricted. The Urea injection system will have to be positioned with the injection direction angled from above.

Exhaust systems can be of either dry or wet design.
The exhaust pipe in a dry system will get very hot. Even if the piping is well insulated, the installation may result in heat issues.

With a wet exhaust system design, it is important to ensure water can’t get through the system the wrong way. It is therefore preferable to place the SCR muffler at a high position above the engine. Thus the exhaust system will act as a water trap.

A part of the exhaust pipe will have to be flexible in order not to transfer motions and vibrations from the engine to the fixed installed SCR system.

Boats with IPS drive typically have a relative short exhaust pipe from the engine to the drive. The space allowed for installation of a SCR system in boats with IPS drive is often even more limiting than those with regular wet exhausts.

The surface temperature of the SCR muffler should not affect or be affected by other hot engine components. The engine’s warm components are insulated including the turbo charging system and the exhaust manifold (water-cooled).

It may be of interest to investigate how much heat the SCR muffler emits and if heat shields could be beneficial to use as a complement to regular insulation methods.

It is desirable for the insulation to be easy to dismount and remount in case of service of the SCR system.

Volvo Penta has developed concepts of how the SCR system could be positioned in the engine compartment. Depending on ship design, installations will differ between the concepts. Two of the installation concepts are shown in figure 4-2. Note the SCR system's size relative to the engine. The concepts are missing some of the pipes connecting the engine with the EATS.

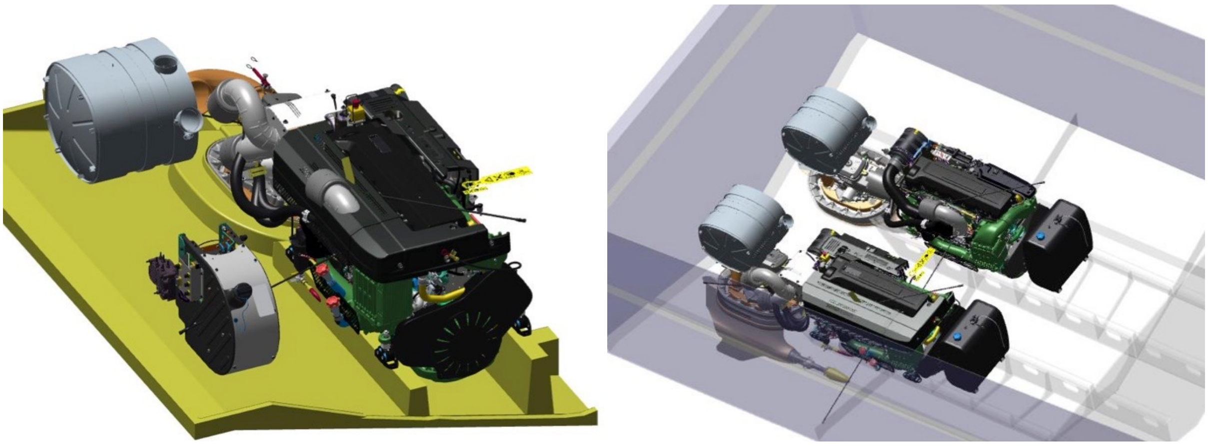

Figure 4-2 Example of two early installation concepts of EATS

4.1.4 Surface temperatures of the SCR muffler

A similar SCR system is in use for Volvo Penta's industrial applications. A test of the surface temperatures of the SCR muffler have been done as part of the development process for industrial engines. The test was performed with a 405 kW D13 engine for Tier4f (An emission standard for industrial application by US Environmental Protection Agency).

The result of the test is summarized below.

Marine engines are generally more powerful than their industrial counterpart. This means the marine SCR system may operate with slightly higher exhaust flows and temperatures than shown in the test.

Figure 4-3 shows a typical design for a SCR muffler. The SCR was initially designed for industrial applications but is used as reference design for the SCR muffler in this study.

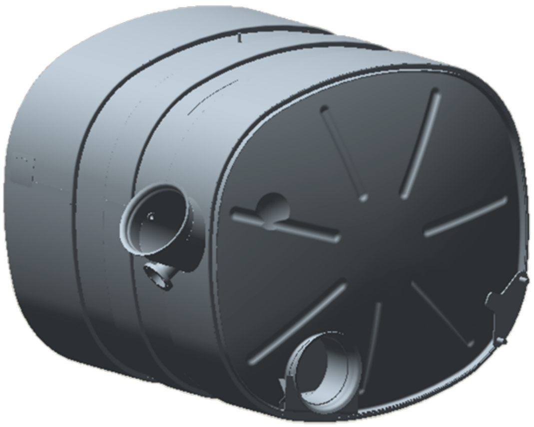

Figure 4-3 SCR muffler

The SCR system needs a temperature of at least 220°C in order to function properly. The maximum exhaust gas temperature at the SCR muffler inlet is restricted to 550°C for both continuous operation and peak value.

The SCR muffler has integrated thermal insulations that cover some areas of the muffler, see table 4-1.

Table 4-1 The location and thickness of the SCR mufflers integrated insulation

Position	**Thickness of heat insulation [mm]**
Mantle area	10
End caps	20
End caps (outer ring)	0
Mounting strap areas	0

Surface temperatures were measured with an IR camera at two operation points of the engine.

Load point 1 (1900 rpm, maximum power)

- Generates high temperature and high exhaust gas flow.
- Exhaust temperature around 520°C and exhaust flow of 0.58 kg/s.

Load point 2 (900 rpm and full load)

- Generates high temperature and low exhaust gas flow.
- Exhaust temperature around 500°C and exhaust flow of 0.2 kg/s.

Thermal images are only shown for Load point 1. The thermal distribution for Load point 2 is the same as in the thermal images shown for Load point 1, only the temperature values differ. Temperature data for both load points are presented.

4.1.4.1 End caps

The highest temperature measured for the end caps was, for both sides, on the outer non insulated ring.

Load point 1
The inlet side had an average surface temperature of 100°C (area excluding outer ring) and a temperature of 240°C on the outer ring.

Load point 2
The inlet side had an average surface temperature of 110°C (area excluding outer ring) and a temperature of 220°C on the outer ring.

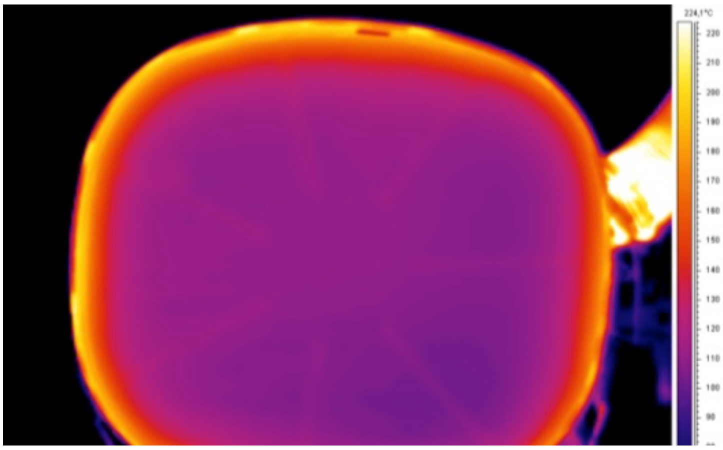

Figure 4-4 Thermal image of end cap at the inlet side for Load point 1

Load point 1
The outlet side had an average surface temperature of 150°C (area excluding outer ring) and a temperature of 270°C on the outer ring.

Load point 2
The outlet side had an average surface temperature of 145°C (area excluding outer ring) and a temperature of 245°C on the outer ring.

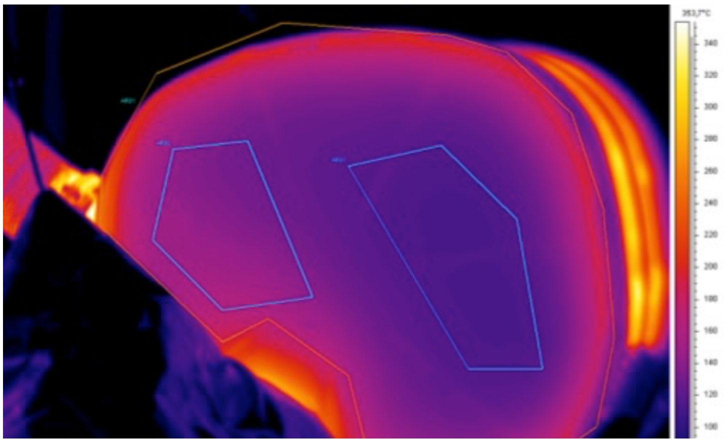

Figure 4-5 Thermal image of end cap at the outlet side for Load point 1

4.1.4.2 Mantle area

The measurements on the mantle area were divided in five sub areas. Area #2 and #4 are where the mounting straps usually are located, and thus not insulated.

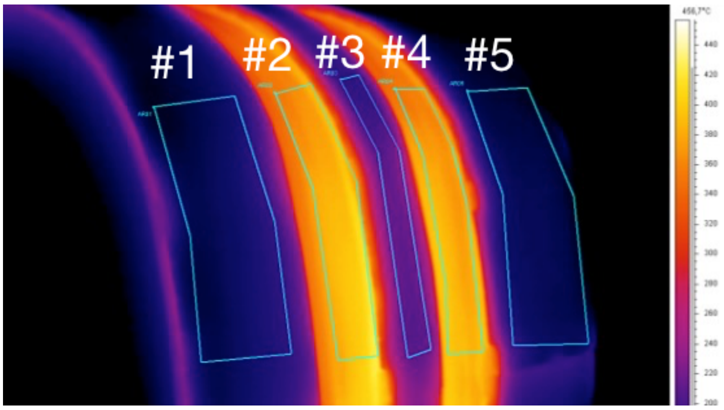

Figure 4-6 Thermal image of mantle area for Load point 1

The average temperatures from each area are presented in table 4-2.

Table 4-2 Surface temperature at the mantle area of the SCR

Load point	Area #1	Area #2	Area #3	Area #4	Area #5
1	180°C	440°C	230°C	430°C	180°C
2	170°C	390°C	212°C	380°C	160°C

The maximum measured surface temperatures for the different load points and areas are presented in table 4-3

Note that the values presented above were average surface temperatures.

Table 4-3 The SCR mufflers maximum surface temperatures

Position	Maximum surface temperature [°C]	
	Load point 1	Load point 2
Mantle area	265	230
End caps	180	140
End caps (outer ring)	270	250
Mounting strap areas	470	420

4.1.5 Test data from a marine development engine

The previous test did not include any measurements of surface temperatures for the exhaust pipe. It did measure the exhaust gas temperature before the SCR muffler. These are not sufficient as it is of interest to investigate temperature difference of the exhaust gas between the engine and SCR muffler.
Additional exhaust temperature data were therefore collected.

A marine D13-600 with a development SCR system was tested in a test cell at Volvo Penta. The engine was running a test simulating load typical from propulsion usage. (E3 standard test cycle)

Data was obtained from the test at four engine load points and is shown in the table 4-4.

Table 4-4 Exhaust gas temperature at different load points during an E3 propeller curve

Speed [rpm]	1900	1729	1520	1197
Torque [Nm]	2235	1841	1397	889
Temp after turbine [°C]	498	374	348	351
Pressure after turbine [kPa]	22.9	16.3	7.8	1.9
Exhaust flow [kg/s]	0.581	0.536	0.378	0.202

4.1.6 Product requirements

The SCR systems insulation solution must meet existing requirements and restrictions. In order to design a good insulation system the requirements importance must be evaluated.

A product requirement matrix is constructed where the relevant requirements, type of restriction and its importance factor are presented (Table 4-5). The range goes from 1 for most important to 3 for less important.

Note that the laws have to be met and are therefore categorized as most important.

A summary of general requirements for the EATS follows after the table.

Table 4-5 Product requirement

Type	**Requirement**	**Importance**
International law	Exposed surface temperature not to exceed **220°C**	2
International law	Non-combustible with non oil-absorbing surface for insulation material	1
International law	Non fixed insulation materials should be covered by sheets of metallic material or equivalent	1
International law	Minimize risk of injury by contact with hot components	1
International law	Materials shall be made of materials with a melting point above 925°C	1
National law	Exposed surfaces exceeding **60°C** shall be insulated or be provided with contact protection	1
National law	Surrounding materials not to exceed **60°C**	1
Design	Easy installation/removal of the insulation for serviceability	2
Design	Retaining exhaust gas temperature up to the SCR muffler	2
Customer	The insulation should take up minimum space	3

General requirements for installation of EATS

- A part of the exhaust pipe before the SCR system should be flexible
- The SCR system should be placed high to ensure that no water enters the system the wrong way when used with wet exhaust
- It is desirable to minimize the piping length between the turbo and SCR muffler to reduce heat losses
- The desired temperature range at the catalyst is 300-500°C

4.2 Research

The research was mainly performed by studying existing insulation solutions for exhaust systems and other engine parts.

4.2.1 EATS installed in boats

Current EATS and insulation used in boats were studied.

4.2.1.1 Styrsöbolaget’s ferries Ärlan and Göta II

A field trip to two of Styrsöbolaget’s ferries was made. The boats are of type car/cargo ferry and are named Ärlan and Göta II. They both features EATS with SCR catalyst developed by the company STT Emtec.

The insulation methods used for the exhaust system differ slightly between the boats. Both ferries have an exhaust system of dry type.
The insulation is believed to have been installed by the boat builders. The manufacture of the insulation is unknown at present.
The insulations solutions are designed to meet the Swedish Transport Agency’s regulated surface temperature of 60°C.

Ärlan

Ärlan has twin Volvo Penta D13-500 engines with SCR systems for propulsion. It uses a blanket-type of insulation solution for the complete EATS and exhaust system. See figure 4-7.

Figure 4-7 Insulation of exhaust system in cargo ferry Ärlan

Göta II

Göta II has a Caterpillar 3508C engine for propulsion delivering 634 kW. The engine was fitted with a EATS with SCR catalyst and particulate filter. (Styrsöbolaget, 2015)

It is using a similar insulation method based on blankets. In addition to blankets it uses aluminum covers where possible. The covers help holding the insulation together and make it easier to keep the engine compartment clean. It also reduces the heat transfer by radiation. The insulation solution is shown in figure 4-8.

Figure 4-8 Insulation of exhaust system in cargo ferry Göta II

4.2.1.2 M/S Sandhamn

The M/S Sandhamn is a passenger ferry operating at Waxholm, Stockholm. It has quadruple installation of Volvo Penta’s D12 MH450 engines. Two of the ferry’s engines are used for field testing of EATS developed by STT Emtec in collaboration with Volvo Penta as engine supplier.

The insulation of the Sandhamn’s dry exhaust system appears to be similar to that used in Göta II. The system is covered by sheets of steel. Some parts use blankets for insulation under the steel covers. Other parts of the system appear to use insulation fiber held together by a steel-net and covered by the steel sheets. Photos of the insulation used in M/S Sandhamn are shown in figure 4-9.

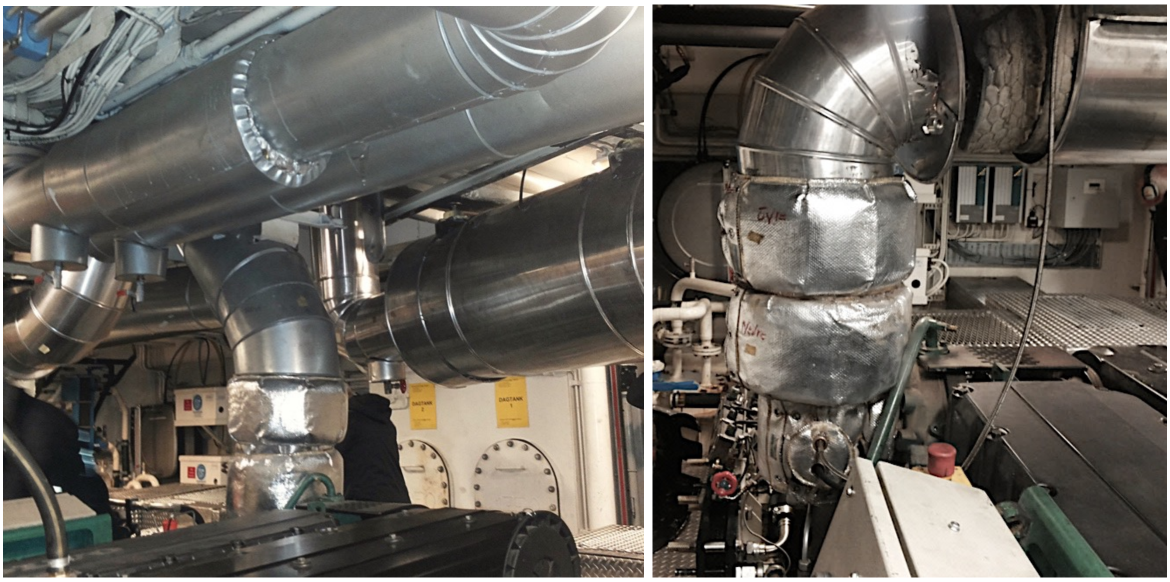

Figure 4-9 Insulation of exhaust system in passenger ferry M/S Sandhamn

4.2.2 STT Emtec

STT Emtec is a Sundsvall based company that develops and sells emission control and performance optimization systems. They have worked closely with Volvo Penta for developing an EATS for diesel engines. Several of STT Emtec's SCR systems are successfully used together with Penta's marine engines.

Insulation of the EATS is done by the boat builder. STT Emtec includes guidance for insulation of the system in the installation instructions. Their recommendations regarding insulation will be summarized below.

The exhaust pipe between the engine and SCR catalyst, the SCR mixer pipe and the SCR muffler must be insulated. The insulation is necessary to retain required operating temperature of EATS at low load conditions and cold ambient temperatures. The surface temperature for the pipes and SCR mixer should be at a level were condensation is avoided. A typical insulation of the system has a minimum of 50 mm thickness.

It is not clear what type of insulation the 50 mm minimum thickness recommendation is based on. The EATS installations seen in Styrsöbolaget's ferries use insulation of blanket type. It is likely that the recommendation applies to a similar type of insulation method.

4.2.3 Insulation methods used for other engine parts

The insulation solutions for other hot components on Volvo Penta's engines were examined.

4.2.3.1 Exhaust bends/risers

Different risers are used for different engine ranges and configurations. Figure 4-10 shows the exhaust bend used with D13 engines, among others. The exhaust bend features an insulation shield installed tightly to the pipe. The shield requires to be fitted to the part at the insulation manufacturing and is therefore not suitable for use with pipes that varies in length due to boat design.

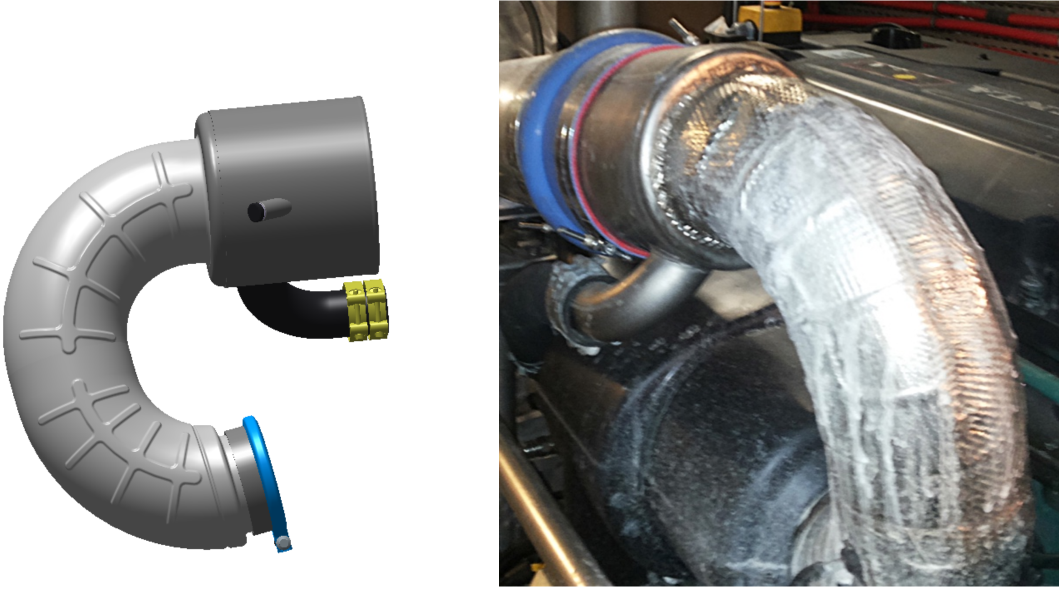

Figure 4-10 Insulated exhaust bend

Figure 4-11 shows a riser used with one of the smaller engine sizes. The riser is insulated by a layer of insulation fibers covered by a hard heat shield. The insulation to the pipe is fitted by the supplier. The insulation method is an effective solution for mass-produced parts of a predetermined geometry.

Figure 4-11 A different insulation method for a riser pipe

Another insulation method for the riser is insulation fabrics very similar to the blankets solution seen in Styrsöbolagte’s ferries. The difference being the fabrics for the riser being custom made for its geometry. Figure 4-12 shows the insulation solution for the riser in SSRS’s rescue boat Ilse Sanne.

Figure 4-12 Fabric/blanket insulation of a Riser

4.2.3.2 Turbochargers

There are several different turbocharger insulation methods in use with Volvo Penta's engines.

One of the methods is shown in figure 4-13. It features an insulation fabric for the turbine housing protected by a black painted steel cover. The cover is mainly used for keeping the insulation fabric in place and to protect the engine components. The cover also reduces some heat losses due to radiation.

Figure 4-13 Turbocharger insulation by insulation fabric protected by a metallic cover

Another similar insulation method is also in use. The insulation fabric is attached to a fiber reinforced plastic cover. (Not pictured) The fabric is reinforced with a thin steel-weave in places where contact with the turbocharger housing occurs. The weave increases the insulation fabric's resistance to wear.

Figure 4-14 shows yet another insulation solution for the turbocharger. An insulation shield is tightly fitted to the turbine housing. A large steel cover that includes some fiber insulation is covering the turbocharger.

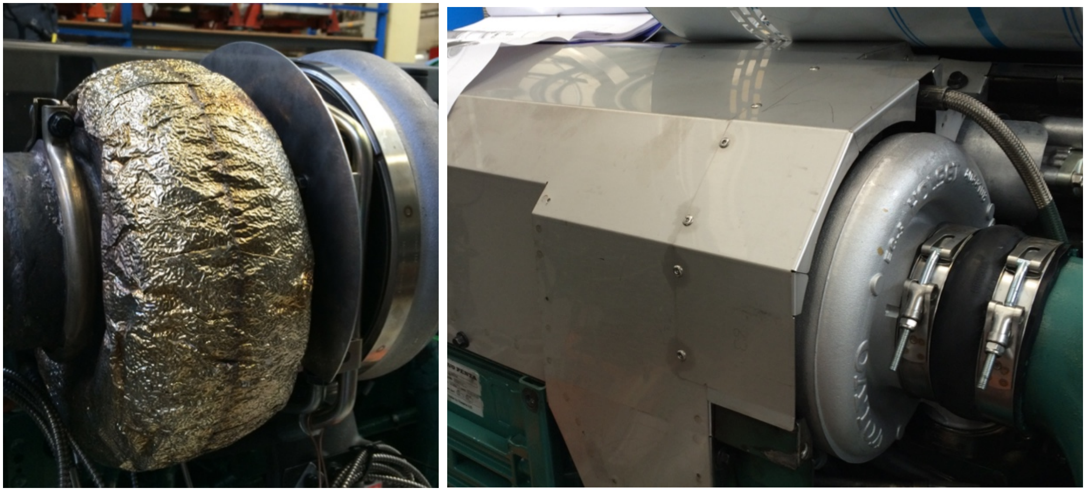

Figure 4-14 Turbocharger with insulation shield and steel cover featuring insulation fibers

4.2.4 Insulation solution for other applications

Insulation solutions for other application currently in use at Volvo Penta were studied. It is of interest to determine if some of those solutions can be of interest for insulations of the SCR system. It is also of interest to learn what suppliers of insulation solutions are used.

4.2.4.1 Test cell insulation at Volvo Penta's workshop

Insulation blanket are used for various needs at Volvo Penta's workshop. They are typical used for temporary insulation needs at engine testing in Penta's test cells. They are available in different sizes and shapes.
The blankets are silica (silicon dioxide) based with aluminum reinforced soft cover. It is padded with 25 mm thick "Superwool 607", a silica based fiber.
The blankets are supplied by "KWA Isolerteknik AB".
The blankets used in the test cells have a raw density of 170 kg/m^3.
Thermal conductivity data supplied of the manufacture are available for the raw densities of 130 and 220 kg/m^3 at different temperatures. See table 4-6.

Table 4-6 Thermal conductivity of the insulation blanket

Temperature [°C]		200	400	600	800	1000
Raw density 130 [kg/m^3]	k [W/mK]	0.0534	0.0898	0.1435	0.2202	0.3250
Raw density 220 [kg/m^3]		0.0519	0.0796	0.1172	0.1682	0.2357

The blanket's sides are joined together with stainless steel staples. The blanket is equipped with hooks for easy installation with the use of wires. No special tools are needed for installation or removal of the insulation blankets. Figure 4-15 shows one sizes available for the blankets.

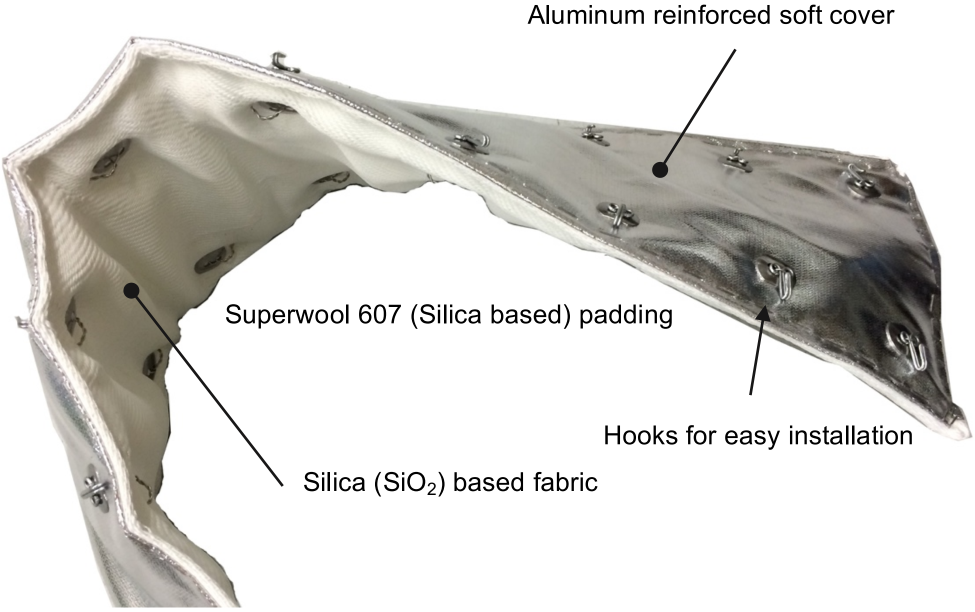

Figure 4-15 Insulation blanket used for temporary insulation needs at Volvo Penta's workshop

4.2.4.2 Industrial pipe insulation

Calcium Silica simulation is usually used as high temperature insulation for pipes and other equipment in industrial facilities. The material is rigid and can withstand a continuous temperature up to 650°C. It comes pre-formed for pipes or as blocks. For pipe it consists of two halves that are applied to the pipe, figure 4-16. The material has a high compressive strength and a high structural integrity even at high temperatures. The material is non-combustible.
The insulation needs a protective jacketing that covers the material against water and other fluids. A sheet of aluminum or steel is typically used for protection and to lower the heat transfer by radiation.
The insulation capacity of the material is slightly poorer than for the "Test cell blankets" previously described. (Industrial Insulation Group, 2008)

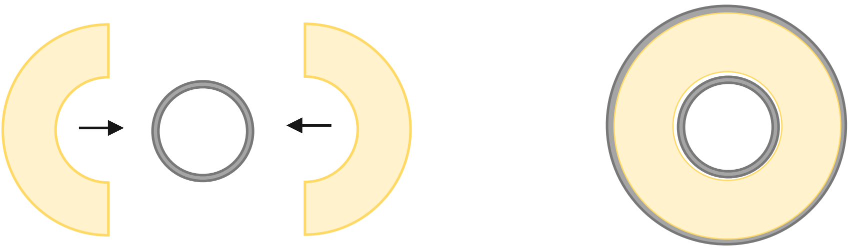

Figure 4-16 The insulation comes in halves that is applied to the pipe and protective by a cover

4.3 Concepts

An insulation solution for the exhaust system including the exhaust pipe up to the SCR and the SCR muffler were to be developed.
Based on the research, several insulation concepts were generated.

To be able to do some basic calculation of insulation thickness and exhaust gas temperatures, the exhaust system's geometry was slightly simplified.
The exhaust pipe up to the SCR muffler was treated as a straight steel pipe. The SCR muffler was approximated as a cylinder with flat circular end caps. The dimensions of the simplified exhaust system are shown in figure 4-17.

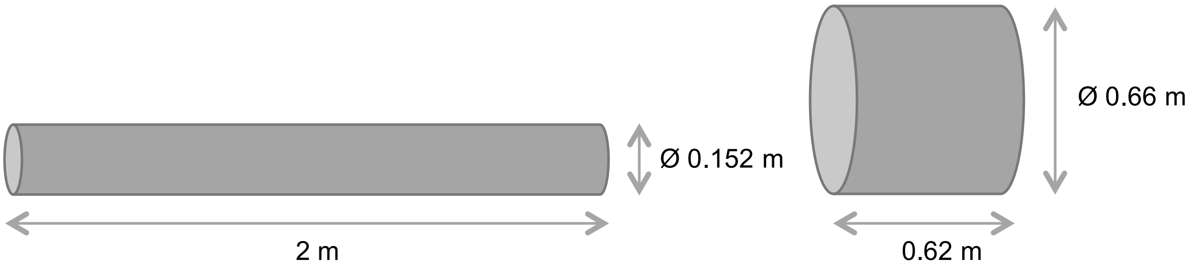

Figure 4-17 The geometry of the simplified exhaust system

Surface temperatures

Data for surface temperatures comes from tests with different engines and load points. The best approach is therefore to evaluate the exhaust pipe and SCR muffler separately.

Surface temperatures of the SCR muffler are available for two engine load points. The surface temperatures of the SCR muffler are summarized in table 4-7.

Table 4-7 Surface temperatures of the SCR muffler

Load point	Engine speed [rpm]	Exhaust flow [kg/s]	Exhaust gas temp [°C]	Surface temp [°C]	
				End caps	Mantle area
1	1900	0.58	520	270	470
2	900	0.20	500	250	420

The temperature range of the exhaust pipe's surface is unknown but can be approximated from the data of the exhaust gas temperature measured at the turbine outlet.

The engine is assumed to be running for a sufficiently long time to ensure that the surface temperature of the exhaust pipe is steady.
It is assumed that the surface temperature is about the same as the exhaust temperature.
Table 4-8 shows the approximated surface temperature of the exhaust pipe based on data from table 4-4.

Table 4-8 Approximated surface temperatures of the exhaust pipe

Load point	Engine speed [rpm]	Exhaust flow [kg/s]	Estimated surface temp [°C]
1	1900	0.58	500
2	1197	0.20	350

4.3.1 Concept A – Blankets

Concept A is very similar to the insulation solution used in cargo ferry Ärlan. (Chapter 4.2.1.1) It uses blankets that are wrapped around the exhaust pipe and SCR muffler. The blankets have an aluminum reinforced fabric facing the surroundings.
The blankets can be custom made in different size to fit the insulation need for a specific engine installation. The method is suitable for exhaust systems that have sensors and other equipment connected to it or when service access to the system is needed, as the method makes the insulation easy to modify.
The insulation is installed by using a similar method as the “test cell blankets” used at Volvo Penta’s workshop. This ensures easy fastening and removing of the insulation, with no special tools needed. It is possible to dismount parts of the insulation for service access or installation of additional equipment to the exhaust system.

4.3.1.1 Insulation thickness

Calculation of required insulation thickness for the concept is done based on material data from the insulation blanket used at Volvo Penta’s test cells.

The thermal conductivity data of the insulation blankets consists of data for raw densities of 130 and 220 kg/m^3 at selected temperatures. (Table 4-6)
Data for the raw density (170 kg/m^3) used at Penta’s test cells was interpolated from the original data. Further, data for the temperatures of interests were interpolated from the original available temperatures. The data used for calculation is presented in table 4-9.

Table 4-9 Thermal conductivity coefficient, *k,* at raw density 170 kg/m^3

Temperature [°C]	250	270	350	420	470	500
Thermal conductivity, *k* [W/mK]	0.0609	0.0641	0.077	0.0899	0.1016	0.1085

The calculations performed were based on surface temperatures at two different engine load points. The surface temperatures used for calculation are summarized in table 4-10.

Table 4-10 Surface temperatures of the exhaust system used for calculation

Surface	Load point 1	Load point 2
SCR mantle area	470°C	420°C
SCR end caps	270°C	250°C
Exhaust pipe mantle area	500°C	350°C

Exhaust pipe

Figure 4-18 shows the geometry of the insulated exhaust pipe. The type of heat transfer, temperature and material heat transfer coefficients for each layer are also shown.

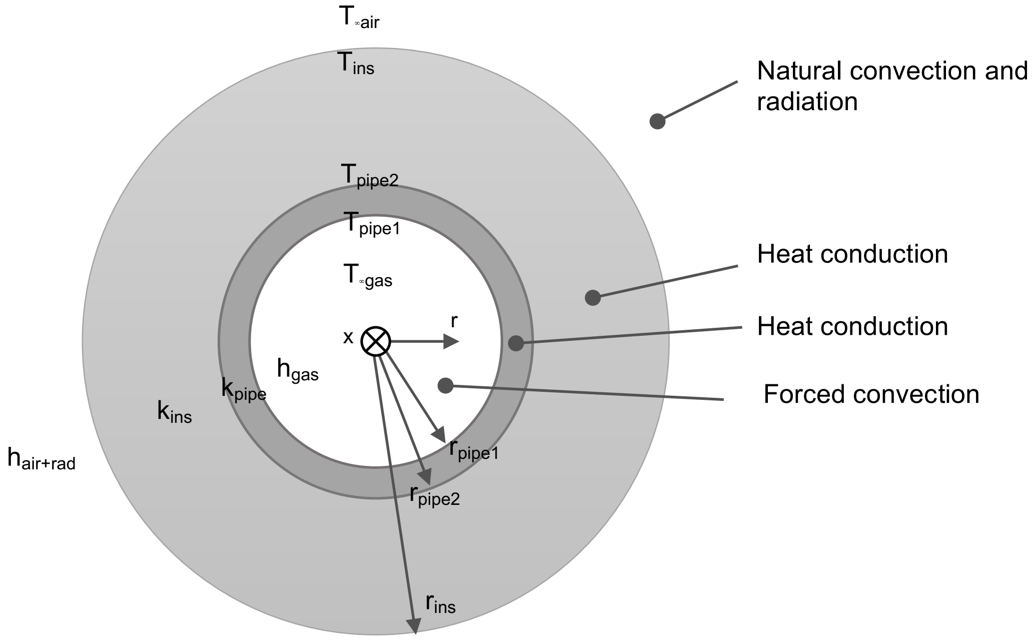

Figure 4-18 Cross-section of the exhaust pipe

The analysis of the insulated pipe was simplified. With only the exhaust gas temperature known, it was assumed that the pipe's wall had the same temperature as the exhaust gas. The thermal resistance of the pipe is much smaller than the thermal resistance of the insulation layer. The heat conduction through the pipe wall is therefore negligible.

The surrounding air in the engine compartment is assumed be constant at 25°C and of natural convection type.

The rate of thermal radiation in the engine compartment is not known, but the same rule of maximum 60°C for exposed surface temperatures applies to the rest of the equipment in the engine compartment. Therefore, it is assumed that no large sources of radiation are present. In addition to other radiation sources, the rate of radiation depends on different factors such as surface size, material, surface temperature and the surrounding temperature of the engine compartment. The large number of unknown factors makes the radiation contribution to the heat transfer hard to estimate. For the convenience of this analysis, the heat transfer by convection and radiation are merged to a combined coefficient. With typical values of free convection heat transfer coefficient of gases to range to about 25 W/m^2K (Cengel & Turner, 2004), the combined convection coefficient is estimated to be 28 W/m^2K.

Figure 4-19 shows the simplified analysis of the insulated pipe.

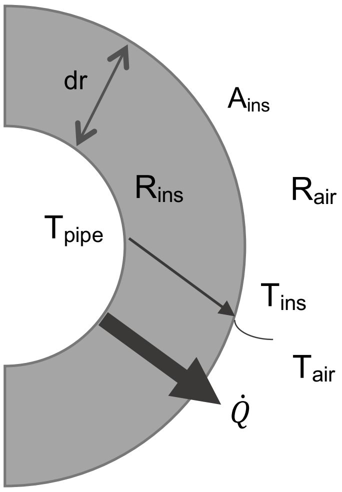

Figure 4-19 Simplified analysis of the insulated pipe

The thermal resistance was calculated for the insulation and surrounding air.

$$R_{total} = R_{ins} + R_{air} = \frac{\ln(r_2/r_1)}{2\pi L k_{ins}} + \frac{1}{h_{\mathrm{air}} A_{ins}} \tag{Eq. 4-1}$$

The rate of heat transfer through the insulation layer and air was calculated.

$$\dot{Q} = \frac{T_{pipe} - T_{air}}{R_{total}} \tag{Eq. 4-2}$$

With the rate of heat transfer constant through the layers, the temperature of the insulations surface was determined as

$$T_{ins} = T_{pipe} - \dot{Q} R_{ins} \tag{Eq. 4-3}$$

The calculations were performed for both engine load points and with the insulation layer of different thickness.

Figure 4-20 shows that the insulation needs to be at least 50 mm thick.

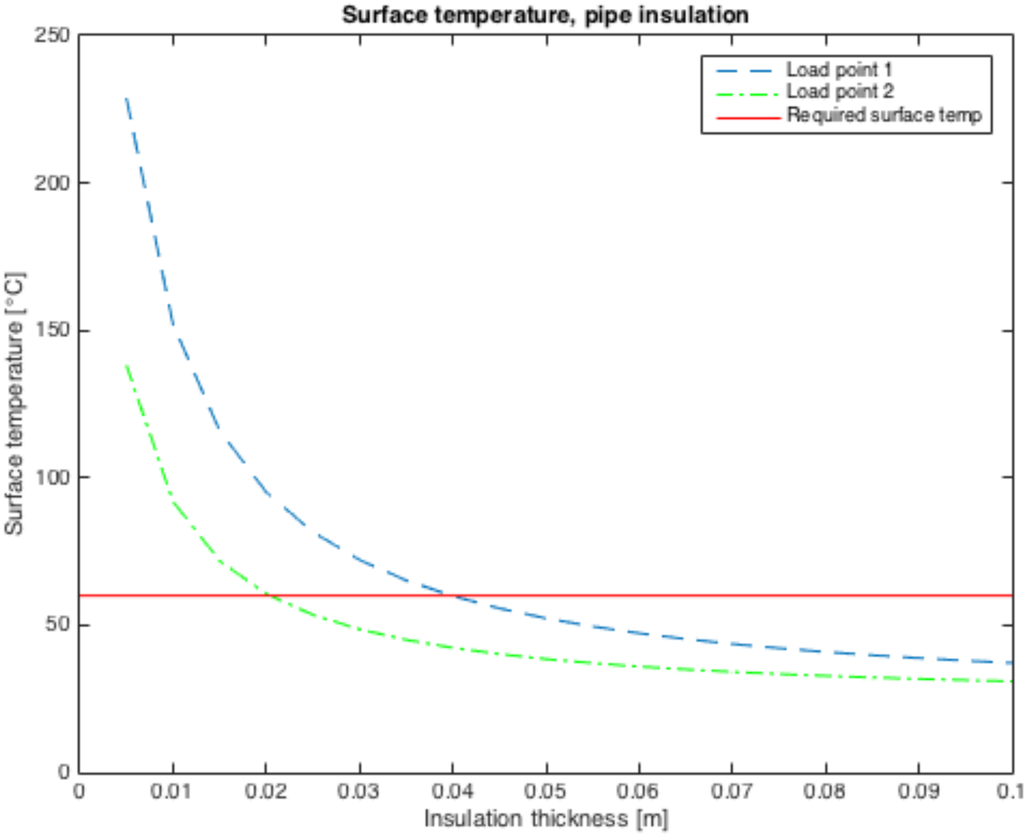

Figure 4-20 Surface temperatures at different insulation thicknesses and load points for the exhaust pipe

SCR muffler

The SCR is modeled as a cylinder with flat end caps. The insulation thickness was calculated from the known surface temperatures of the warmest places at the mantle area and end caps of the SCR muffler. The fact that the SCR muffler already featured some integrated insulation was not taken into account.
Figure 4-21 shows the analysis of the insulation at the mantle area of SCR muffler.

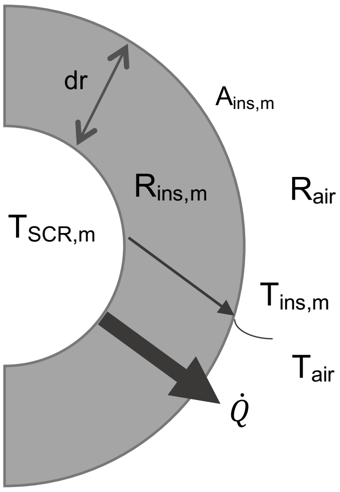

Figure 4-21 Analysis of the insulated mantle area of the SCR muffler

The same types of calculation were performed as with the pipe. The result is shown in figure 4-22.

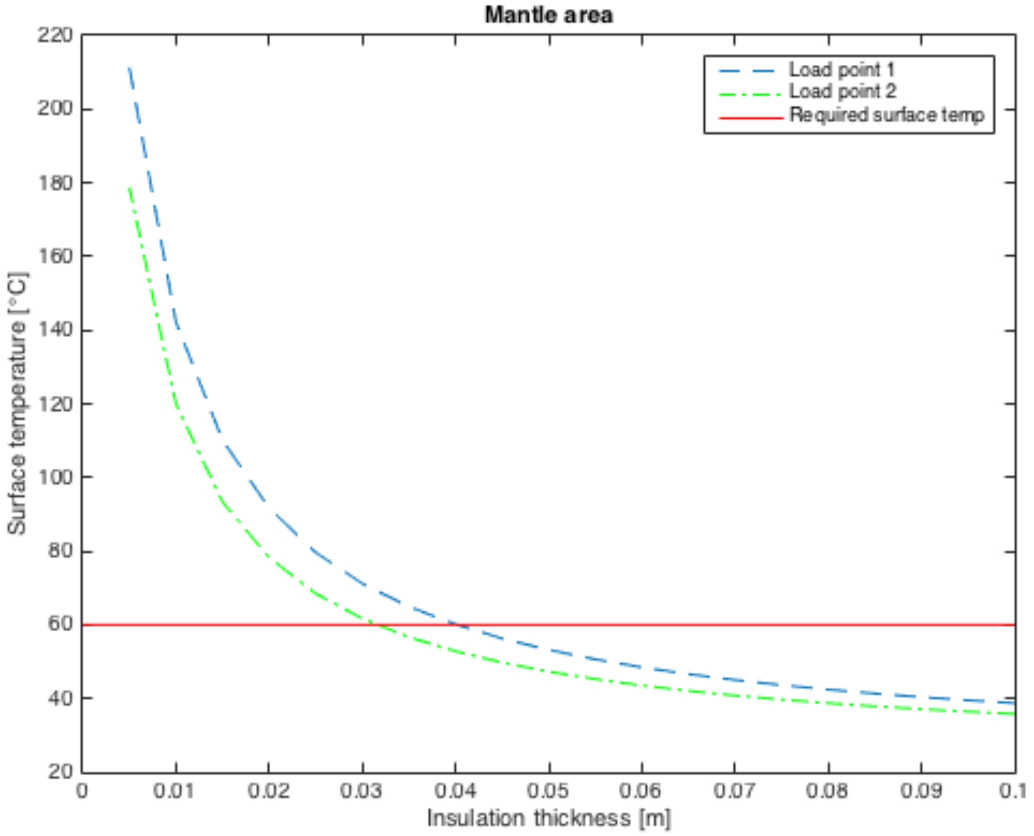

Figure 4-22 Surface temperatures at different insulation thicknesses and load points for the SCR muffler mantle area

The end caps were modeled as a plane circular wall, shown in figure 4-23.

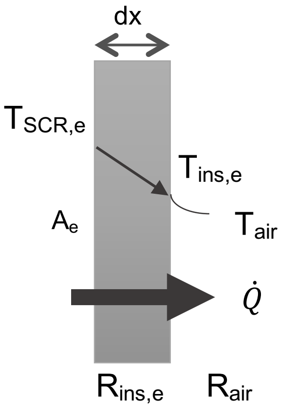

Figure 4-23 Analysis of the end caps

The thermal resistance is calculated as

$$R_{total} = R_{ins,e} + R_{air} = \frac{L}{kA_{SCR,e}} + \frac{1}{h_{\mathrm{air}}A_e} \tag{Eq. 4-4}$$

The rate of heat transfer through the insulation layer and air was calculated.

$$\dot{Q} = \frac{T_{pipe} - T_{air}}{R_{total}} \qquad \text{(Eq. 4-5)}$$

With the rate of heat transfer constant trough the layers, the surface temperature at the insulation is calculated as

$$T_{ins,e} = T_{SCR,e} - \dot{Q}R_{ins} \qquad \text{(Eq. 4-6)}$$

The calculations were performed for both engine load points and with the insulation layer of different thickness.

Figure 4-24 shows that the insulation for the end caps needs to be about 20 mm thick.

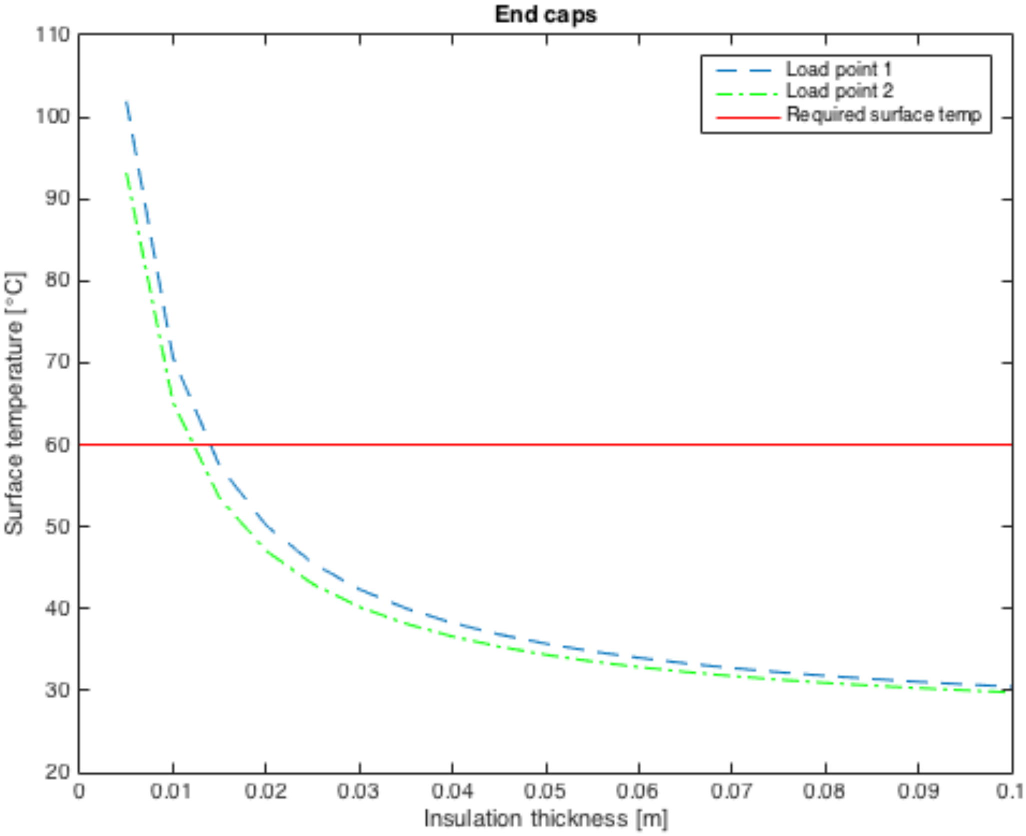

Figure 4-24 Surface temperatures at different insulation thicknesses and load points for the SCR muffler end caps

4.3.1.2 Exhaust gas temperature drop

It is of interest to determine how large the exhaust gas temperature drop is between the turbine outlet and the SCR inlet.
It is essential to maintain a high exhaust inlet temperature to the SCR in order to ensure optimal NO_x conversion rate.

The exhaust pipe to the SCR is modeled as a straight insulated pipe with dimensions as in figure 4-11.
The exhaust gas temperature drop, $\Delta T = T_{in} - T_{out}$, occurs due to heat loss through the insulated pipe, see figure 4-25.

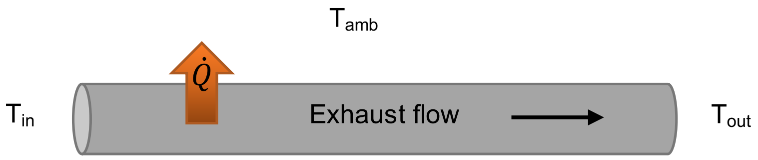

Figure 4-25 Exhaust temperature drop through insulated pipe

The heat transfer between the hot exhaust gas running through the pipe and the surrounding air can be modeled as a heat exchanger.
The surrounding air is considered constant and of 25°C. The air's combined convection coefficient is taken to be the same as before, 28 W/m^2K.

Figure 4-26 shows the temperature behavior of the fluids during the heat exchange.

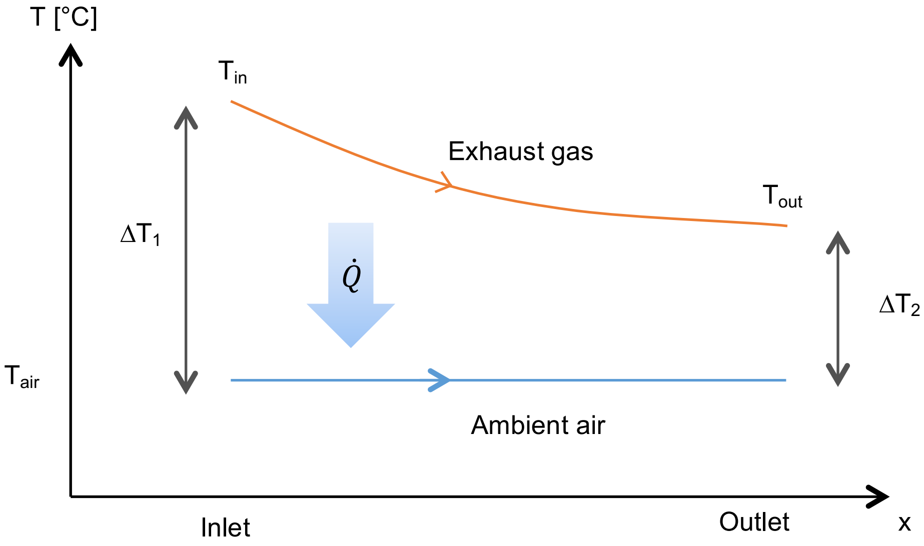

Figure 4-26 Temperature behavior of the heat exchanger

In order to do calculation on the heat exchange, properties data for the exhaust gas is necessary. The composition of diesel emissions was explained in chapter 2-3. The exhaust gas concentration resembles that of air fairly well. Both consist in vast majority of nitrogen and oxygen. The difference of the properties of air and diesel exhaust gas is approximately 2%. (DieselNet, 2015)

The exhaust gas properties can therefore be estimated to be equal of the properties for air. Properties for air at different temperatures and pressures are easy accessible in literature.
The pressure of the gas in the exhaust pipe was around atmospheric pressure for all engine load points.

Table 4-11 shows the properties for air at atmospheric pressure and the temperature of interest.

Table 4-11 Properties of air at 1 atm pressure (Cengel & Turner, 2004)

Temperature, [°C]	Density, ρ [kg/m^3]	Specific heat, c_p [J/kgK]	Thermal conductivity, k [W/mK]	Dynamic viscosity, μ [kg/ms]	Kinematic viscosity, v [m^2/m]	Prandtl number, Pr
350	0.5664	1056	0.04721	3.101e^{-5}	5.475e^{-5}	0.6937
500	0.4565	1093	0.05572	3.563e^{-5}	7.806e^{-5}	0.6937

The heat convection coefficients were estimated according to the theory in chapter 3-6. The *Re* indicated that the flow was turbulent at both engine load points. The heat convection coefficients are calculated as

$$h_{gas,350} = \frac{0.023kRe^{0.8}Pr^{1/3}}{D} = 22.22\ W/m^2K \qquad \text{(Eq. 4-7)}$$

and

$$h_{gas,500} = \frac{0.023kRe^{0.8}Pr^{1/3}}{D} = 55.13\ W/m^2K \qquad \text{(Eq. 4-8)}$$

The theory of heat exchanger in chapter 3-4 gives that the rate of heat transfer from the hot fluid, the exhaust gas, must be equal to the rate of heat transfer to the cold fluid, the surrounding air.
The rate of heat transfer from the exhaust gas is given by

$$\dot{Q} = \dot{m}C_p\Delta T \qquad \text{(Eq. 4-9)}$$

and the rate of heat transfer to the surrounding air is given by

$$\dot{Q} = \frac{\Delta T_{lm}}{R_{tot}} \qquad \text{(Eq. 4-10)}$$

where LMTD is given by figure x and defined as

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \qquad \text{(Eq. 4-11)}$$

and the thermal resistance defined as in equation 4-1 with addition of the resistance for the exhaust gas resulting in the total thermal resistance defined as

$$R_{tot} = R_{gas} + R_{ins} + R_{air} \qquad \text{(Eq. 4-12)}$$

Combining equations 4-9 to 4-12 and solving for the outlet temperature T_{out} gives

$$T_{out} = (T_{in} - T_{air})e^{\left(\frac{-1}{\dot{m}c_p R_{tot}}\right)} + T_{air} \tag{Eq. 4-13}$$

The temperature difference, defined as $\Delta T = T_{in} - T_{out}$, is shown in figure 4-27 for different insulation thicknesses and load points.

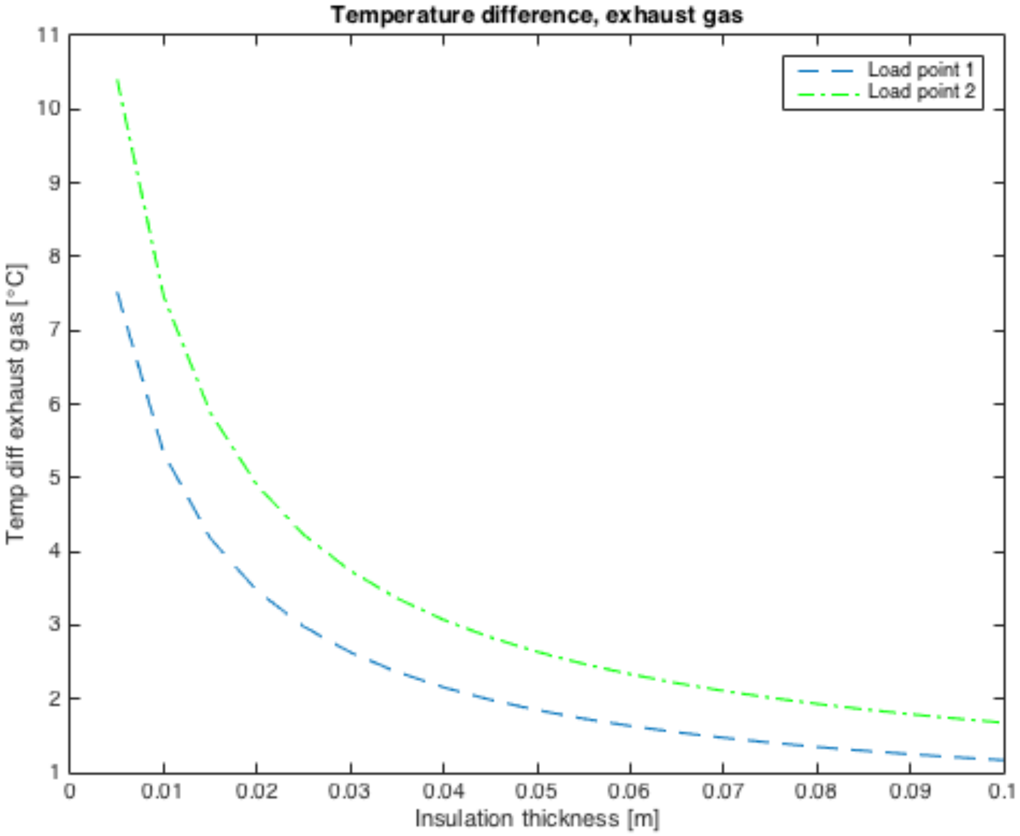

Figure 4-27 Exhaust gas temperature drop for different insulation thicknesses and load points

It is noticed that the temperature drop is somewhat larger for the load point with lower exhaust gas mass flow and temperature.

4.3.2 Concept B – Blankets with covers

Concept B is similar to concept A but with the addition of a thin protective cover of aluminum. Concept B looks very much like the insulation solution used for Styrsöbolaget's cargo ferry Göta II. (Chapter 4.2.1.1.) For parts of the exhaust system where the cover can't be fitted, blankets similar to concept A will be used. Figure 4-28 shows the design of the insulation solution.

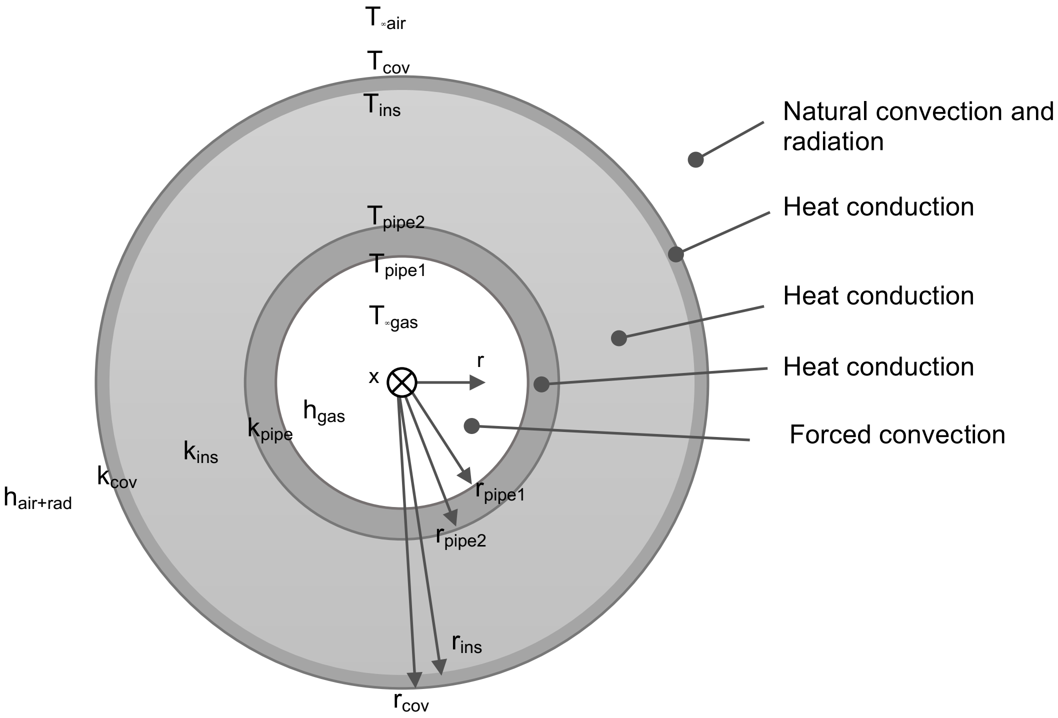

Figure 4-28 Analysis of concept 2 insulation design

In addition to help keep the underlying insulation material in place, the cover will reduce heat transfer by radiation.

The thermal conduction resistance provided by the cover is believed to be negligible compared to the insulation layer.

The conduction coefficient for aluminum was taken to be 237 W/mK at room temperature. (Cengel & Turner, 2004)

The thermal conduction resistance for the cover for the SCR muffler with 50 mm insulation for engine load point 1 is calculated to

$$R_{cov} = \frac{\ln(r_{cov}/r_{ins})}{2\pi L k_{ins}} = 1.0476 \cdot 10^{-6}\ °C/W \qquad \text{(Eq. 4-14)}$$

The thermal resistance of the cover is very small compared to the thermal resistance of the insulation layer and therefore negligible.

The advantage with the cover is reduced heat transfer by radiation, structural support for the insulation material, more professional looking insulation and easier cleaning of the engine compartment. The disadvantage is a more complex installation procedure.

4.3.3 Concept C – Insulation fibers covered by sheet metal

Concept C is similar to the insulation method used in M/S Sandhamn. It uses insulation fibers that is rolled over the pipes and held together by a metallic mesh. A steel sheet covering the insulation fibers gives it additional support and protection. The steel cover also reduces the heat transfer by radiation.

Insulation blankets are used for the parts of the exhaust system, where sheet cover is not suitable or does not fit.

4.3.4 Concept D – Calcium silica insulation

Concept D is based on the insulation method seen in chapter 4.2.42. It uses a calcium silica material for insulation of pipes that is commonly used at industrial facilities. The insulation consists of two rigid halves that are fitted to the pipe. The insulation material is held together and protected by an aluminum jacketing. The cover reduces the rate of heat transfer by radiation.

The cover must be sealed to protect the insulation material for fluids such as water or oil spray.

4.3.5 Concept E – Fibers encapsulated by a heat shield

Concept E use an insulation methods similar to the one seen on the riser in figure 4-11 in chapter 4.2.4. The pipe and SCR muffler is covered with insulation fibers and enclosed with a metallic shell.

4.4 Concept evaluation

The concepts were evaluated with Pugh’s concept selection method.
Criteria were listed. A reference concept was chosen based on the current insulation methods for EATS that were studied in chapter 4.2.1. Pros and cons for each concept were valued against the reference concept. The concepts were then ranked base on their score. A decision was made on which concepts that should be further developed. (Ulrich & Eppinger, 2012)

Table 4-12 Concept selection matrix

	Concepts				
Selection criteria	A (Ref)	B	C	D	E
Easy installation/removal	0	-	-	-	-
No special tools	0	-	-	-	-
Works with flexible pipe	0	0	0	-	-
Adaptable length	0	0	-	0	-
Connect cables/sensors	0	-	-	-	-
Insulation thickness	0	0	0	-	+
Easy to keep clean	0	+	+	+	+
Professional look	0	+	+	+	+
Sum +’s	0	2	2	2	3
Sum 0’s	8	3	2	1	0
Sum -’s	0	3	4	5	5
Net score	0	-1	-2	-3	-3
Rank	1	2	3	4	4
Continue?	Yes	Yes	No	No	Combine

Pugh’s concept selection matrix ranks the reference concept (concept A) as the best. It is noted that all of the other concepts get a negative net score.
A decision on which concept to consider and develop further was done based on their rank and the selected criteria.

Concept C is relative similar to Concept B, but believed to be slightly more complicated to install/remove.
Concept D is based on an insulation method commonly used for industrial application and may not be suitable for marine application.

Concept C and D was rejected.

Concept A

Concept A is the easiest and most customizable solution. It is easy to dismount and remount without any special tools. It is suitable for insulation of pipes as well as other equipment. The material is flexible and can be applied to irregularly shaped parts and segments of the exhaust system where space is limited.
The blanket has an aluminum reinforced soft cover, as seen on the “Test cell blanket” in chapter 4.2.4.1. This should help the insulation solution to reduce some of the heat transferred by radiation and make it relatively easy to keep clean.
An insulation design that is custom-made to fit the SCR muffler perfectly can be done as the SCR muffler design does not change between installations.

Concept B

Concept B is very similar to Concept A but with the addition of an aluminum jacketing that covers the insulation fabric. The cover protects the insulation material, reduces heat transfer by radiation, provides structural strength to the system, makes it easier to keep clean and gives it a more professional look.

The reinforced aluminum soft cover from concept A should only be used for parts of the insulation where lack of space makes the hard cover unsuitable.

While the exhaust pipe should use the protective hard cover as suitable, the SCR muffler can have a more permanent insulation solution as its geometry is predetermined.

Concept E

Concept E is a more advanced approach for the insulation. The insulation is closely fitted to the warm exhaust part. The solution requires pre-determined geometry of the parts and installation performed by the insulation manufacturer. The insulation is thinner than the other concepts, but it is a permanent insulation solution that can’t easily be removed if needed.

The insulation method might be not suitable for the exhaust pipe as its length and geometry varies with installations. The exhaust pipe design needs to be carefully planned for the use of this insulation method.

A combination of concept B and E might therefore be a better solution. **Concept B-E** is created. The insulation method of concept B is applied to the exhaust pipe and the more advanced insulation method of concept E is used for the SCR muffler as its design is pre-determined. However, it is unclear at this point if the insulation method is suitable for the SCR muffler’s large surface area.

Concept scoring

The final concepts are evaluated a second time with a concept scoring matrix that further examines the concepts difference.

The selection criteria were revisited and weighted by importance. Each concept is rated according to table 4-13. Concept A is kept as the overall reference but each criteria has a separate reference point, marked as bold. (Ulrich & Eppinger, 2012)

Table 4-13 Rating system for the weight selection matrix

Relative performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	**3**
Better than reference	4
Much better than reference	5

Table 4-14 shows the weighted selection matrix. The concepts are ranked based on their score.

Table 4-14 Matrix for the second round of concept selection

		Concepts					
Selection criteria	**Weight**	A (ref)		B		B-E	
		Rating	Score	Rating	Score	Rating	Score
Installation process	15%	**3**	0.45	2	0.30	1	0.15
Easy dismount/reapply	10%	**3**	0.30	2	0.20	2	0.20
No special tools	10%	**3**	0.30	3	0.30	2	0.20
Works with flexible pipe	15%	**3**	0.45	3	0.45	3	0.45
Adaptable length	15%	**3**	0.45	3	0.45	3	0.45
Connect cables/sensors	10%	**3**	0.30	2	0.20	1	0.10
Radiation heat shield	5%	2	0.10	**3**	0.15	3	0.15
Insulation thickness	10%	**3**	0.30	3	0.30	4	0.40
Easy to keep clean	5%	**3**	0.15	4	0.20	3	0.15
Professional appearance	5%	2	0.10	**3**	0.15	3	0.15
Total Score		2.9		2.7		2.4	
Rank		1		2		3	
Continue?		Yes		No		No	

The reference concept A gets the best score in the second concept selection matrix as well as the first. Concept A is therefore considered as the winning concept.

5 Result

In this section the result of the project is presented.

The concept evaluation in chapter 4.4 resulted in concept A as the best insulation solution for the complete exhaust system.
Concept A uses blankets for insulation similar to those seen in Styrsöbolaget’s ferry Ärlan. The blankets have an aluminum reinforced soft cover similar to the blankets used for insulation needs at Volvo Penta’s workshop, chapter 4.2.4.1.
The design of the SCR muffler is not dependent on the boat design. Its insulation solution can therefore be tailored to closely fit its shape. Regular blankets can be used, or preferably an insulation fabric that is custom-made for the shape of the SCR muffler should be used.
The insulation thickness needed to meet the required surface temperature of 60°C is about 50 mm for the exhaust pipe, according the calculation performed in chapter 4.3.1.1.
The exhaust gas temperature drop between the engine and SCR muffler is estimated to be between 2-4°C for 50 mm insulation thickness, according to the calculation in chapter 4.3.1.2.

The insulation solution of concept A closely resembles the method used in ferry Ärlan, see figure 5-1.

Figure 5-1 The insulation method used in ferry Ärlan closely resembles that of concept A

6 Conclusion

In this section the method and result of the project are discussed.

6.1 Research

The research was mainly focused on insulation methods currently used for marine exhaust systems. Some solution for other hot engine components were also explored. It is believed that the study will benefit from a wider research range where additional insulation solution can be investigated.
Contact with some insulation manufactures to learn which solutions they recommend and the price of different insulation solutions is advised. The price of the insulations methods was left out of this study.

The insulation materials that is used for the different methods needs to be studied more in-depth. The material used for the concepts featured in this project is based on the material found with the blanket solution studied in chapter 4.2.4.1. It is a mineral wool based on silica fibers.
A similar type of material is believed to be in use for other insulation solutions of the same type. The density of the material can be varied in order to meet certain insulating performance.
It is recommended to perform further studies of different types of insulation materials in order to get a better understanding of its thermal properties and insulating performance.

Two local boat builders were contacted in order to gather more information about the insulation methods typically used for marine exhaust systems. Unfortunately, no response was received before the project’s deadline.

6.2 Calculations

Basic heat transfer calculations were performed to determine the necessary insulation thickness to meet the required surface temperature. Calculations were also performed in order to estimate the temperature difference of the exhaust gas between the engine and SCR. The accuracy the results were reasonably good when compared for actual insulation thicknesses used with similar types of insulation methods.

Several assumptions were made during the analysis. Especially hard to approximate were factors concerning the surroundings of the engine compartment.
The thermal condition of the surroundings in the engine compartment were estimated to be 25°C, ventilated and with no major sources of radiation. The convection coefficient of the ambient air was estimated using data available in reference literature.
The contribution of the thermal radiation was combined with the convection coefficient due to the uncertainties of the surroundings and to simplify the calculations.
To improve the accuracy of the result, a better estimations of the convection coefficient and heat transfer by radiation is necessary. Especially the impact of the heat transfer by radiation needs further studying.

The insulation material's conductivity coefficient is based on data form the mineral wool material used with the blanket solution described in 4.2.4.1. The range of the *k*-value is believed to be a good estimation of materials typical found in that type of insulation solution. It is, however, recommended to further investigate the properties of additional materials that can be used for insulation.

A more complete analysis of the thermal behavior of the EATS is recommended in order to determine the most effective insulation solution.
The analysis is preferably performed with computational simulation software where additional factors such as exhaust gas flow behavior can be taken into account.

6.3 Result

A good insulation solution for the EATS is essential in order to keep the correct operational temperature range for the SCR and to ensure desired performance is achieved.

The winning concept in this study is the easiest and most customizable insulation solution that meets the required surface temperature. As seen in the research study (chapter 4.2), it is also a solution commonly used for insulation of marine exhaust systems.
Concept B with its aluminum covers might be more professional in appearance, easier to keep clean and superior to minimize heat loss due to radiation. However, the construction make it more complicated to dismount/remount in case of service or modifications of the system.
To improve the evaluation of the concepts, it is recommended to further investigate how much the aluminum cover reduces heat transfer by radiation and improves the insulating performance.

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