Exhaust Gas Cleaning with Selective Catalytic Reduction (SCR)

TMR4905 - Master Thesis

by

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MASTER THESIS DESCRIPTION

Student's name:	Magnus Selås
Course:	TMR4905
Title:	Exhaust Gas Cleaning with Selective Catalytic Reduction *Rensing av eksosgass med Selektiv Katalytisk Reduksjon*

Background

In a research program on reduction of NOx and particle emissions from diesel engines a SCR-system have been installed in the Machinery Laboratory at Marine Technology Centre.
The conversion efficiency of NOx in the SCR system depends among several other factors on the feed rate of the reduction agent: too low feed rate will give NOx emissions and too high feed rate may produce emissions of ammonia.
The SCR system, especially the catalyst, may experience degradation during operation. Special emphasis should be put on assessment of degradation mechanisms, in particular due to temperature variations in the catalyst.

Overall Aim and Focus

This assignment should deal with the operational aspects of the SCR-system with emphasis on the NOx reduction efficiency.

The MSc-assignment should be prepared based on the following points

1. General description of exhaust emissions from ships
   General description of SCR systems on ships
2. Degradation of SCR systems during operation.
   Experimental investigation of temperature variations and thermal loading of the catalyst.
   Assessment of possible relations between catalyst temperature and degradation
3. Experimental investigation of SCR system reduction efficiency and identification of important factors that have impact on the efficiency.
   Experimental investigation on relationships between reduction efficiency and ammonia slip.
   Assessment of SCR systems performance data from ships in operation.

The MSc assignment text should be included in the report.

The report should be written like a research report, with an abstract, conclusions, contents list, reference list, etc.

During preparation of the report it is important that the candidate emphasizes easily understood and well written text. For ease of reading the report should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.

All used sources must be completely documented. For textbooks and periodicals, author, title, year, page number and eventually figure number must be specified.

In accordance with current regulations NTNU reserves the right to use any results from the thesis work in connection with teaching and research activities.

Three -3- examples of the report are required. One example should be a complete original including the original assignment text and appendices. Two examples should be complete copies of the original. A complete copy of all material on digital form on CD-ROM in Word-format or other relevant format should be handed in together with the written material.

Deadline: 2010-06-14
Submission date: 2010-06-11
Department: Department of Marine Technology
Supervisor: Harald Valland

Trondheim, January 21 2010

Harald Valland

Harald Valland, NTNU/IMT.

Preface

This report presents the work of my Master Thesis conducted spring 2010, code TMR4905. The master thesis is based on the project thesis that was carried out fall 2009. The objective is to gain in-depth knowledge of a topic, in my case Selective Catalytic Reduction (SCR). The Master Thesis is a complementary part of the MSc program in Marine Technology at NTNU, and counts for 30 credits.

The thesis was carried out in cooperation with MARINTEK and to some extent Höegh LNG. The work has been part of a research program at MARINTEK that investigates the effect of a SCR system with respect to NO_x and PM emissions. Höegh LNG has installed this system on two of their newbuilds.

The work process has been good, but with some delays and complications. As a result of the project thesis, I had many ideas for experiments I wanted to conduct in the laboratory. The first experiment was conducted late February 2010. Then we discovered some errors that took MARINTEK long time to fix, together with them facing the challenges of dealing with multiple projects simultaneously that delayed the process. Overall three experiments have been conducted, with the last two at beginning of May 2010. This has resulted in a heavy work load at the end of the process, and the need for limitations in the focus areas have been present. The focus has been on degrading and performance of the SCR, with respect to NO_x reduction efficiency solemnly. The influence of PM has been given less priority.

I have tried to gain some operational experience from shipping companies that makes use of SCR in their daily operation. This was done by sending out a survey to various companies in Norway. Although all of these participated, the the level of detail in their

answers was varying. This is partly due to their “priorities” and partly due to the level of detail the survey was constructed and they not being able to collect the data needed. This of course has limited the conclusions I can make of these answers.
Together with this, the emission test results from HLNG has also been delayed also contributing to increased work load at the end. However the datas were interesting, and the knowledge gained from the lab has given me a good foundation for recommendations to HLNG.

There are numerous persons deserving credits for invaluable help during my work. First of all I would like to thank my supervisor Professor Harald Valland for great guidance and good, educating conversations. My friends at MARINTEK, Erik Hennie, Jørgen B. Nielsen and Ingebrigt Valberg deserves a debt of gratitude for guidance and help in the laboratory. Ole Johan Nedrelid has been an impeccable contact person towards HLNG. At last Jan de Wit and his colleagues from Dansk Gasteknisk Senter deserves credits for their service attitude and valued response to my enquiry.

The report is submitted in three copies to the Department of Marine Technology, NTNU.

Trondheim, June 11, 2010

Student Technicae Magnus Selås

Abstract

This thesis presents the work around three laboratory experiments conducted in the machinery laboratory at MARINTEK with focus on performance and degrading mechanisms of a Selective Catalytic Reduction system. Höegh LNG has contributed to the thesis from an industrial perspective together with various Norwegian shipping companies.

An introduction to emissions from combustion engines is given, with focus of the real pollutants as $\mathrm{NO_x}$, $\mathrm{SO_x}$, CO, HC and PM. $\mathrm{CO_2}$ has not been defined as a real pollutant as it's not itself toxic, but still is a major concern due to it's contribution to the greenhouse effect. The real pollutants only represents about 0,6% of the total emissions from a combustion engine. An introduction to today's and future emission limits has been presented.

The system consists of a catalyst that contains ceramic stones with a honeycomb shape. The honeycombs contain the active material that reacts with the $\mathrm{NH_3}$ introduced in the exhaust gas and reduce the $\mathrm{NO_x}$ to $\mathrm{N_2}$ and $\mathrm{H_2O}$. The honeycombs may be coated with the active material or homogeneously extruded. The control unit controls the urea feed rate, and the urea react with water and together with the exhaust heat becomes $\mathrm{NH_3}$. The system efficiency is dependent on the ammonia feed rate and a 90 to 95% reduction of $\mathrm{NO_x}$ is possible. Higher efficiency is possible, however with increased risk of $\mathrm{NH_3}$ slip.

Degrading mechanisms have been investigated with respect to fatigue and deposits. The $\mathrm{SO_2}$ to $\mathrm{SO_3}$ conversion rate sets the basis for formation of deposits, and hence should be reduced as much as possible. With respect to fatigue, we investigated with a laboratory experiment whether the temperature variations were sufficient to cause any thermal strain on the honeycombs. This hypothesis was undermined as the temperature variations logged were in the lower edge of 10 °C.

Whether logging of temperatures can function as indicators of degrading of the catalyst were investigated in a second experiment. The approach was to search for a correlation between the temperature in the catalyst material (T_{Center}) and the catalyst activity as

degrading of the lab catalyst require many hours of operation. We did not find a clear connection between the two, however a connection between the activity and temperature difference $\Delta T = T_2 - T_1$ was discovered. This will be a topic for further investigation by MARINTEK.

The performance of the SCR in the machinery lab has been documented, with a reduction efficiency of 95% in compliance with international ammonia slip level requirement. A bleed of the turbocharger compressor was performed in order see if increased the exhaust gas temperature would increase the reduction efficiency. This was not the case as we achieved same reduction efficiency with somewhat higher slip. The increased $\mathrm{NO_x}$ emission level has been corrected for. A FTIR gas analyzer was rented by MARINTEK in order to verify the accuracy of their Horiba PG-250. When comparing the two instruments, deviations were neglectable.

The number one challenge for SCR according to shipping companies is to ensure satisfying reduction efficiency when the engine is experiencing frequent load changes. Together with this the challenge is to get SCR working properly with low speed two stroke engines operating on HFO.

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Acronyms

AHTS Anchor Handling Tug and Supply

CAPEX Capital Expenditure

CARB California Air Resources Board

DP Dynamic Positioning

DWP Deep Water Port

EPA Environmental Protection Agency

FSRU Floating Storage and Regasification Unit

HFO Heavy Fuel Oil

IF Inorganic Fraction

IMO International Maritime Organization

IMR Inspection Maintenance and Repair

KMB Kompetanseprosjekt Med Brukermedvirkning

LNG Liquified Natural Gas

MARPOL International Convention for the Prevention of Pollution from Ships, 1973

MEPC Marine Environmental Protection Committee

MGO Marine Gas Oil

MMBtu “Thousand Thousand” British Thermal Unit - 1kWh = 3412 Btu

NOx Nitrogen Oxides

OPEX Operational Expenditure

PM Particulate Material

PSV Platform Supply Vessel

SECA Sulphur Emission Controlled Area

SCR Selective Catalytic Reduction

SOF Soluble Organic Fraction

SOx Sulphur Oxides

SRV Shuttle Regasification Vessel

TC Turbocharger

USEC United States East Coast

Chapter 1

Introduction

In the machinery laboratory at MARINTEK and NTNU a SCR-system has been installed in the occasion of a research program (KMB) on NO_x and PM reduction efficiency. The objective of the master thesis is to get acquainted with the system in operation, how the system looses efficiency during operation (degrading) and how the system performs under different prevailing conditions (performance). The performance part has been with focus on NO_x reduction efficiency in this thesis. The approach to investigate these topics is divided into two parts: laboratory experiments and end user experiences. Laboratory research has been done in good cooperation with MARINTEK in the machinery lab. The end user experiences are collected first of all from Höegh LNG, but also from various Norwegian shipping companies.

1.1 Research

In total three experiments have been conducted in the laboratory. They have all had multiple objectives with respect to both degrading and performance focus. The first lab was performed to investigate a hypothesis with origin from the work done in the project thesis. Based on the findings in this experiment a second lab was planned and executed. In between these two main lab experiments, a third lab was set up in connection with operation on “White Diesel”, which is topic of research for a fellow master student. Due to short amount of time to prepare for this I used this as an opportunity to get indicators in preparations for my second lab. The experiments were conducted at the following dates:

- 18.02.2010 - First experiment after refitting of the turbocharger.
- 05.05.2010 - “White Diesel” experiment (Control Unit calibrated)
- 10.05.2010 - First prepared experiment after calibration of the Control Unit with FTIR

1.2 End User Experiences

Together with the laboratory activity, I have been in contact with various shipping companies in order to gain their experiences with SCR. These are mostly offshore shipping companies with their business mostly centred on contracts in the North Sea. They are here under strict regulations as they operate within the SECA area. Together with this I have gained experience data from Höegh LNG with SCR used on dual fuel engines and exhaust gas boilers. The intention is to draw the experience of these companies into the research and find parameters for successful operation of SCR in the industry.

1.3 Structure of Report

The material presented in this report is divided into three parts:

Part 1 consists of an introduction to emissions from the shipping industry together with their present and future compliance requirements. This part also includes a general introduction to and description of the SCR system.

Part 2 is about degrading mechanisms.

Part 3 is about performance.

I have chosen not to structure the report by the order of the lab experiments, as each lab experiment contains objectives both within degrading and performance. The degrading chapter describes in more detail how the lab experiment was conducted, which will be the same for the performance part. I believe it will be better for the reader to focus on one type of results at once. Each part also contains elements from the end user experiences. At last I will give a presentation and discussion to the result and recommendation for further work within the topic of SCR.

Part I

Background

Chapter 2

Emissions from Ships

Emissions from ships have been of common interest for several years, and various methods for emission reduction have been developed in recent years through research and development from engine manufacturers and specialized companies. This is due to international and national authorities' respond to concern over air pollution. Emissions from marine diesel engines consist of nitrogen, oxygen, carbon dioxide and water vapour. Smaller amount of carbon monoxide, oxides of sulphur and nitrogen and particulate material are also present and the ones which should be reduced due to their harmful effect.

$$\underbrace{O_2+N_2}_{Air}+\underbrace{\underbrace{HC+S}_{Fuel\ Oil}+Ca}_{Lube\ Oil}\rightarrow\underbrace{O_2+N_2}_{Air}+\underbrace{CO_2}_{Carbon\ Dioxide}+\underbrace{H_2O}_{Water}+\underbrace{SO_x}_{Sulphur\ Oxides}+\underbrace{CO}_{Carbon\ Monoxide}$$

$$+\underbrace{HC}_{Hydrocarbons}+\underbrace{NO_x}_{Nitrogen\ Oxides}+\underbrace{PM}_{Particulate\ Material}$$

As shown in figure 2.2, the pollutants represent only about 0,3% of the total emissions from a medium speed diesel engine, burning fuel with an average of 3% sulphur content. Of this the major pollutants are NO_x and SO_x.

2.1 Sulphur Oxides (SO_x)

Sulphur Oxides (SO_x) are produced by oxidation of sulphur in the fuel. Shipping is one of the major contributors to SO_x emissions due to the high sulphur content in the fuel burned.

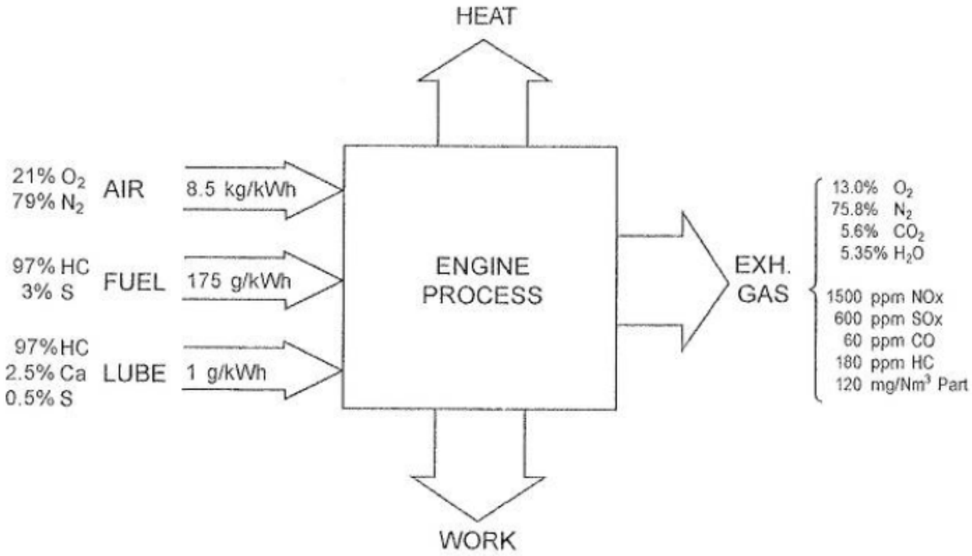

Figure 2.1: Emissions from engine process (Low speed 2-stroke diesel engine [22])

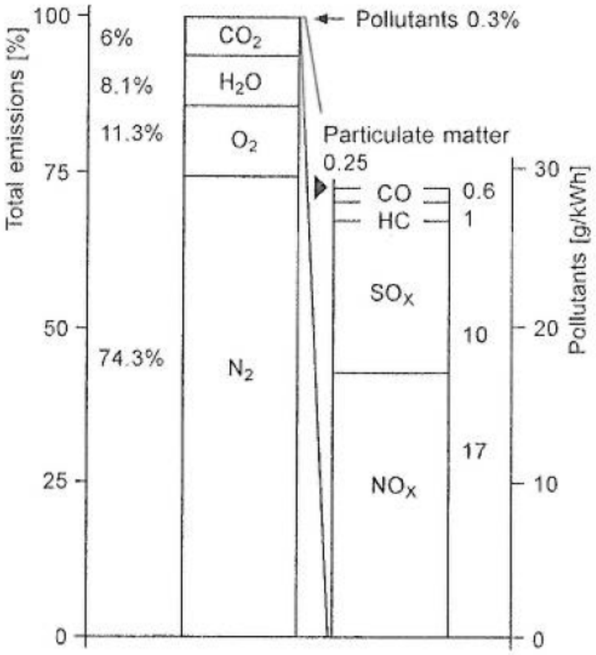

Figure 2.2: Different emissions share of total [22]

A study from 1990 showed that shipping contributes to about 4 per cent of the total SO_x emissions in Europe. The amount of SO_x produced is equal to the sulphur content of the fuel burned, and mostly comprise sulphur dioxide with some sulphur trioxide. Thus the combustion process cannot control the amount of SO_x produced. Sulphur oxides have an unpleasant odour and are the number one contributor to acid rain, and once emitted SO_x can be carried over a large area in the atmosphere before it's deposited in lakes and streams, reducing their alkalinity [22]. SO_x can be reduced as mentioned easily with burning bunkers with low sulphur content. For example with sulphur content of about 3 per cent in the fuel, this leads to 64 kg of SO_x per ton fuel burned. If this is reduced to 1 per cent the emitted SO_x is about 21 kg per ton burned, which is a significant reduction. Some methods for after treatment of the exhaust gas in order to reduce SO_x emissions exist, where the most commonly used is a scrubber. When a SCR system is installed with the purpose of reducing NO_x, the sulphur content of the fuel is important in order to reduce the downgrading of the catalyst, and for regulation of the system.

2.2 Nitrogen Oxides (NO_x)

Nitrogen oxides (NO_x) are generated during the combustion from nitrogen and oxygen at high temperatures in the cylinder. NO_x are of special interest of authorities due their possible carcinogenic effect, contribution to photochemical smog formation over cities and acid rain. The major influences of the formation of NO_x in combustion engines are the temperature and concentration of oxygen in the combustion. Also the residence time of the combustion play a role, thus high temperature and long residence time will increase the amount of NO_x. This is the reason for why low speed two stroke engines generate a larger amount of NO_x, than medium speed four stroke engines.
As the NO_x production is dependent of combustion, there are several methods for reduction. We may divide them into three categories as in figure 2.3.

Selective Catalytic Reduction is a method placed in the post-treatment batch, as it cleans the exhaust, independent of possible pre- and internal treatment. This is a very effective measure, compared to the others, although some of the other measures can report with a quite significant reduction as well.

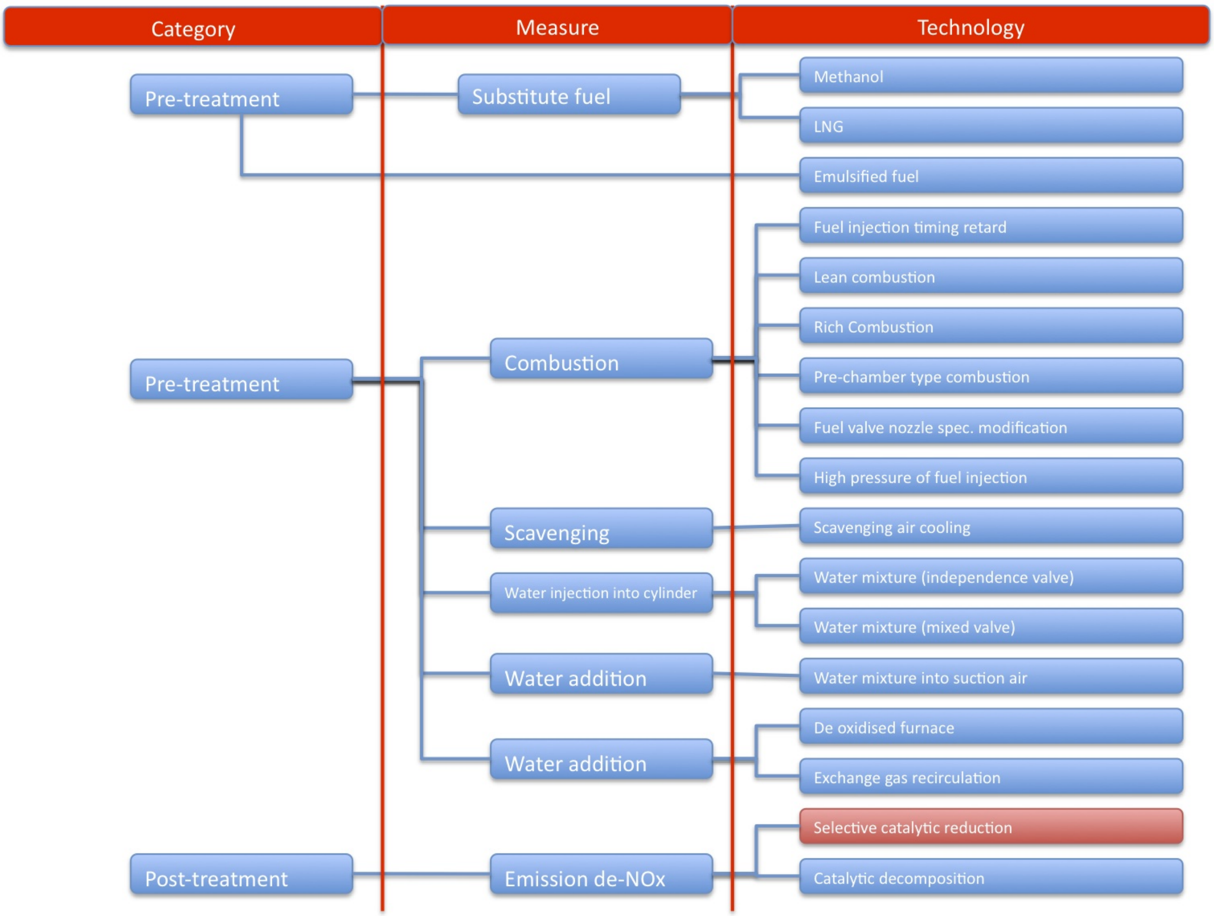

Figure 2.3: NO_x emission control alternatives

2.3 Carbon Dioxide (CO_2)

Carbon dioxide is not itself toxic, but represents a threat to the atmosphere and is recognized as a greenhouse gas. Therefore it contributes to global warming although it's not itself toxic. As we can see from figure 2.2, about 6 per cent of the total emissions from a low speed two-stroke engine is CO_2. CO_2 will always be present when burning fossil fuel, however due to their thermal efficiency the emissions from the diesel engine is the lowest when comparing all heat engines. The only way to reduce the CO_2 emissions is to reduce the amount of fuel burned [22], as the amount is proportional to the bunkers consumption. Reduction of CO_2 in the maritime industry involves optimizing fleet schedule reduce voyage days between ports and planning the trading pattern to minimize ballast voyages and voyages for bunkering. Also optimizing the capacity of the fleet and size of the vessel to reduce the total CO_2 emissions per unit cargo shipped is a focus area as well as slow steaming.

2.4 Particulate Material (PM)

PM emissions are one of the focus areas for MARINTEK in connection with SCR, however this thesis emphasize mostly on NO_x. Particle Emissions can be divided into three main components: Soot, Soluble Organic Fraction (SOF) and Inorganic Fraction (IF). Most particulate material results from incomplete combustion of the hydrocarbons in the fuel and lube oil [6]. More than 50 per cent of the total PM emissions are soot, which is the visible black smoke. PM are particles as small as 10 nm, and 90 per cent of the total particulate materials are smaller than 1 μm [13]. The formation process of PM is dependent of many factors

- The combustion and expansion process
- Fuel quality (sulphur and ash content)
- Lubrication oil quality and consumption
- Combustion temperature
- Exhaust gas cooling

In recent years, the harmful effect of particulate matter has been a topic for discussion. However it is now documented that inhaling of these particles may be a cause to premature death, asthma and lung cancer and other cardiovascular issues. This is one of the reasons for the recent growth in research about how to reduce these emissions

2.4.1 Soot

The soot fraction of PM is the visible smoke in the exhaust and is made up of carbonaceous material originating from the fuel and lube oil. Soot formation takes place in a diesel combustion process between about 1000 and 2800 °K, and pressure about 50-100 atm. The time available for the particles to form is within milliseconds, and the growth can be separated into two stages. The first stage is for the particles to form, and these particles are very small (less than 2 nm in diameter). The second stage (stage "Surface Growth" in figure 2.4) is where the particle grows, which includes surface growth, coagulation and aggregation.

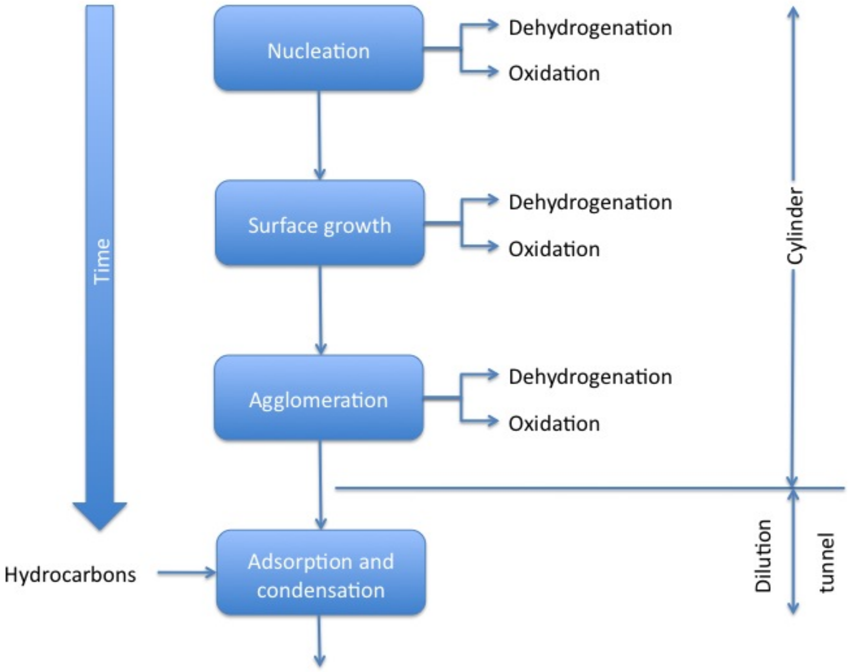

Figure 2.4: Formation of particles [6]

2.4.2 Soluble Organic Fraction (SOF)

The SOF of the particle is mainly unburned hydrocarbons (HC) from fuel and lubrication oil [16]. The reason for the unburned fuel may be several in a diesel engine. During the mixing and combustion there may be areas in the cylinder where the mixture is too rich or lean to support the flame [13]. Incomplete mixing of the fuel may therefore result in unburned fuel escaping into the exhaust gas. Other reasons may be wall quenching[1] and the SAC volume of the fuel injector nozzle.

The SAC volume is the volume in the injection nozzle filled with fuel after injection, and this will be heated and evaporated during the combustion and expansion. When this

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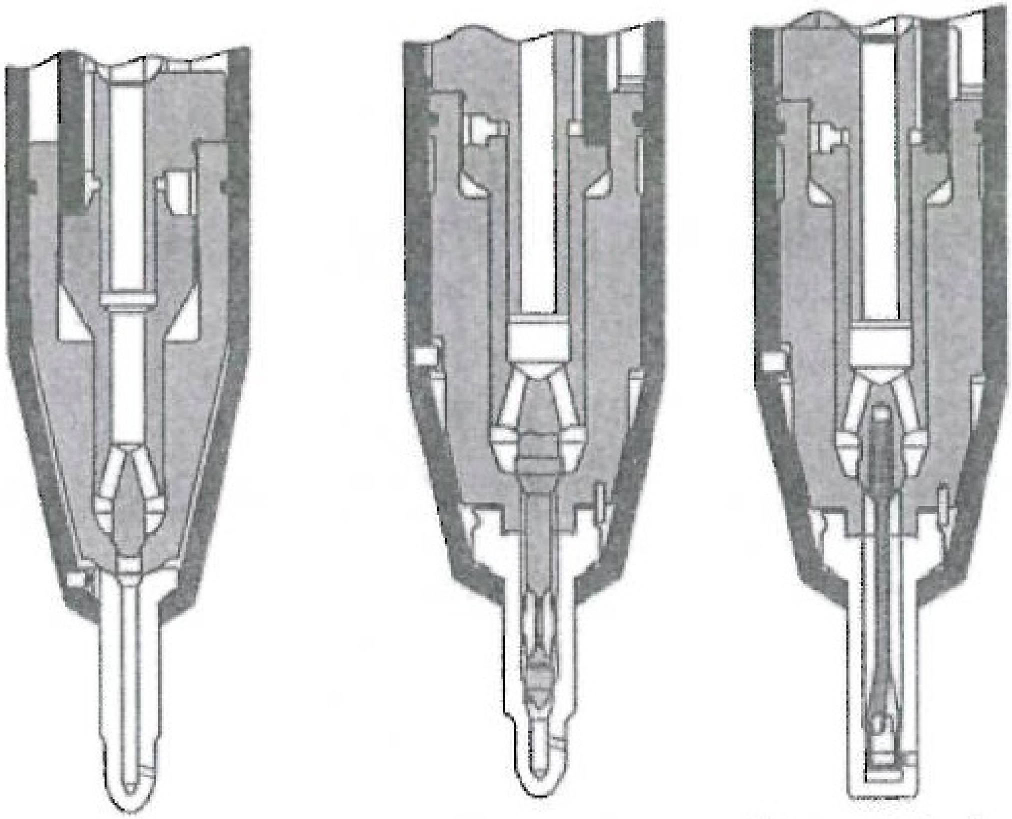
[1] Close to the cylinder wall temperature is too low to support the combustion due to cooling.



(a) Conventional fuel valve, Sac volume 1690 mm3 (b) Mini-sac valve, Sac volume of 520 mm3 (c) Slide-type fuel valve, Sac volume of 0 mm3

Figure 2.5: Fuel Nozzles

leaves the nozzle for the next injection it escapes the nozzle at low velocity, resulting in poor atomization.

2.4.3 Inorganic Fraction

Inorganic fractions consist of non-volatile, semi-volatile and volatile compounds like sulphates and nitrates, ash and water [13]. The fraction is directly linked to the amount of fuel injected into the cylinder and is difficult to remove.

2.5 Regulations & Limits

Exhaust emissions limits are set by IMO in the MARPOL 73/78 Annex VI; Regulations for the Prevention of Air Pollution from Ships. This annex was added to the convention in 1997 and set limits for SO_x and NO_x emissions from the exhaust for the worldwide trade. However there are some areas that are defined as special SO_x Emissions Control Areas (SECA) and these areas are under stricter regulations to which sulphur content allowed in the fuel oil for seagoing vessels. Among these areas we find the North Sea, English channel and the Baltic Sea. Coast of California and other special areas along the US coast are also defined as emission controlled areas (CARB), set by California Environmental Protection Agency. Today the global cap for the allowed sulphur content in the fuel are 4,5% m/m for the worldwide trade, the sulphur content must not exceed 1,5% m/m in the SECAs. Alternatively they may use alternative post-treatment strategies to reduce the SO_x emissions, as a scrubber. The NO_x Technical Code under Annex VI sets the regulations for NO_x emissions, and this is a result of the MEPC's agreement in 2005 to undertake a review of the Annex VI. In October 2008 the Annex VI was revised, and limits for SO_x emissions in the future was set. The important changes of the Annex VI were

Figure 2.6: SECA Areas

Globally

- From 1st of January 2012 the sulphur cap will be reduced from 4,5% m/m to 3,5% m/m
- Further reduction to 0,50% m/m as from 1st January 2020.

SECAs

- Reduction to 1% m/m from the current 1,5% from July 2010
- Further reduction to 0,1% m/m by 2015.

2.5.1 NO_x Technical Code

When we look into the NO_x emissions regulation, we usually refer to the Tier levels, where we today operate within the Tier I level from 2005. Tier II will be the standard in emissions for engines installed after January 2011, and introduce a reduction between 15,5 per cent and 21,8 depending on the engine's operation parameters. January 2016 the Tier III level will enter into force, however this is only valid for defined local areas near shore. Outside these areas, Tier level II will be valid. Tier III level corresponds to an 80% reduction in NO_x emissions over the whole speed regions for marine engines; see figure 2.7 for Tier I, II and III limits.

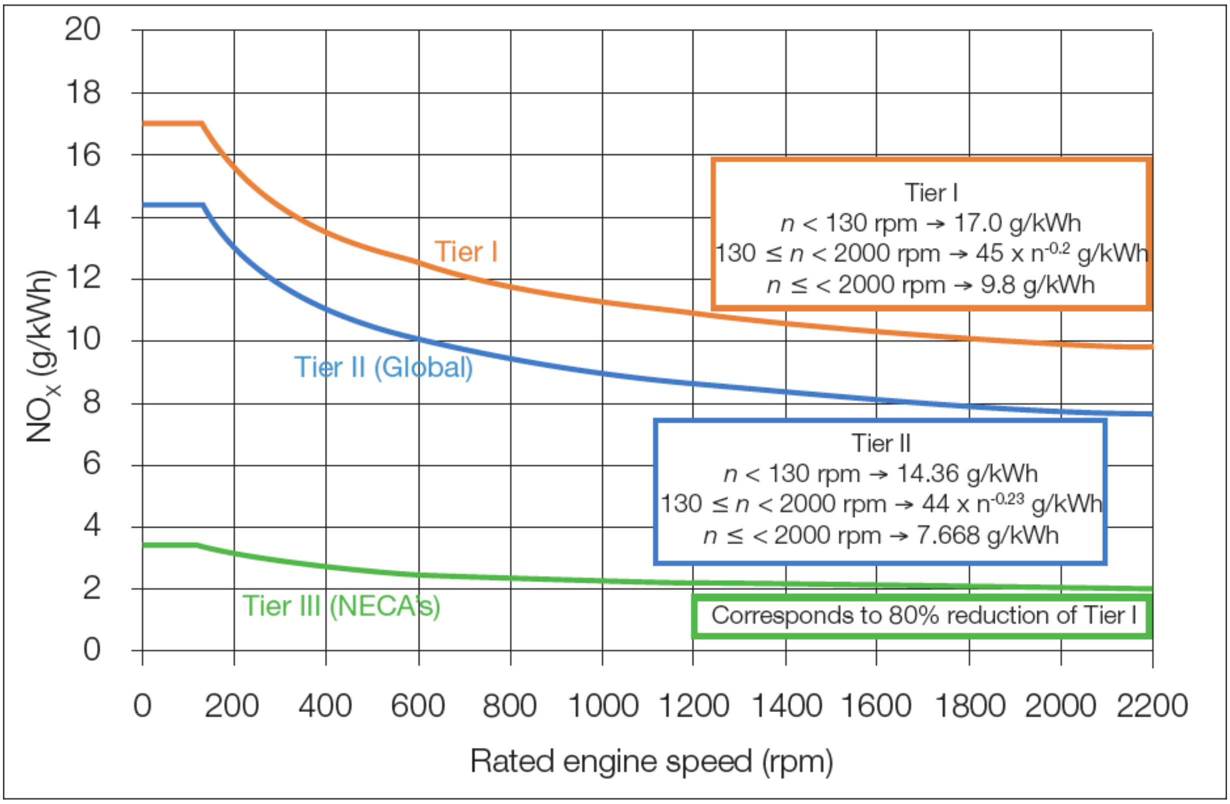


Figure 2.7: Tier Emission Levels [11]

Chapter 3

System Description of SCR

In this chapter an introduction to Selective Catalytic Reduction is given with respect to its components, working method and features. The system consists of a control unit which regulates the reduction agent's feed rate and a catalyst where the oxidation takes place. A system layout is presented in appendix D.

3.1 General Description

Selective Catalytic Reduction (SCR) is a system that reduces the NO_x in the exhaust gas into harmless nitrogen (N_2) and water (H_2O). This is done by adding a reduction agent as urea or ammonia to the exhaust flow. This system is placed under the post-treatment category of reduction measures for NO_x and works independent of the combustion process. Depending on different engine types and parameters, the SCR unit in general will have reduction efficiency of more than 90%. The efficiency are directly linked to the amount of urea added to the exhaust gas flow, thus in theory the system are capable of reducing all NO_x, however then with high risk of a considerable amount of ammonia slipping through the system.

For urea the stoichiometric reaction that takes place in the reactor is as follows

$$\underbrace{4NO}_{Nitrogen\ Oxides} + \underbrace{2\left(NH_2\right)_2 CO}_{Urea} + \underbrace{O_2}_{Oxygen} \rightarrow \underbrace{4N_2}_{Nitrogen} + \underbrace{4H_2O}_{Water} + \underbrace{2CO_2}_{Carbon\ Dioxide}$$

For ammonia the reactions are as follows

$$\underbrace{4NO}_{Nitrogen\ Oxide} + \underbrace{4NH_3}_{Ammonia} + \underbrace{O_2}_{Oxygen} \rightarrow \underbrace{4N_2}_{Nitrogen} + \underbrace{6H_2O}_{Water}$$

$$\underbrace{2NO_2}_{Nitrogen\ Dioxide} + \underbrace{4NH_3}_{Ammonia} + \underbrace{O_2}_{Oxygen} \rightarrow \underbrace{3N_2}_{Nitrogen} + \underbrace{6H_2O}_{Water}$$

$$\underbrace{NO}_{Nitrogen\ Oxide} + \underbrace{2NO_2}_{Nitrogen\ Dioxide} + \underbrace{2NH_3}_{Ammonia} \rightarrow \underbrace{2N_2}_{Nitrogen} + \underbrace{3H_2O}_{Water}$$

The most preferred reduction agent is ammonia in the form of a 40% urea solution of urea in water as urea is a stable and safe to store onboard, as opposed to ammonia. The urea is hydrolyzed to ammonia as the urea evaporates moisture with the heat of the exhaust gas. The reaction is as follows

$$(NH_2)_2\,CO + H_20 \rightarrow 2NH_3 + CO_2$$

Urea is also what will be used in the lab, but as a premixed 40% solution in water. Other benefits of the system are that it also will oxidize some of the soot particles and HC in the exhaust gas. The system has requirements to the fuel quality and exhaust gas temperature. The needed temperature for the reaction to take place is between 250 and 500 °C. This results in a different installation for two-stroke and four-stroke engines respectively. Two strokes engines have a lower exhaust temperature and therefore the SCR reactor must be placed between the exhaust gas receiver and the turbocharger. This is shown in 3.1 sketched by Wärtsilä. For the medium speed four stroke engine the exhaust temperature are within the limits of the SCR system also downstream the turbocharger. Therefore the SCR can be mounted at a separate location as long as inlet pressure is high enough to ensure a adequate flow through the catalyst.

A Selective Catalytic Reduction system represents a large additional investment and some additional operating cost. The operating cost includes maintenance and cost of urea. H+H Umwelt und Industrietechnik GmbH [7] list the following capital and operational expenditure

CAPEX: 30-50 €/kW

OPEX: 5-8 €/kWh

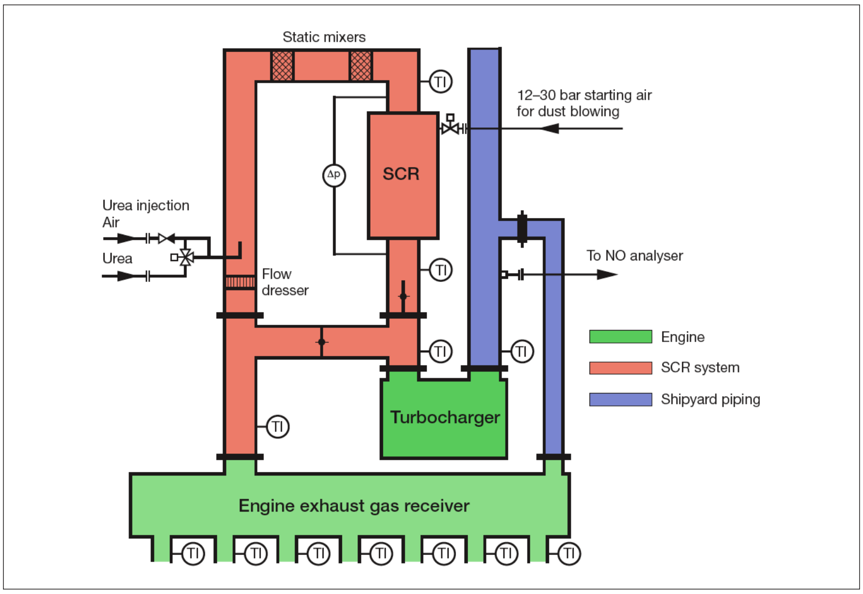
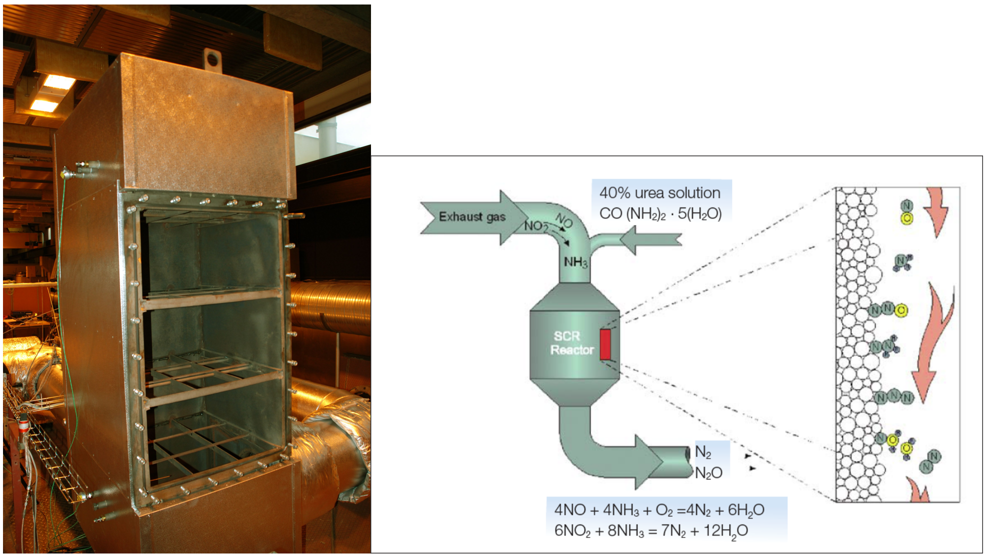


Figure 3.1: System layout for 2-stroke engine [17]

3.2 Catalyst

The catalyst is located in the exhaust system after the mixing of the exhaust gas and the urea solution. It is in the catalyst where the reaction takes place. The mixed gas flow enters the catalyst and flows through a set of ceramic stones with a honeycomb shape. The holes are rather small (≃4x4 mm for the catalyst in the lab) and depending on the design parameters, these sets limits to the sulphur content in the fuel used. The sulphur content will also have an influence on the temperature needed for the reaction to take place. The needed temperature will increase rapidly from 0 to about 1,5% sulphur content. There are two reasons for the temperature window for the reactor to work. If the temperature is too high the ammonia (Urea solution) will burn rather than react with the nitrogen oxides, and if it is too low the reaction rate will be to low. This will result in a condensation of ammonia sulphate and ammonia bisulphate that will destroy the catalyst, see chapter 4. The hole area in the ceramic stones are optimized for a certain dust content and if the temperature is violated, the pressure drop will increase across the catalyst and eventually block the flow. A bypass valve will always be installed to bypass the whole SCR system if needed, or in case of emergency. As the reduction rate of the SCR system makes it by far the most effective system on the market today we tend to see that the vessels with SCR



(a) Catalyst cabinet in MARINTEK laboratory

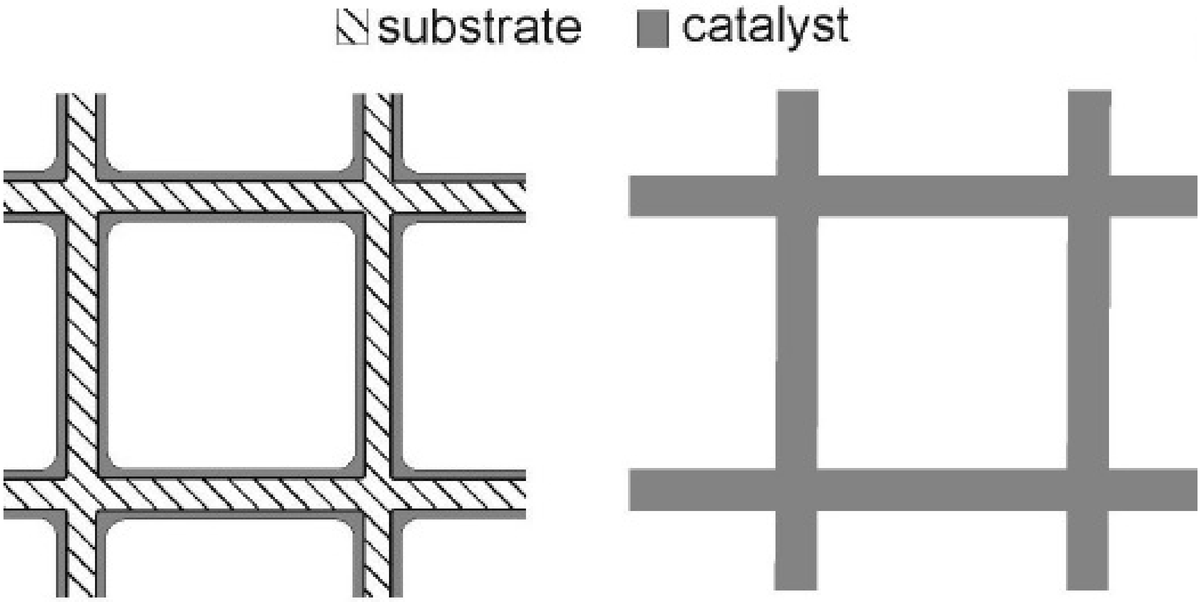
(b) Reaction in the SCR Catalyst

Figure 3.2: Catalyst

installed, mostly are vessels with special emission limits requirements. The most common use of the system for these vessels is to activate the SCR when needed due to special requirements and shut it down when no special regulations are present. This will reduce the operational costs of urea consumption and reduce degrading.

3.3 Catalyst Material (Honeycombs)

Today most applied catalysts are based on TiO_2 (Titanium di-Oxide) doped by Tungsten using Vanadium as active component. These catalysts are characterized by a high activity even at low temperature and high selectivity for NO_2 as product [12]. Zeolite may also be used as a base instead of TiO_2, and will give some differences in NO_x-convention rate over the temperature window for SCR operation. We have two types of catalysts on the market today; those that are coated with the active component, and those that are homogenous extruded honeycombs.



(a) Wascoat (coated) Honeycomb (b) Homogenously Extruded

Figure 3.3: Honeycombs

3.3.1 Coated Honeycombs

The coated honeycombs have a support material shaped after the desired parameters for the honeycomb. The support material functions as a carrier for the active material that is on top. Dipping it into an aqueous solution, usually TiO_2, does the coating of the carrier. After the coating the honeycomb is dried and calcined. The active material is usually Vanadium applied by impregnation.

3.3.2 Homogenously Extruded Honeycombs

In a homogenously extruded type, the material is uniform in all parts of the honeycomb. It is produced by mixing the active component with the support material prior to the shaping of the honeycomb. After the material has been extruded to an appropriate honeycomb structure, the material composition is balanced again to check for errors, before it's calcined. As this production method produces more active material per volume, the total volume of the honeycomb may be reduced and still maintain the same rate of NO_x-conversion, see figure 3.4. The most applied catalyst material today is the homogenously

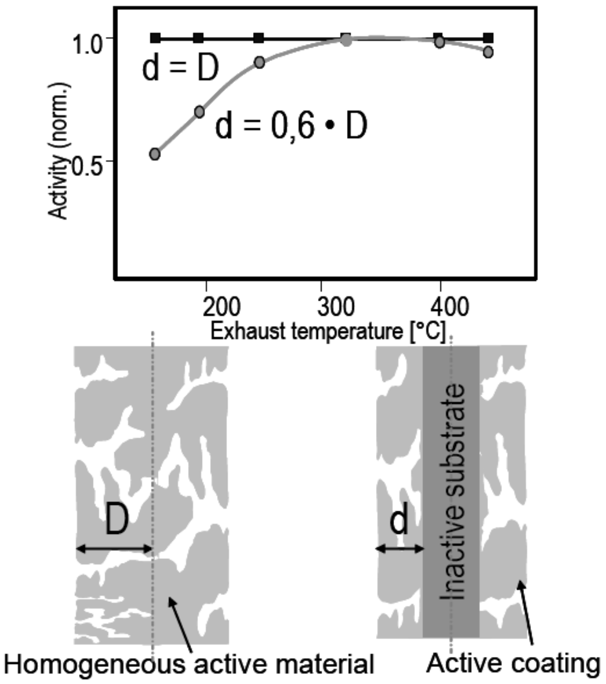


Figure 3.4: Wall Thickness

extruded honeycomb. This type is found in Yarwil's SCR system. Yarwil uses their "Vollkat" catalyst material, which has a proven long lifetime of 75000 hours. What separates Vollkat to other homogenously extruded honeycombs, if any, is protected as a professional secret. As mentioned the homogenously extruded honeycomb will result in a smaller honeycomb volume. This again will result in a reduced backpressure to the engine. The honeycombs are installed in sealed canisters that will improve their mechanical lifetime.

3.4 Control Unit

The control unit is the SCR system's brain and consist of a process computer and an ammonia dosing unit. The computer takes input from different measuring units in the system and from the engine. This data is again processed and gives input to the dosing unit that regulates the amount of ammonia fed into the exhaust gas flow. The most important input parameter fed into the control unit is engine load. The correspondence between engine load and NO_x are measured in the engine testbed [11]. Based on these results, the process computer controls the ammonia feed rate. Too low feed rate results in poor NO_x conversion, too high in ammonia slipping through the catalyst referred to as slip. Usually there are no continuos feed of NO_x reduction data fed into the control unit during operation. The other parameter that is read by the control unit is the inlet and outlet temperatures of the catalyst. These are the indicators that tells the control unit when it is acceptable to initiate the urea feed based on what sulphur content present in the fuel used. The control units are rigged with a different set of alarms to signal fault conditions in the system.

3.5 Soot Blower

The soot blower is an important function of the SCR system. The soot blower contributes to maintaining the catalyst throughput holes clean from soot and other deposits. At the catalyst cabinet there are installed air jets, which inject air at high pressure into the catalyst. The cleanness of the catalyst is of importance to its efficiency, and therefore the soot blower is indispensable. However there is still little knowledge about the effect of the soot blowing when it comes to emissions of particles. A test performed in the laboratory at MARINTEK on the SCR system, indicates that the system has a reduction effect on PM emissions, however the PM emissions increased significantly downstream to the catalyst after a soot blowing was performed.

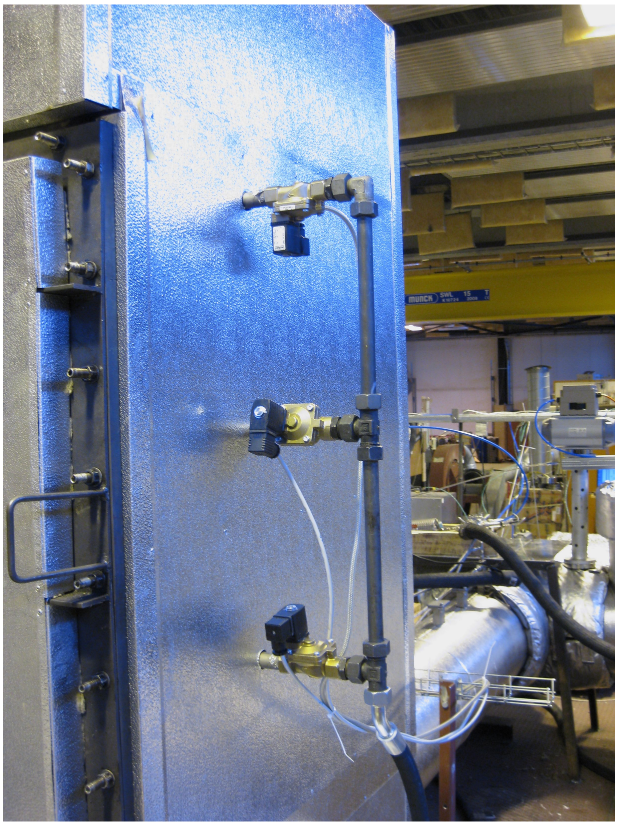


Figure 3.5: Soot Blower Injection

Part II

Degrading Mechanisms

Chapter 4

Degrading of Catalyst

When addressing the concerns regarding degrading or deactivation of the catalyst over time we already know the major contributors to this. Selective Catalytic Reduction is a well-tested system from operation through 30 years or more. The challenge is to find measures in order to remove or limit the degrading process. The two main concerns when it comes to catalyst degrading is fatigue of and deposits in the ceramic material. A more detailed description of the two is given in the following sections.

4.1 Fatigue of Honeycombs

A reported problem with the honeycombs is their low fatigue limit. This makes them vulnerable to vibration and thermal strain. Once installed in the exhaust system the catalyst is exposed to a broad diversity of stress, caused by mechanical, thermal and vibration sources. During operation the catalyst may face frequent changes in temperature due to variations in the engine load. Stress caused by vibration in the system is one of the key parameters that SCR manufacturers assess when designing a system for a client. It's crucial that vibrations of the SCR, usually caused by the engines, do not meet the resonant frequency of the surroundings. As the honeycombs have mechanical properties much similar to ceramic material they have a low fatigue limit.

The other aspect that is not well covered in research and other literature is whether the temperature variations may be a contributor to cause thermal strain. We know that ceramics is a substance well capable of sustaining high temperatures, thus in order for this to be a concern the temperature variations must be of significance. When dealing with temperatures in the catalyst we tend to see them in the region of the exhaust gas temperature downstream the turbocharger. It is therefore first of all in the transient operation we interested to see the variations, which is a part of the research presented in chapter 5.

4.2 Deposits in Catalyst Material

The part of degrading mechanism with the highest focus in the industry is the problem with deposits in the catalyst. The major concerns are the formation of ammonia sulphate $(NH_4)_2SO_4$ and ammonia bisulphate NH_4HSO_4, which is a product of too low exhaust temperatures and too high urea feed rate. The formation of these is best presented in a flow diagram as in figure 4.1.

4.2.1 SO_2 to SO_3 Conversion

The formation of ammonia sulphate and ammonia bisulphate are closely linked to the level of SO_3 present in the exhaust gas. As a result of the combustion almost all of the sulphur is converted into SO_2. Some of this SO_2, about 1%, is oxidized to SO_3 following the combustion. This is mainly due to the presence of vanadium origin from the fuel and lube oil that has a catalytic effect on this reaction. Vanadium is also present as the active material in the honeycombs contributing to a further increase of about 2% of SO_3. The sulphur trioxide reacts with the water vapour in the exhaust gas and converts to gaseous sulphuric acid [18]. There are two ways of controlling the SO_3 formation: By varying the amount of vanadium in the active material or by limiting the temperatures as seen in figure 4.2. The two upper lines describes how the activity in the catalyst varies with temperature and the two lower curves displays the oxidation rate of SO_2. As we know, it is hard in power plants to vary the exhaust gas temperature, hence the manufacturers' challenge is to optimize the amount of vanadium with respect to activity and SO_2 oxidation rate. Halldor Topsøe gives the following formula for $DeNO_x$ activity [5]

$$A_{DeNOx} = k_1 \times A_S \times C^a \times \eta$$

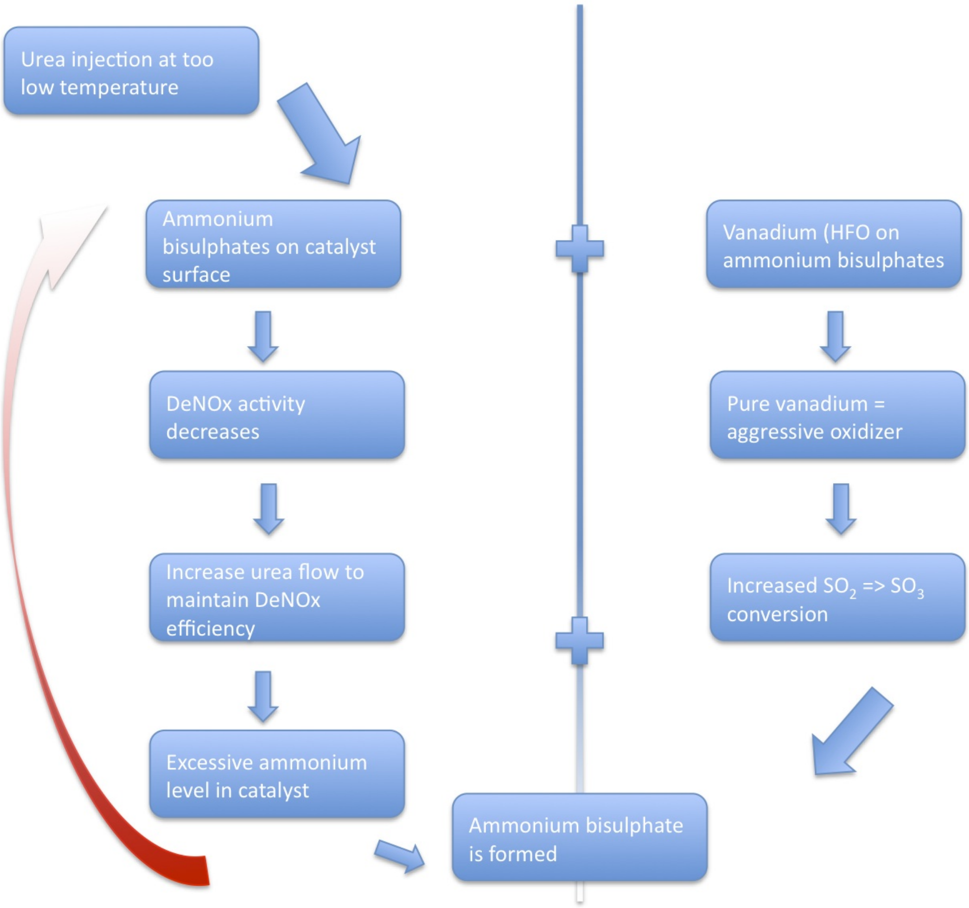


Figure 4.1: Formation of ammonium bisulphate - The “Evil Spiral” [9]

where A_S is the specific active surface area $(\frac{mm^2}{mm^3})$, C is the percentage of vanadium in the catalyst and η is the effectiveness factor accounting for the resistance towards diffusion of NO_x and ammonia to the catalyst active sites. Diffusion is explained by that not all of the active material in the honeycomb's channels that are utilized when it comes to NO_x conversion. Research shows that the reaction only takes place in the part of the channel where the gas flow is laminar. When the exhaust gas enters the channel the flow is laminar only a given length before it becomes turbulent. The oxidation of SO_2 is not limited by diffusion and thus takes place in the entire catalyst mass and we get

$$A_{SO_2} = k_2 \times W \times C$$

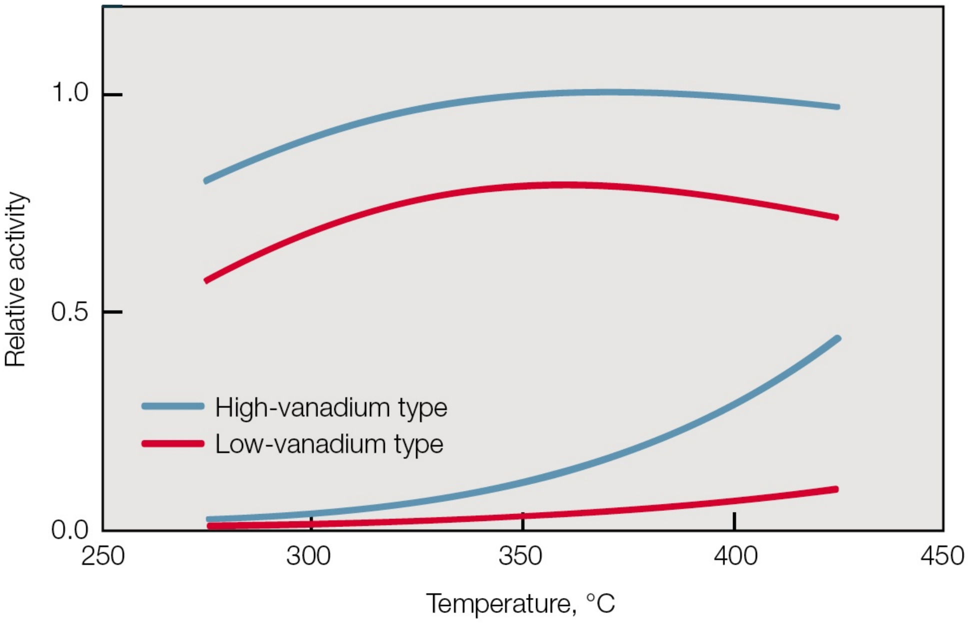


Figure 4.2: DeNo_x activity and SO_2 oxidation characteristics [5]

where A_{SO_2} is the activity towards SO_2 oxidation and W is the bulk density of the catalyst. Thus the best possible catalyst for a power plant minimizes

$$\frac{A_{SO_2}}{A_{DeNOx}} = k \times \frac{W}{A_S} \times C^{1-a} \times \eta^{-1}$$

4.2.2 Formation of Ammonia Sulphate and Ammonia Bisulphate [18]

The formation of these deposits are again dependent on the exhaust gas temperature and ammonia (NH_3) content. The formation of ammonia bisulphate (4.1) and ammonia sulphate (4.2) can be expressed with the following equations.

$$NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4 \tag{4.1}$$

$$2NH_3 + SO_3 + H_2O \rightarrow (NH_4)_2\,SO_4 \tag{4.2}$$

If we again take a look at figure 4.1 we see that the formation of ammonium sulphate and bisulphate will have give an evil spiral when it comes to degrading. These ammonia salts will function as an insulating layer on the catalyst surface and reduce the exhaust gas' exposure to the active material resulting in lower efficiency and less activity on the surface. This again will result in higher ammonia slip as less of the ammonia will be utilized for NO_x conversion. Together will this, when the NO_x reduction efficiency decreases end users tend to increase the feed rate in order to maintain the efficiency making matters worse. As wee see, the root cause of this evil spiral is when urea and ammonia are injected at too low temperatures resulting in low activity and slower reaction, hence higher levels of excessive ammonia present in the catalyst. The deposits may also cause corrosion as they have an acid pH of $< 1{,}4$.

There are ways to reduce the formation of and the negative effects of these deposits. By introducing magnesium oxide into the exhaust gas, we are able to reduce the content of SO_3 and make the removal of the deposits easier [18]. The reactions are as follows

$$MgO + SO_3 \rightarrow MgSO_4 \tag{4.3}$$

$$MgO + 2NH_4HSO_4 \rightarrow (NH_4)_2\,Mg\,(SO_4)_2 + H_2O \tag{4.4}$$

The magnesium oxide captures the SO_3 and forms magnesium sulphate which is a harmless salt (4.3), and reacts with the ammonia salt to form ammonium magnesium sulphate (4.4). This is a friable substance that has a melting point at about 400 °C, which makes it easier to remove by soot blowing and cleaning with regular water as it is very soluble.

4.2.3 Crystallizing of Urea in Injector Nozzle

At the end of the degrading mechanisms we must mention the crystallizing of urea in the injector nozzle. Before each experiment we thoroughly clean the nozzle due to crystallized urea. If this is not performed periodically the nozzle will deliver lower feed rate and eventually be clogged. The increased back-pressure to the feed pumps on the control unit may cause malfunctioning due to this. After each test the lab team have been surprised by the amount of urea that has collected after just one experiment with a few hours of testing. Figure 4.3 shows the amount of urea before the experiment 10.05.2010. The reason for the crystallizing is due to lack of circulation after the feed has stopped and a rapid drop in temperatures. The nozzle is also protected by a cap that allows the urea to store between the nozzle and the cap.

(a) Upper Nozzle

(b) Bottom Nozzle

Figure 4.3: Urea Injection Nozzles

Chapter 5

Temperature Variations in Catalyst

5.1 Background

When investigating the degrading mechanisms in the catalyst we must address the problem with the honeycomb's known low fatigue limit. Fatigue due to vibrations in the catalyst cabinet is a familiar problem, and we wish to investigate the contribution from thermal variations. We know little about the temperature differences inside the catalyst, and if they are of significance they may cause fatigue due to thermal strain.

The hypothesis is that in transient load conditions of the engine, the temperatures in the catalyst may vary in such large amount that the honeycombs experience thermal loads that may lead to reduced fatigue limit of the material. The catalyst material in the catalyst used is the "Vollkat" material used by Yarwil, and they do not reveal exactly what substances are present in these honeycombs. Most likely we see a material based on Titanium di-Oxide (TiO_2) or zeolite doped by tungsten using vanadium as the active component. The honeycombs are of the homogenously extruded type that makes the composition uniform over the whole cross section of the honeycomb. Their mechanical properties are much similar to ceramic material characterized by a low ultimate strength and capable of sustaining high temperatures. The goal of the first experiment is to investigate temperatures inside the catalyst in order to identify variations, and figure out if this may be a topic for further investigation.

5.2 Refitting of Turbocharger on KR3

The test engine used in the laboratory for SCR testing is a Rolls Royce KR3 with an output of 500kW. The KR3 has been refitted with a new more effective turbocharger in January 2010. The parameters that have changed as a consequence of this operation are presented in table 5.1.

KR3 Parameters at 100% Load		
Parameter	*Before*	*After*
Power [kW]	500	500
Engine Speed [RPM]	750	750
Fuel Consumption [g/s]	29,9	27,7
λ	2,3	2,78
Pressure Air Reciever [kPa]	2,48	2,85
Temperature Air Reciever [°C]	48,5	50,7
Pressure Exhaust Reciever [kPa]	1,6	1,9
Exhaust temp. before Turbine [°C]	584	473
Air Consumption [kg/s]	1,02	1,14
Exhaust Flow [kg/s]	1,05	1,17
NO_x [ppm]	976	1033

Table 5.1: Key engine parameters before and after TC Refitting (MGO)

The NO_x emitted has increased after refitting the engine with a new turbocharger, at the same time the exhaust temperature have decreased together with increased air flow. The generation of NO_x is dependent on both combustion temperatures and the residence time of the combustion, with the combustion temperature as the most significant factor. From table 5.1 we see that we have increased pressure and temperature in the air receiver. This leads to increased pressure and temperature at the beginning of the compression fase of the combustion process. As the physical parameters of the engine is unchanged, we will most likely have a shorter ignition delay, and higher temperatures in the ignition, generating more NO_x. To get the exact answer to how this has changed, we need to perform a dynamic analysis of the engine's combustion behavior to find the maximum effective pressure and find the Rate Of Heat Released (ROHR) curve. Then if we assume that the maximum temperature at the ignition is higher, we must turn to the increased air flow to find out why we have such high reduction in exhaust temperature. The air flow is one of the major factors to determine the exhaust temperature. Increased air flow and air-fuel ratio λ will reduce the exhaust temperature measured in the exhaust gas receiver, and this is the reason for the reduced exhaust temperature at the KR3 after the refitting.

5.3 Execution

5.3.1 Engine Loads and Exhaust Temperatures

We intended to measure PM emissions, NO_x emissions and temperature at the following engine loads:

- 30%
- 50%
- 75%
- 100%

Also the transient temperatures between these load conditions were logged. The ISO standard loads for engine testing are

- 25%
- 50%
- 75%
- 100%

The reason for why we are using 30% load instead of 25% is that the exhaust gas temperatures are too low too start the urea feed. We intended to measure at all of the 4 load conditions, however we experienced some challenges with utilizing 30% load. After the new turbocharger was installed we experienced a drop in exhaust gas temperatures for all engine loads, and for this reason 30% load could not be used. The system has been calibrated for operation at MGO, as the minimum temperature is 290 °C to initiate urea feed. The MGO used in the lab holds a sulphur content below 0,05% by mass. The experiments are also meant to be done with HFO as well. The HFO used in the lab holds

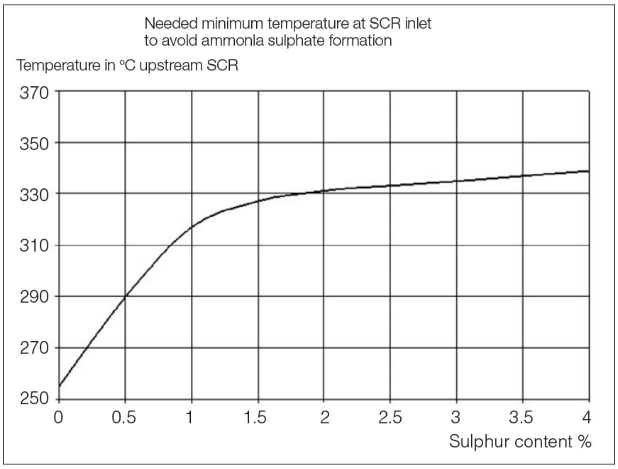


Figure 5.1: Minimum exhaust temperature depending on sulphur content in the fuel

a sulphur content of 1,0%. According to figure 5.1, we should have a minimum exhaust temperature of about 320 °C for operation at HFO at all load conditions. This is in order to ensure that we have optimal operation with respect to reduction efficiency and avoid formation of deposits. The curve in figure 5.1 is a general curve for SCR catalysts, and are not specifically designed for the Yarwil catalyst in our laboratory. As we see from table 5.2 we are for HFO operation barely within the limit of exhaust temperature at 75% load and more.

The measured exhaust gas temperatures upstream and downstream the turbocharger, before and after the refitting are presented in table 5.2.

Exhaust Gas Temperatures					
Date	*Load*	*30%*	*50%*	*75%*	*100%*
25-11-2009	Before Turbine [°C]	379	469	532	584
	After Turbine [°C]	300	351	378	396
18-02-2010	Before Turbine [°C]	344	395	433	473
	After Turbine [°C]	300	319	324	329

Table 5.2: Exhaust temperautres before and after TC Refitting

For this reason the experiment was only carried out at 50% MCR and higher with HFO.

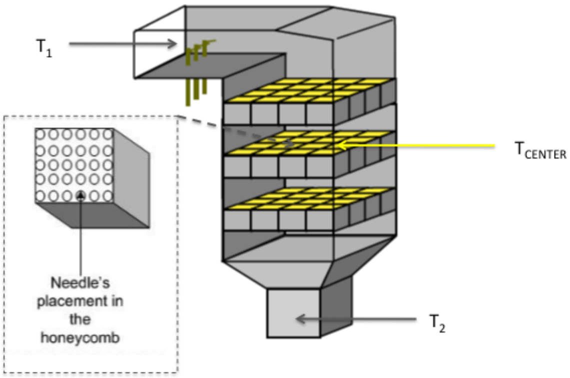


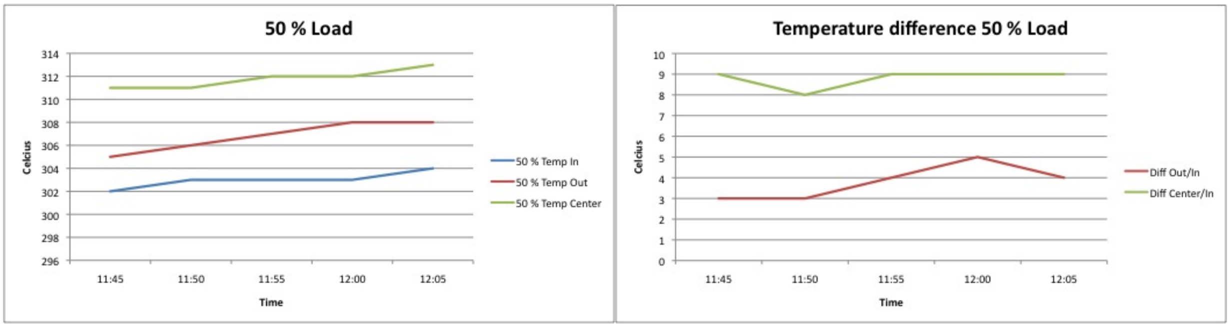
Figure 5.2: Points of measurements in experiment.

5.3.2 Measurements

Sensors in the catalyst cabinet, one at each location, measure the inlet and outlet temperatures. These sensors are mounted by maker and are displayed at the systems control unit. Additionally a third sensor has been mounted by MARINTEK on my request in order to log the temperature in centre of the catalyst. The centre sensor is mounted with the needle tip positioned into the catalyst's honeycomb, and therefore is not directly exposed to the exhaust gas as seen in figure 5.2. This needle measure the current temperature in the catalyst material. As the reaction that takes place in the catalyst is somewhat exothermic [1], we expect to see a rise in the temperature over the catalyst. The experiment will be conducted two times with use of MGO and HFO respectively. For logging of the PM emissions the Dekati ELPI and TSI SMTS were used, and for the NO_x measurements we used the Horiba PG-250 portable gas analyzer. The temperatures were registered manually into a spreadsheet. For stationary conditions temperatures were registered with 5 minutes intervals, while in transient conditions we measured every minute. This was mainly in order to get more accurate detection of the transient temperatures as they changed more rapidly.

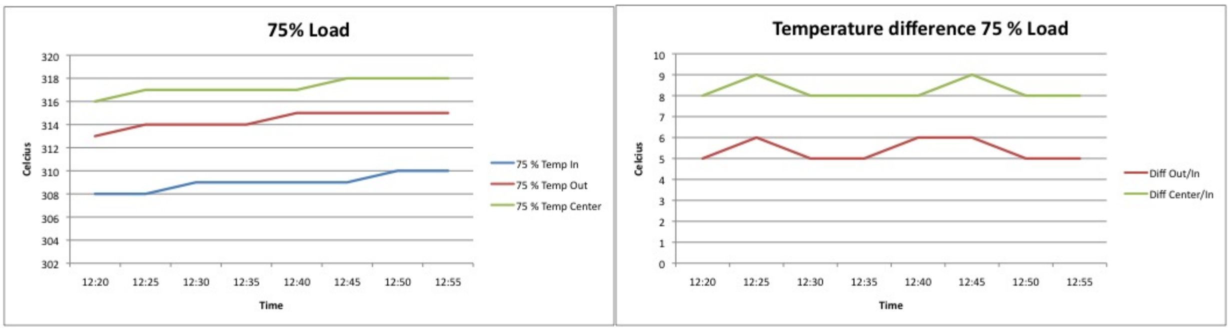
5.4 Results

The temperature variation are present, but not as significant as expected. As the system is stabilized we tend to see a temperature difference in the lower edge of 10 °C. We first consider the temperatures at stationary conditions for operation on MGO.



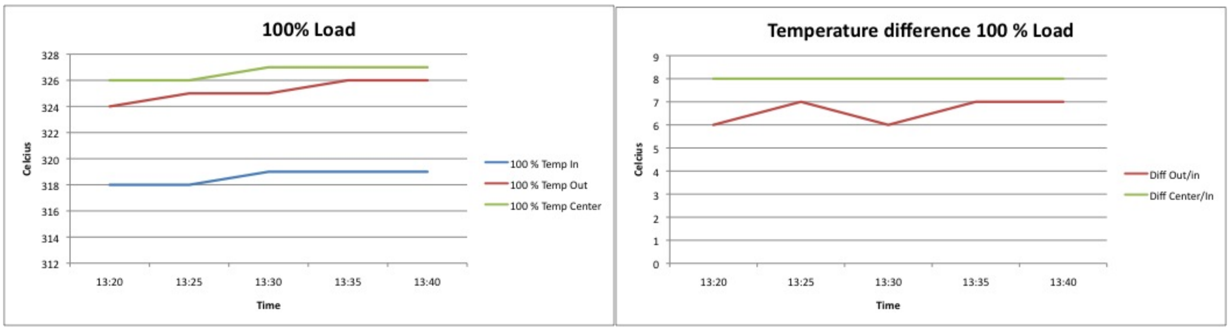
(a) Temperatures (b) Temperature difference

Figure 5.3: Measurements at 50% Load



(a) Temperatures (b) Temperature difference

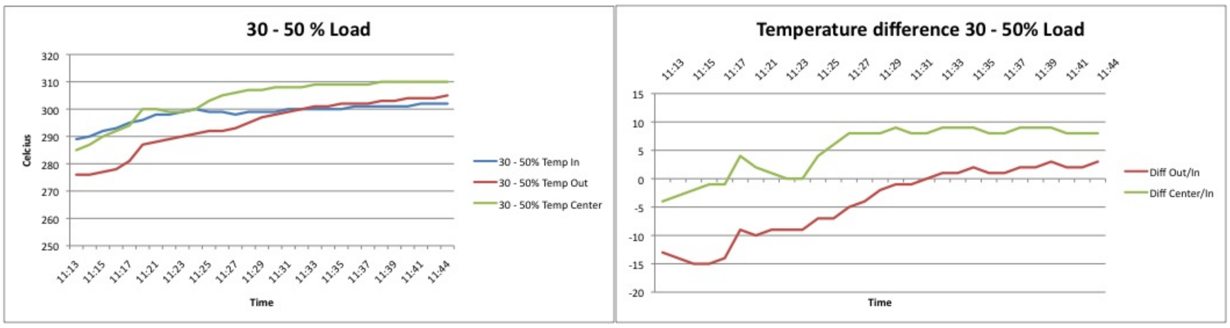
Figure 5.4: Measurements at 75% Load



(a) Temperatures (b) Temperature difference

Figure 5.5: Measurements at 100% Load

Here we see that in all cases the outlet temperature of the catalyst is higher than inlet. The complete overview of the temperatures and temperature differences for both MGO and HFO is listed in appendix A. The increase in temperature over the catalyst can be explained by the exothermic reaction that takes place in the catalyst. As the reaction takes place at the catalyst surface we find reason to believe at this point that the heat is exchanged from the catalyst wall to the exhaust gas. The results for the transient conditions are presented in figure 5.6, 5.7 and 5.8. Here we tend to see higher variations between T_1,T_2 and T_{Center} although they are at no point striking compared to what expected by the lab-team. The largest variations are without doubt during the start-up of the system. Although they are present it is doubtful that they are sufficient to cause any thermal strain of the ceramic material. During normal operation for vessels in commercial trade we generally don't see frequent load variation, which will not contribute to the effect if we assume the strain is a product of temperature variation and engine load change frequency. However this is only partly true. Mostly vessels equipped with SCR are offshore vessels with a lot of DP activity, which gives frequent load variations on the engine. As we see from the results the temperature does not vary significantly with change of engine load, and with this we again may conclude that it is only in the start-up phase we tend to see the large variations, which again probably are not sufficient to cause thermal strain.

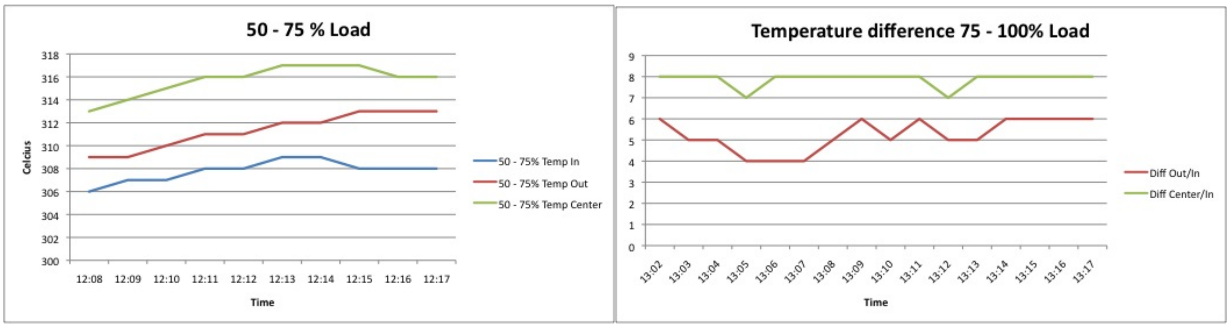


(a) Temperatures (b) Temperature difference

Figure 5.6: MGO Measurements at 30-50% Load

5.5 Discussion of Results

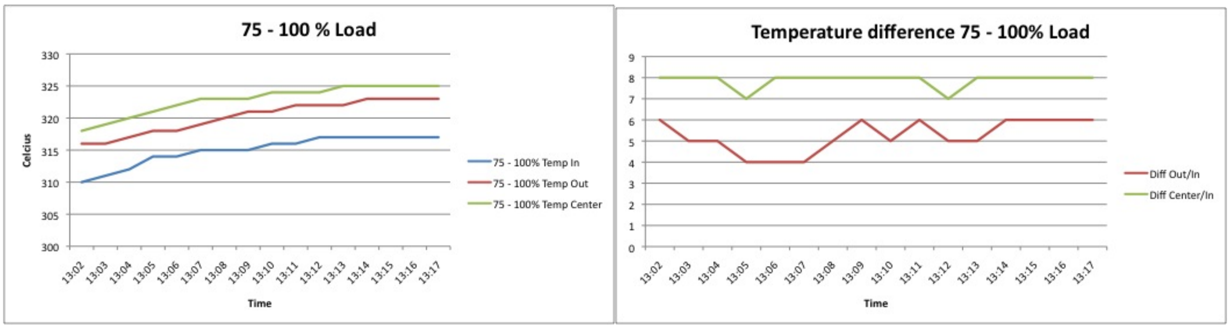
As for the temperature differences logged, we will conclude based on these findings that the differences are not of significance when it comes to stress due to thermal load. The temperature were logged at three places in the catalyst, and will therefore give us an indication of how the exhaust gas temperature changes over the catalyst. Whether these logged temperatures are completely accurate is on the other hand quite uncertain. In order



(a) Temperatures

(b) Temperature difference

Figure 5.7: MGO Measurements at 50-75% Load



(a) Temperatures

(b) Temperature difference

Figure 5.8: MGO Measurements at 75-100% Load

to recognize these as acceptable data we need to assume that the exhaust gas temperature is close to uniform over the cross-section of the catalyst. This seems unlikely, however we may ask our self how likely it is that the temperature varies in such large scale that it will influence the final conclusions.

If we further consider the additional temperature sensor that was installed, this was placed in the catalyst material and is therefore not a measurement of the exhaust gas temperature at that point in the catalyst. We assume the gas temperature lies somewhere between inlet and outlet temperature in all cases of measurements. On the other hand, this positioning of the T_{Center} measurement pin has proved to us that the reaction that takes place is somewhat exothermic.

5.6 Further work

As the temperature differences were small, we see no reason for spending much time and effort in trying to limit the source of errors for this experiment. The need of action if this should be tested again, is to install more sensors over the cross-section of the catalyst in order to check whether the temperature is uniform. As the hypothesis about thermal load is close to rejected, we can see one reason for future monitoring of the temperatures. This is to see if the temperatures logged in the catalyst may be a guide to other performance or degrading related issues. One possibility is that if we log the temperature in the catalyst material to be the same as in “new” condition after several running hours, and we see a drop in difference for the temperature in and out of the catalyst, this can give us an indicator for degrading. This means that a reduced heat transfer between the catalyst material and the exhaust gas indicates settlement of deposits and that this undesired layer is slowing the reaction down. This is a topic for further testing and lab experiments. This will not require more temperature sensors to be installed in the catalyst as we in later experiments can use the same set-up to search for these indicators.

Chapter 6

Temperature as Indicator of Degrading

6.1 Background

To investigate the temperature's connection to degrading further we had to plan and execute a new experiment with another focus. The experiment is a continuation of the first experiment and its findings. We concluded with the fact that the probability for degrading of the catalyst due to thermal strain in ceramic material is limited. On the other hand we did see the exothermic reaction's influence on the exhaust gas temperature. The work presented in this chapter is centered on the hypothesis that the temperatures may indicate whether the catalyst has been degraded. As degrading is almost impossible to investigate in a laboratory environment we here need to identify a possible correlation between temperatures and catalyst activity. The hypothesis has evolved from the findings and conclusions in the last experiment and most of the content in this chapter comes from the second experiment conducted in the laboratory, where we now have calibrated the urea feed rate according to the new engine performance.

6.2 Hypothesis

If we take a look at the measurements done in chapter 5, we have the three different temperatures logged as described in section 5.4. T_{center} is as known placed in the catalyst material, T_1 and T_2 is the temperature upstream and downstream the catalyst respectively. The interesting figures in this experiment is the $\Delta T = T_2 - T_1$ under different load conditions. The catalyst activity is dependent on the exhaust gas temperature and the urea feed rate [15]. As we see from the last experiment in figure 5.3, 5.4 and 5.5, the temperature T_{Center} increases with higher engine load, due to increased activity. From the hypothesis, the temperature T_{center} will therefore set the basis for the heat exchanged, ΔT. For an entirely new catalyst we should be able to find a baseline for ΔT under different load conditions after the urea control unit has been calibrated. What we want to investigate in this experiment is what happens with the heat exchanged between the catalyst material and exhaust gas after the system has experienced several running hours. After significant operation time the catalyst are bound to have some sort of deposits covering the honeycomb's surface. This may function as an insulating layer and thus reduce the heat exchange. If we compare the heat exchange at this point with measurements for the same catalyst in new condition we should be able to detect a difference. The approach for us in a laboratory environment with a new catalyst, is to search for a connection between the heat exchanged and the catalyst activity as the activity is likely to decrease with deposits in the catalyst [9].

6.2.1 Experience from Exhaust Gas Boilers [2]

A lot of research has been done on this topic related to exhaust gas boilers, where the exhaust gas heat are used for steam production. It is a common problem that soot and calcium make a coat inside the heat exchanger and reduce the heat transfer. For all heat exchangers we can calculate the temperature efficiency ε with the Epsilon NTU method, characterized by

$$\varepsilon = \varepsilon(\kappa, z) \Rightarrow \varepsilon = \frac{1 - e^{z(\kappa-1)}}{1 - \kappa(e^{z(\kappa-1)})}$$

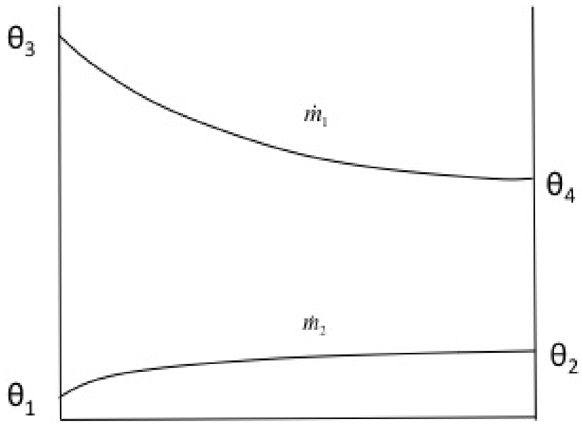


Figure 6.1: Temperatures in paralell flow heat exchanger

The kappa κ represents the relation between the minor and major heat capacities ($\dot{C}_{min}$ and $\dot{C}_{max}$) of the two mediums in the heat exchanger. For an exhaust gas boiler we have

$$\kappa = \frac{\dot{C}_{min}}{\dot{C}_{max}} \rightarrow 0 \; as \; \dot{C}_{max} >> \dot{C}_{min}$$

as we deal with a water/air heat exchanger. When $\kappa \rightarrow 0$ we can reduce the equation to

$$\varepsilon \simeq 1 - e^{-\kappa} \Rightarrow \varepsilon \simeq 1 - e^{-\frac{kF}{\dot{C}_{min}}}$$

Where k is the thermal efficiency number, F is the the heat exchanger area. Based on empirical data we know how the thermal efficiency number k develops as a function of deposits' layer thickness and type [2]. With this data we can calculate the expected temperature efficiency ε of the heat exchanger.

Then how can this theory be applied for my problem as we have only one medium flowing through a catalyst with constant temperature. The temperatures in the catalyst are known from the first laboratory experiment, but not the thermal efficiency number. However, with this formula, we can for a given heat exchanger be able to calculate the thermal efficiency number k, when inlet and outlet temperatures are known for both the exhaust gas and the water. With this, we may be able to apply the theory to our problem. For a given heat exchanger (e.g. parallel flow) where the temperatures are known, we may have a situation as in figure 6.1 For this heat exchanger we have a temperature efficiency of

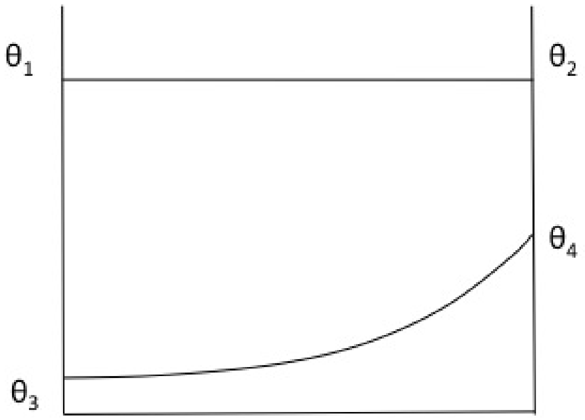


Figure 6.2: Temperatures in catalyst

$$\varepsilon = \frac{\theta_3 - \theta_4}{\theta_3 - \theta_1}$$

which is the measured temperature difference, divided by the maximum theoretical difference for the selected mass flow $\dot{m}$ (water or exhaust gas) [14]. For the catalyst we have a situation as shown in figure 6.2 and the temperature efficiency therefore becomes

$$\varepsilon = \frac{\theta_3 - \theta_4}{\theta_3 - \theta_2}$$

where θ_1 and $\theta_2 = T_{Center}$, $\theta_3 = T_1$ and $\theta_4 = T_2$. As we know the temperature efficiency ε, we should be able to find a value for the thermal efficiency number k and investigate how k changes during the operation time if we see changes in the temperatures logged. For our situation it is hard to find the effective area F where the heat is exchanged, thus we will find a value for $k \times F$. With this we will be able to track the difference in k as the area is constant. The expression will be as follows

$$\varepsilon \simeq 1 - e^{-\kappa} \Rightarrow \varepsilon \simeq 1 - e^{-\frac{kF}{\dot{C_{min}}}}$$

$$e^{-\frac{kF}{\dot{C_{min}}}} = 1 - \varepsilon$$

$$\ln e^{-\frac{kF}{\dot{C_{min}}}} = \ln(1 - \varepsilon)$$

$$-\frac{kF}{\dot{C_{min}}} = \ln(1 - \varepsilon)$$

$$kF = -\ln(1-\varepsilon)\dot{C_{min}}$$

In order to utilize this formula, we need to assume the criterion $\kappa = \frac{\dot{C_{min}}}{\dot{C_{max}}} \to 0$ are fulfilled for the catalyst as well, which is reasonable as the catalyst material is bound to have higher heat capacity than the exhaust gas.

6.3 Experience from laboratory experiment with “White Diesel”

Before performing the second lab test, we did a test with the engine operating on “white diesel”, which is diesel with 30% water added, resulting in a mass factor of water at 23,1%. This technique for NO_x reduction known as water addition are explained in the project thesis, and a short description will be given here. Water addition is one of the primary methods for NO_x reduction (figure 2.3), and involves lowering the temperatures in combustion with the heat capacity of the water “stealing” heat during the compression fase. The rule of thumb is that one percent water equals one percent reduction in NO_x emitted. This experiment was under time constraints and was a short introduction for the lab team to experience operation on white diesel. Therefore we only performed the test at 50% and 75% MCR, doing a gradually changeover from MGO to white diesel at 50% load. After the all MGO in the pipes was consumed the engine was operating solemnly on white diesel. We then registered following key data presented in table 6.1.

“White Diesel”		
Parameter	*“White Diesel”*	*MGO*
Fuel Consumption [g/s (g/kWh)]	19,9 (284)	14,2 (204,6)
λ	2,96	3,2
Exhaust temp. before Turbine [°C]	380	395
HC Emission [ppm]	14	172
CO Emission [ppm]	38	132
CO_2 Emission [%]	4,88	4,5
NO_x [ppm]	822	966

Table 6.1: Key parameters for operation on White Diesel compared to MGO at 50% Load

As we see, the reduction in real pollutants are present, while the CO_2 emissions has increased. This can be explained with the increased fuel consumption due to the reduced net heating value of the fuel. The water added to the fuel successfully “steals” heat from the combustion, which is somewhat displayed in the exhaust temperature.

Before this test, the SCR control unit had been calibrated by a Yarwil technician after refitting the turbocharger, for operation on pure MGO. As the NO_x emissions are higher in operation on MGO, we were now overdosing urea into the SCR catalyst. This had consequences for both the temperatures logged (T_1,T_2 and T_{Center}) and the NO_x reduction efficiency. The measurements were done at the beginning and at the end of the operation time at 50% load; therefore the start measurements will represent operation at pure MGO and the end measurements operation at white diesel. The results for each of the operating conditions are presented in table 6.2.

Temperatures and NO_x emissions		
Parameter	*MGO*	*“White Diesel”*
T_1 [°C]	296	296
T_2 [°C]	299	305
T_{Center} [°C]	306	306
NO_x (Upstream SCR)[ppm]	973	852
NO_x (Downstream SCR) [ppm]	73	7,2
NO_x eduction [%]	92	99

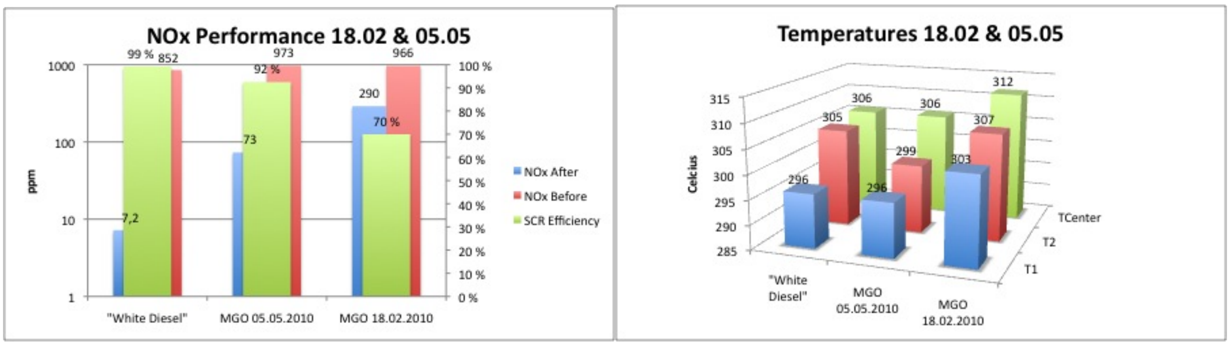
Table 6.2: Temperatures and NO_x emissions for test 05.05.2010 at 50% Load

When comparing these results with the first lab experiment where the feed rate was significant lower, we have now a higher reduction efficiency presented in table 6.3 and figure 6.3.

Based on these results it is impossible to make any conclusions. As we see from table 6.3 and figure 6.3b, we cannot see a connection between the temperature T_1,T_2 and T_{Center} and NO_x reduction efficiency. However there are as known strong correlation between NO_x reduction efficiency and increased urea feed rate as expected. After the adjusting the feed rate it has been increased from 6,5 to 7,5 $\frac{l}{h}$ at MGO an increase of approximately 15,4%, which has resulted in a increased NO_x reduction efficiency of about 31%. With the operation on white diesel, we had a primary reduction by the white diesel of NO_x at $1 - \frac{852}{973} \simeq 12,5\%$. The engine delivered now 852 ppm into the catalyst compared to 973

Comparison with experiment 18.02.2010			
Parameter	*MGO 18.02.2010*	*MGO 05.05.2010 (Calibrated Feed)*	*"White Diesel"*
T_1 [°C]	303	296	296
T_2 [°C]	307	299	305
T_{Center} [°C]	312	306	306
NO_x (Before SCR)[ppm]	966	973	852
NO_x (After SCR) [ppm]	290	73	7,2
NO_x Reduction [%]	70	92	99

Table 6.3: Comparison experiments MGO 05.05.2010, 18.02.2010 and "White Diesel"



(a) NO_x Performance

(b) Temperatures

Figure 6.3: Temperature and NO_x performance 18.02 and 05.05

ppm at MGO, which results in a overdosing of urea into the catalyst. As we see from table 6.3 the reduction efficiency are high, but most likely with a considerable amount of ammonia slip.

To get back to the focus on temperatures and degrading, we can as indicated not see any correlation between T_{Center} and the activity on the catalyst surface. The temperature T_{Center} seems to mostly be dependent of T_1. With this in mind we prepared for a more detailed experiment with operation on MGO solemnly.

6.4 Execution

To use temperatures as indicator of degrading we must in the lab see the connection between activity and temperatures. We assume the activity is reduced when we have deposits in the catalyst and for us to vary the activity, we must vary the feed rate. After calibrating the urea control system, the feed rate was 7,5 $\frac{l}{h}$ at 50% load. The feed rate could be adjusted by changing a k-factor that for 7,5 $\frac{l}{h}$ is 100%, and we adjusted it by setting the k-factor to the values for testing presented in table 6.4. The k-factor must not be confused with the thermal efficiency number k as it is just a figure for easy adjustment of feed rate. The intention with this experiment was to do measurements at all ISO loads (see section 5.3) from 50 to 100% for both HFO and MGO. However due to the many changes in urea feed rate, we had to concentrate on doing measurements at 50% load at MGO solemnly. It takes some time for the system to stabilize after a change in the feed rate, and the team decided to focus on acquiring good test data to minimize the sources of errors. We started with a factor k=100% in order to get a reference value for the system and set a baseline for comparison. Then we gradually decreased the k-factor to 50% before we started with k-factors larger than 100% as presented in table 6.4. The reason for the k-factor of 126% during the bleed operation is the increased NO_x emissions when bleeding the compressor and was a test point described in more detail in chapter 8. After doing measurements with different k-factors we decided to do some modifications to the engine to evaluate the exhaust gas temperature's influence on the ammonia slip. The modifications done were to start a bleed in the exhaust gas stream between the exhaust manifold and turbocharger compressor. This is in order to reduce the airflow and hence increase the exhaust temperature. Together with this, we also reduced the flow of the cooling medium to the air receiver, which contribute to a similar effect. The properties of the engine performance are listed in table 6.5.

k-factor tested	
Normal Operation	*Bleed*
100%	100%
95%	90%
90%	80%
80%	70%
70%	60%
60%	50%
50%	110%
110%	*126%*
120%	N/A

Table 6.4: k-factors tested for normal operation and compressor bleed (chronological)

Compressor bleed data		
Parameter	*Normal*	*Bleed*
Temp. Air reciever [°C]	37,6	71,7
Temp. After turbine [°C]	321	357
Air consumption [kg/kWh]	9,2	8,89
Exhaust flow [kg/kWh]	9,4	9,09
λ	3,1	2,98
NO_x [ppm]	981	1236

Table 6.5: Changed parameters as result of compressor bleed

The k-factor was then changed accordingly in the same rate as before the bleed of the engine. It is a pity that we were not able to do measurements for operation at HFO. As seen from the last experiment we had lower temperature efficiency for the HFO at 1% sulphur content, which is probably connected with the higher dust content in the exhaust gas. Measurements were done at the beginning and end of each test point, as it takes the system some time to stabilize after changes.

6.5 Results & Comments

As mentioned, degrading is hard to investigate properly in a laboratory environment due to the short time of operation. We are not able to measure changes in the catalyst over time and hence must rely on indicators and predictions. The main purpose is to investigate the correlation between the activity in the catalyst and temperature at the catalyst surface represented by T_{Center}. In order to do so, we need to define the term activity. In the literature and by SCR manufacturers the activity is referred to as the NO_x reduction rate or more precisely the amount of NO_x that is converted into N_2 and H_2O vapour. We know that exhaust gas temperature is of importance for the catalyst in order to assure the reaction speed is sufficient. We also know that the needed exhaust temperature increase with the sulphur content in the fuel. However the main influence on the NO_x conversion rate is the urea feed rate. This we got confirmed in this experiment as well, presented in figure 6.4 for both before and after the bleed of the compressor. The red pillar represents the load point with k-factor 126% where we only have NO_x readings available[1].

(a) Normal Operation

(b) Bleed of compressor

Figure 6.4: Urea feed rate and NO_x reduction efficiency (activity)

For the temperatures, if they are connected to the activity, we should according to the hypothesis see a fall in T_{Center} together with the fall in urea feed rate as the NO_x reduction rate declined accordingly. As shown in figure 6.5 this is not the case as T_{Center} is close to constant during the feed rate drop. However the temperature increases from 314 to 316 as the k-factor is increased from 50 to 120%, displayed in figure 6.5 and figure 6.6 for the

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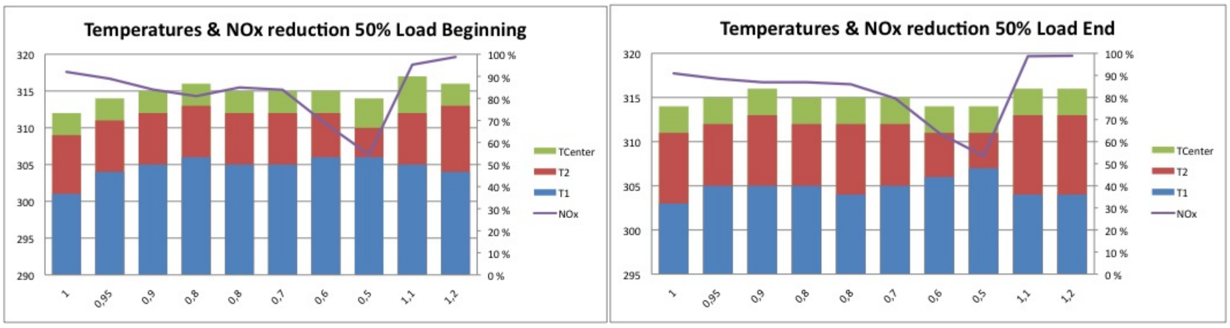
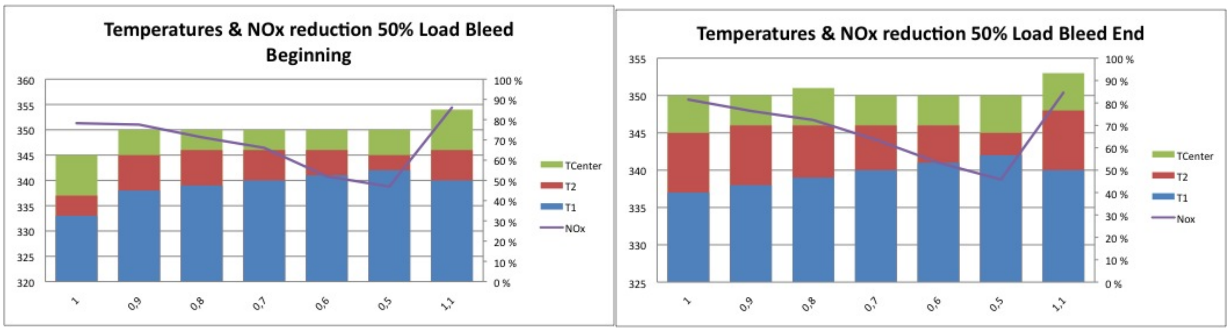
[1] The results will be presented chronological and not by size of k-factor.

bleed operation.



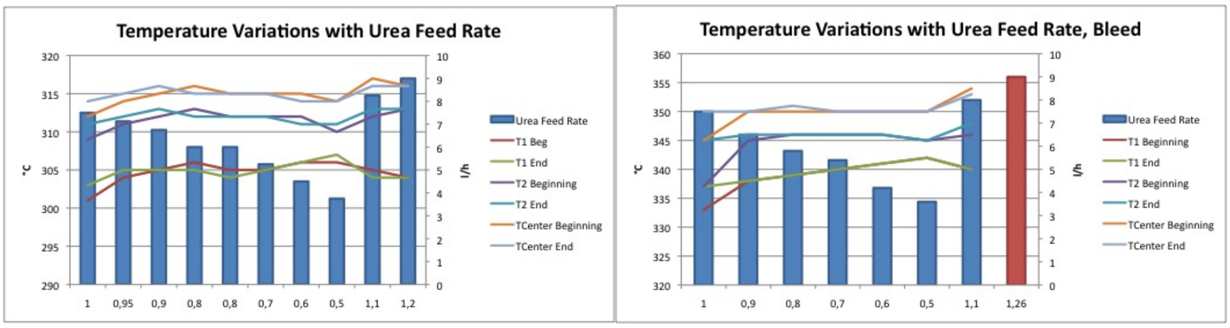
(a) Beginning (b) End

Figure 6.5: Temperatures logged and SCR efficiency



(a) Beginning (b) End

Figure 6.6: Temperatures logged and SCR efficiency when bleeding the compressor



(a) Normal operation (b) Compressor bleed

Figure 6.7: Temperature variations with change of urea feed rate

If we summarize the information that is brought to us by these figures we can draw the following conclusions

- The NO_x reduction efficiency declines with reduced urea feed rate. We have relatively low changes in T_{Center} as we vary the urea feed rate.
- T_1 varies with the urea feed rate. Increased feed rate gives lower inlet temperature. The explanation for this is that the urea solution, which mainly consists of water, is stealing heat from the exhaust gas as it is injected into the gas flow with its high heat capacity.
- As T_1 falls, we see T_{Center} remaining approximately constant, and T_2 seems to follow T_{Center}.
- The temperature difference ΔT seems to follow the NO_x reduction efficiency as we change the urea feed rate, displayed in figure 6.5 and 6.6 as the red area.

Based on these results it is hard to claim that we have a connection between ΔT and the degrading of the catalyst. However, we clearly see a connection between ΔT and the NO_x reduction efficiency (activity). As we see no connection between the activity and variation in T_{Center}, maybe we need to change assumption to how heat is transferred in the catalyst. The hypothesis has been based on that the reaction and activity generates heat in the catalyst material and its surface, which again is responsible for heating the exhaust gas. These findings clearly indicates that it is the ΔT that connects with the NO_x reduction efficiency instead of the T_{Center} parameter. This means that the theory about ΔT is a result of heat exchanged between the catalyst surface and exhaust gas most likely is wrong. By approaching the reaction the other way around, the findings make more sense. The reaction that takes place converting NO_x to N_2 and H_2O is exothermic as mentioned earlier. That means that it is the reaction itself causing heat increase. Higher activity and NO_x conversion rate are likely to give us higher temperature difference, hence the trend connection in figure 6.5 and 6.6. With this in mind, we may also conclude that the heat is exchanged from the reaction to the catalyst surface, and not the other way around as believed earlier. If we take a look at figure 6.8 it shows that the reaction takes place in the pores of the catalyst wall, and the wall will then be heated by the reaction.

The only thing speaking against this is the fact that the T_{Center} always are higher than T_2,

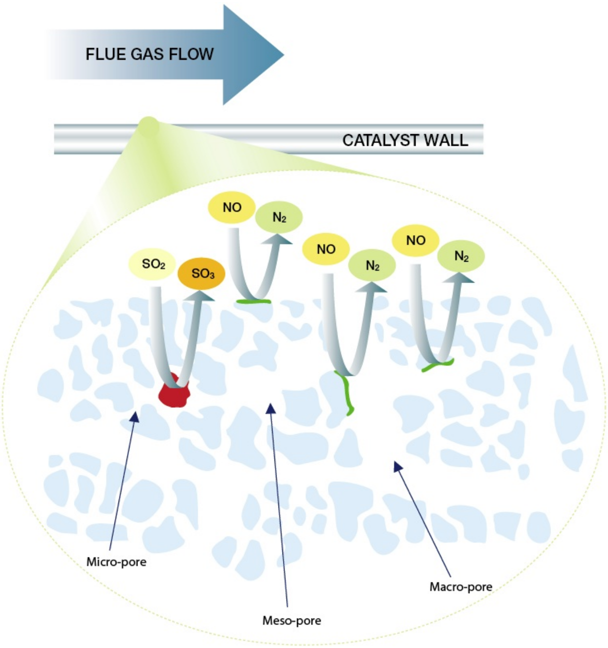


Figure 6.8: Reaction in pores

which violates fundamental thermodynamic theory. The explanation for this can only be speculation, however we should have reason to believe that the exhaust gas may be cooled on its way down the catalyst to the T_2 sensor after the reaction has taken place.

As we now have changed our approach to how the heat is exchanged in the catalyst we find it hard to continue the work around the Epsilon NTU method for appliance on SCR, especially as we tend to see no correlation between T_{Center} and the activity. On the other hand it should be possible to find a similar value to the thermal efficiency number k for SCR systems as well that indicates the amount of degrading by reduced activity. This will require significant time in the lab to achieve degrading, or by actively degrading the system to acquire empirical data.

When it comes to degrading these figures may gives us an indication after all. We know for sure that degrading of the catalyst takes place almost at a constant time during operation due to formation of deposits as ammonia sulphate and ammonia bisulphate. These layers in the catalyst are known to slow the activity down, and we have all reason to believe that this can be displayed by logging temperatures and calculate ΔT.

Chapter 7

Feedback from Shipping Companies

During the work with the master thesis I contacted numerous shipping companies to hear some of their experiences with SCR. The intention was to examine whether the topics we have covered in the lab have any relevance to the daily problems these companies face on an everyday basis. After initiating contact I made a survey for them to fill out. The survey consisted of 25 questions for them to fill out. The survey is presented in appendix C. For a shipping company to install this type of expensive equipment the vessel is likely to spend a large time of the total operation within emission control areas. Thus it is no surprise that the shipping companies in Norway most likely to have this type of vessel installed are the vessels trading in the North Sea. Among these we usually find offshore supply companies that have vessels like PSV, AHTS, IMR etc. in their fleet. All shipping companies contacted operated within this segment, with one minor exception. Teekay Shipping operate shuttle tankers in the North Sea and east coast of Brazil. The particular vessel they had installed a SCR on was a small LPG tanker and was a part of a research project. The other shipping companies that participated are listed in table 7.1 together with the vessel type that has SCR installed in their fleet. If we take a look at the vessels, they are all offshore service vessels with diesel electric propulsion. The main engines are usually smaller generators connected to a medium speed 4-stroke engine. To be in compliance with regulations all of these shipping companies operate the vessels on MGO. A company that adds value to this survey is the results from Teekay's LPG tanker. This vessel had the SCR connected to a 2-stroke low speed engine operated at HFO. Although the sulphur content is not known they experienced different success with the SCR system than the other companies.

Survey Shipping Companies						
Company	*Vessel Type*	*Engine Type*	*Fuel*	*Reported Reduction*	*SCR Maker*	*Experience*
Eidesvik	FSV	MaK M25 (2540 kW)	MGO	≃ 50-60%	Argillon GmbH	Good
Simon Møkster	AHTS & FSV	Caterpillar	MGO	50-96%	H+H Umwelt	Good
Havila Offshore	AHTS/PSV/ FSV	MaK, Cat, MTU (1800-6000 kW)	MGO	84-90%	Munters, H+H, Argillon	Good
Teekay Shipping	LPG	MAN B&W (5700 bhp)	HFO	75-85%	Haldor Topsøe	Bad

Table 7.1: Feedback from shipping companies

Most of the companies, except for Simon Møkster and Havila, have no equipment for sampling and analyzing of the exhaust gas, thus there are limited information to collect with respect to their current emission level. Havila also have SCR units where the control unit get input data from a continuously monitoring system to correct the feed rate during operation as the reduction efficiency degreases over time. In general, the companies report reduction efficiency at 80 to 95% when the SCR is used under ideal operating conditions. As the offshore vessels have a large part of their operation operating on DP (about 80%), the engine have a lot of transient load, see figure 7.1. This introduces new challenges to the SCR system as the temperatures constantly change. Simon Møkster reports that due to this operation the real reduction is about 50 to 60% at maximum, and that the efficiency of the SCR is the main challenge to their operation today. Havila on the other hand lists corrosion as their main challenge with the operation of SCR. The effect and reason for corrosion is explained further in chapter 4.

All of the offshore shipping companies reports very little trouble with their SCR units, and as mentioned this I believe is due to the operation on MGO. The companies do no further maintenance than what is recommended by the maker, which is limited. Every 6-8 years or after 24000 running hours they change the honeycombs, together with an inspection during main class overhauls. This is well in line with what makers of SCR systems lists as the expected lifetime.

The only company for which the SCR did not live up to its expectations is Teekay. They experienced significant problems with SCR connected to a low speed 2-stroke engine. This is however not surprising when operating the engine on HFO. The system was a part of

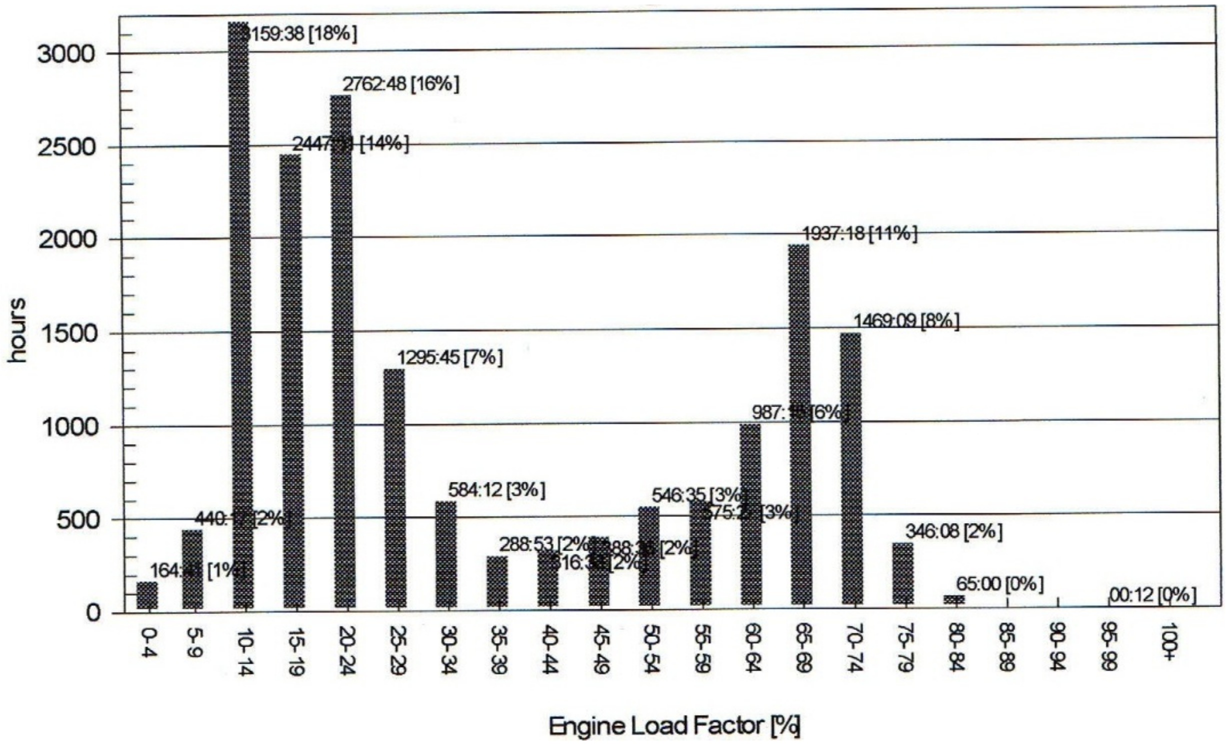


Figure 7.1: Load chart - PSV [20]

a research program, and was shut down in February 2006. The major problem was with rapid clogging of the system, thus they needed to change the honeycombs ever 3rd to 6th month. The maker on the other hand expected a lifetime of 3 years. The vessel was trading in a regular patter with a load of 85% in 18-20 hours a time. The indicator they used for evaluating the condition of the SCR was the exhaust gas backpressure, which the 2-stroke engine is very sensitive to. This is a classic example of the challenges linked to SCR connected to a 2-stroke engine operating on HFO: Low temperatures, high SO_2 content and SO_2 to SO_3 conversion.

In general the SCR system seems to deliver according to the companies' expectations. However if we look at the world merchant fleet the offshore vessels are already "Best in Class" when it comes to emissions. The future challenge is to get SCR functioning stable on existing and newbuilds with 2-stroke engines. In january 2020 the global sulphur cap shall be 0,5% and there is no reason for why other segments in commercial shipping should not use SCR, as reduced sulphur content is good in respect of NO_x abatement technology.

Part III

Performance

Chapter 8

Performance of SCR

8.1 Background

The research of SCR performance has been conducted in the laboratory in the same experiments as we investigated degrading. In first experiment conducted in February 2010 we found that refitting the turbocharger definitely had changed engine performance, hence the low NO_x reduction efficency. For the three loads tested we had the following reduction efficiency presented in table 8.1. The "Beginning" and "End" notations represents as before measurements at beginning and end of the test point. As presented we reported a reduction efficiency about 20% lower then the expected performance of the system. We knew that this most likely was related to the engine's turbocharger refitting. By looking at the figures in table 5.1 we see that the exhaust temperature has decreased and the NO_x emission have increased. The temperatures are most likely still sufficient to achieve optimum performance, but the increased NO_x emissions have large consequences for the reduction efficiency. The SCR control unit regulates the feed rate based on the NO_x emissions measured in the engine test bed. As this now has changed we were at this point

NO_x reduction efficiency at MGO			
Load	*50%*	*75%*	*100%*
Beginning	0,727	0,629	0,629
End	0,700	0,657	0,650
Average	0,7135	0,643	0,6395

Table 8.1: NO_x reduction efficiency MGO

feeding to little urea per ppm NO_x into the exhaust gas to achieve the desired reduction efficiency. After this experiment we contacted Yarwil and they sent their technician to recalibrate the system prior to the second experiment. With this now functioning we are also able to change the urea feed rate by ourselves during the execution of the test. The goal of the test is to identify the systems maximum performance capability when and when not in compliance with international regulations with respect to NH_3 slip.

8.2 Hypothesis

As we discovered in the last experiment, the reduction rate was far below reported reduction efficiency for a SCR system. Earlier test indicates that the SCR system shall have a reduction efficiency of about 90%, and the last test gave a reduction of about 70%. This is far from the desired results, and the focus of this experiment is to find the system's maximum reduction efficiency, within the allowed limits of ammonia slip. The system has been set up with a 50% safety margin to prevent ammonia slip above regulations in the test facility, and this is probably one of the reasons for the low oxidation rate. The amount of ammonia slipping through the system must not exceed 10 ppm [10]. The theory is that we should be able to reach a reduction efficiency of about 95% within the 10 ppm restriction. It is also interesting to check what it is possible to achieve when exceeding this limit as a test in the lab. The reduction efficiency depends on the amount of urea introduced and the exhaust gas temperature. As we saw in the last experiment, temperatures for start-up of the SCR system were calibrated for operation at MGO, initiating feed at 290 °C. The catalyst will have highest efficiency with temperatures higher than 340 °C degrees, which are far away from our temperatures, and this may set constraints to the maximum efficiency to our system. We expect, however, to see a much higher efficiency due to increased feed rate in this test. The ammonia slip will be measured with a FTIR instrument that will be explained further in the following chapter.

8.2.1 Measuring accuracy of Horiba PG-250 NO_x Readings

In the first experiment we tried to measure the ammonia slip with a portable ammonia measurement device, to see if we were in compliance with regulations for ammonia slip. The device was not functioning properly as the NO_x in the exhaust gas was picked up by the device and registered as NH_3. One of the things we would like to investigate is whether this also happen for other instruments as the Horiba PG-250 normally used in the lab for emission sampling? Of course, the Horiba are not capable of measuring ammonia. However the ammonia content in the exhaust gas may contaminate the measurement of NO_x as both contain nitrogen. In this experiment we will rent equipment for accurate measurements from Sintef's chemistry department. This is called FTIR, and the principles behind FTIR and Horiba's measurements will be explained below.

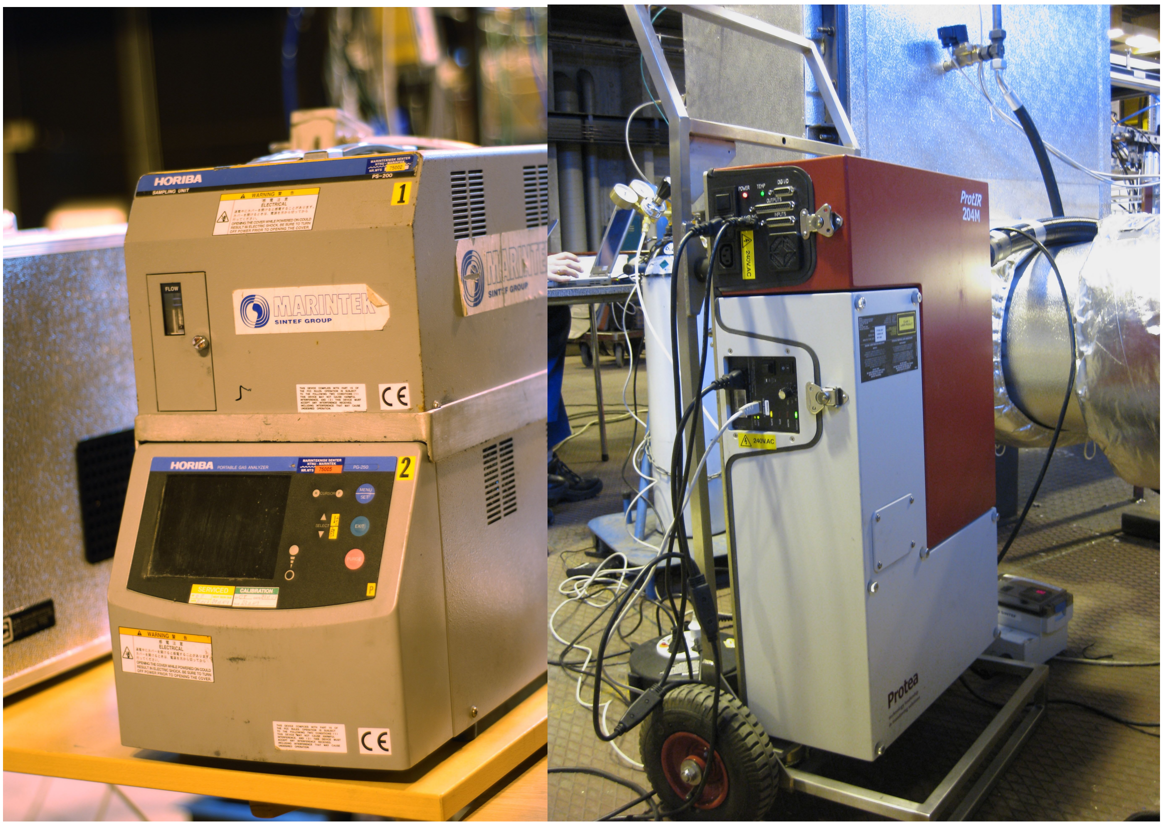
Horiba PG-250

The PG-250 is a portable stack gas analyzer, that uses non-dispersive IR detection for CO, SO_2, CO_2 and chemiluminescence (cross-flow modulation) for NO_x [8]. Non-dispersive IR detection is based on electro-optically measuring of the gas concentration by the concentration's ability to absorb a specific wavelength in the infrared spectrum. The absorption indicates the concentration of certain gases. The weakness of such instruments is that many gases adsorb well in the infrared area and components may interfere in measurements as e.g. CO_2 and H_2O, and many others (SO_2, NO_2) interfere with H_2O. For this reason we send the sample gas through a condensator removing the water vapour H_2O before analyzed so we get a dry air sample. As we don't know if NO_2 and NH_3 are cross-sensitive, and we will use the FTIR to measure the difference in NO_x content between the two, if any.

Fourier Transform Infrared (FTIR) spectroscopy

Infrared frequencies are to high for digitalization (about 10^{13}Hz), and to make this possible the FTIR uses an interferometer to "move" this into a frequency interval that is suitable for digitalization [21]. The interferometer reduces the frequency with a factor of about 10^{10} to a readable area, and then fourier transform takes it back to the frequency domain from time domain. As this method will give us more accurate results we can compare the deviation in NO_x readings on the PG-250 and the FTIR, and the ammonia content in the exhaust gas downstream the catalyst.

The reason for why this should be tested is to find out if the emission logging by shipowners are accurate when measuring with respect to SCR. Maybe the reported emission data will be higher that reported, or in best lower.



(a) Horiba PG-250

(b) Protea 204 M/C - FTIR

Figure 8.1: Gas analyzers used in lab

8.3 Results and Comments

After refitting the turbocharger and adjustment of the SCR control unit, the urea feed was now set up in the way that producer would for systems in commercial operation. Changing the k-factor could now as mentioned earlier change the feed rate, and a k-factor of 100% gives a feed rate of approximately 7,5 $\frac{l}{h}$ at 50% MCR. By changing the k-factor in the way showed in section 6.4 we got the feed rates listed in table 8.2. The calculated feed rate is the k-factor multiplied with the baseline feed at 7,5 $\frac{l}{h}$. The "read" column represents the actual feed rate at a given time during the operation with the respective k-factor. It is important to state that the feed rate may fluctuate with $\pm$ 0,5 $\frac{l}{h}$ at a given load.

The feed rate is without doubt the main contributor to the reduction efficiency. If it was not for the undesired ammonia slip, close to 100% reduction efficiency could be achieved at all stages in stationary operation. However, as ammonia is a hazardous gas we wish to

k-factor and urea feed rate		
k-factor	*Feed calculated*	*Feed read*
100%	7,5	7,5
95%	7,125	7
90%	6,75	6,5
80%	6	5,9
70%	5,25	5,1
60%	4,5	4,2
50%	3,75	3,6
110%	8,25	8
120%	9	8,7

Table 8.2: Urea feed rate correspondent with k-factor

minimize the slip, and the worldwide limit for ammonia slip is at 10 ppm with a possible increase to 20 ppm in the near future [10]. Ammonia is toxic to water-dwelling organisms and is one of the gases important in “acid rain” playing an important part in the long range transport of acidic pollutants. It can also contribute to localized soil acidification [3]. For normal operation we logged ammonia slip with the FTIR as presented in table 8.3 and figure 8.2 As shown, we have some amounts of ammonia slip, but still within the allowed limits in commercial trade. It is when we start the overdosing of the system we get ammonia slip above the current limits. The slip does not follow a linear development. With this in mind we may ask what are the major influences of ammonia slip and hence can contribute to a reduction. The catalyst temperature may be of influence as it has influence on the reaction speed. With higher temperature, more ammonia will be utilized, hence

Ammonia Slip			
Test Point	*k-factor*	*Feed Rate* ($\frac{l}{h}$)	*Slip (ppm)*
1	100%	7,5	6,9
2	95%	7,125	6,33
3	90%	6,75	5,88
4	80%	6	5,64
5	70%	5,25	4,44
6	60%	4,5	3,96
7	50%	3,75	3,33
8	110%	8,25	9,64
9	120%	9	16,33

Table 8.3: Urea feed rate and ammonia slip

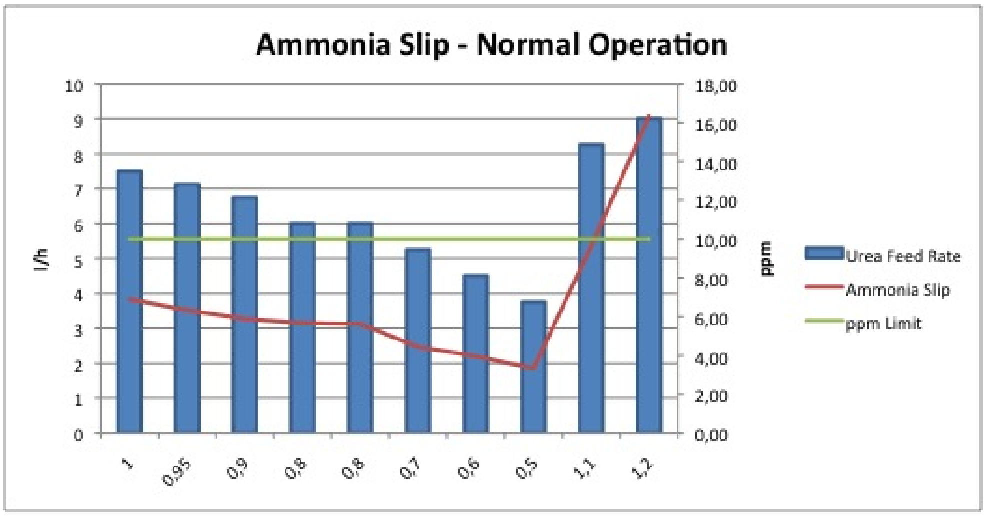


Figure 8.2: Urea feed rate and ammonia slip

lower slip. Argillon GmbH lists the curve in figure 8.3 for how the temperature influences the catalyst activity. The temperature limits figure 8.3 are equivalent to ≃ 300 and 400 °C. Argillon also states that the temperature distribution can be more or less strict depending on the design temperature of the catalyst.
The point above brings us to the next plausible cause for the slip, and this is the design of the SCR catalyst. The SCR in our laboratory was build on a specification with engine parameters that has changed after the refitting of the turbocharger. Most importantly is the increased flow rate $\dot{m}_{exhaust}$, which may result in a shorter available time for the reaction to take place. It is hard to analyze whether the design of the catalyst is the major reason for the ammonia slip. However, the modification described in section 6.4 gives us increased exhaust temperature without compromising on engine load that again will change the urea feed rate's baseline. The turbocharger refitting does have influence on the combustion process, that is clearly indicated with a 20% increase in NO_x emitted from the engine (table 6.5). During the normal operation of the engine we had a NO_x level of about 950 ppm, which is now increased to about 1200 ppm. This again will have consequences for the readings of the urea feed rate and k-levels. The adjustment of the feed rate is based on the amount of NO_x emitted at a given load with a given fuel quality. As we when bleeding the compressor have the same engine load, but with higher NO_x emissions, we have too low feed rate.

With this we have performed a recalculation to find what k-level the feed rate correspond

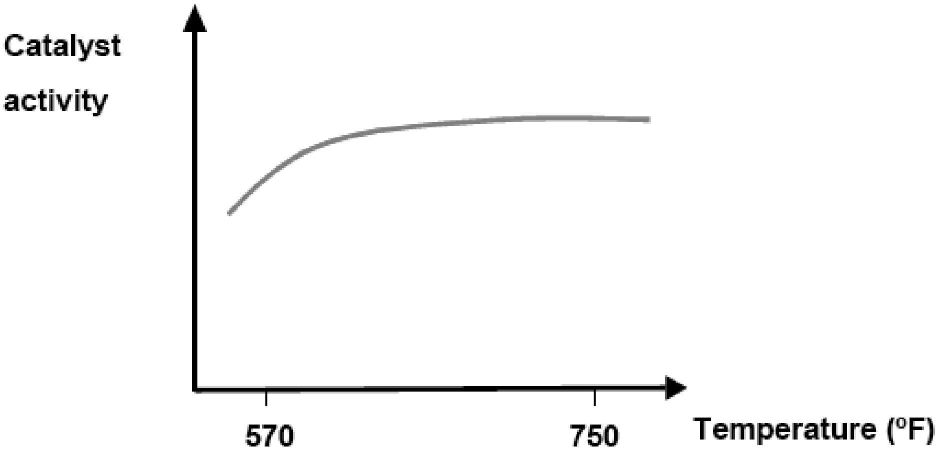


Figure 8.3: Activity as function of exhaust temperature [15]

k-levels and corresponding NO_x					
k-baseline	*Feed baseline* ($\frac{l}{h}$)	*Feed bleed* ($\frac{l}{h}$)	*Actual k-factor*	*Baseline* NO_x *(%)*	*Bleed* NO_x *(%)*
100%	7,5	9,39	0,80	84	80
90%	6,75	8,45	0,72	82	77
80%	6	7,51	0,64	72	72
70%	5,25	6,57	0,56	61	65
60%	4,5	5,63	0,48	54	53
50%	3,75	4,70	0,40	N/A	46
110%	8,25	10,33	0,88	85	85
120%	9	11,27	0,96	89	94

Table 8.4: Corrected k-values and NO_x for comparison

to in reality for the bleed operation, called k_{actual}. The assumption that sets the basis for this calculation, is that the relationship between urea feed rate and the amount of NO_x emitted is linear. The results are presented in table 8.4. As displayed in table 6.4 we did a test point at k=126%. This was done at the very end of the experiment to see the reduction efficiency for $k_{actual} = 100\%$ for the bleed operation as

$$k_{normal\ operation} = \frac{NO_{x_{Bleed}}}{NO_{x_{Normal\ Operation}}} \cdot 100\% = 126\%$$

Only the NO_x emissions were logged at this test point due to time constraints, hence the pillars representing this test point are marked with the color red. Below follows an explanation of the table properties in table 8.4

k baseline and **feed baseline** represents the k-factor and feed rate adjusted by Yarwil for normal operation of the engine at MGO.

Feed Bleed represents the necessary feed rate to maintain the NO_x reduction efficiency for normal operation when bleeding the compressor. The rate is calculated with formula 8.1 and the NO_x values represent the average of all measurements during the experiment.

$$Feed\ Rate_{Bleed} = \frac{NO_{x_{Bleed}} \cdot Feed\ Rate_{Normal\ Operation}}{NO_{x_{Normal\ Operation}}} \tag{8.1}$$

Actual k-factor represents the effective k-factor for the bleed operation as we have a feed rate according to standard presented in 2nd left column

$$Actual\ k - factor = \frac{Feed\ Rate_{Normal\ Operation}}{Feed\ Rate_{Bleed}} \tag{8.2}$$

The NO_x baseline and NO_x bleed columns represents the average NO_x reduction of beginning and end of the measurement point. As the actual k-factor for the operation with the compressor bleed are not “round” values, we have interpolated between nearby measured values for the NO_x baseline. As an example the value formula for k_{actual} will be

$$NO_{X_{0,64}} = NO_{X_{0,7}} - \left[\frac{0,7 - 0,64}{0,7 - 0,6} \left(NO_{X_{0,7}} - NO_{X_{0,6}} \right) \right] \tag{8.3}$$

This again is assuming a linear development between the two solid measurement points. In order to compare the slip level between the two operating conditions we must find the corresponding slip level to the actual k-factors for the baseline operation as well. The values are presented in table 8.5 and the values in between solid data are interpolated as shown for the NO_x levels (equation 8.3).
A comparison between the two operation conditions is illustrated graphically in figure 8.4. Figure 8.4 clearly shows that there are no signs of less slip as we increase the exhaust temperature. In fact the figure shows higher slip. This result indicates that the temperature increase are not sufficient to reduce the ammonia slip, hence we have reached the catalyst’s maximum capacity as it is unlikely that further increased temperatures would reduce the

k-levels and corresponding ammonia slip					
k-baseline	*Feed baseline* ($\frac{l}{h}$)	*Feed bleed* ($\frac{l}{h}$)	*Actual k-factor*	*Baseline slip (ppm)*	*Bleed slip (ppm)*
100%	7,5	9,39	0,80	5,66	5,88
90%	6,75	8,45	0,72	4,44	5,82
80%	6	7,51	0,64	4,15	5,21
70%	5,25	6,57	0,56	3,70	4,69
60%	4,5	5,63	0,48	3,33	3,78
50%	3,75	4,70	0,40	N/A	3,21
110%	8,25	10,33	0,88	5,88	6,04
120%	9	11,27	0,96	6,33	N/A

Table 8.5: Corrected k-values and ammonia slip for comparison

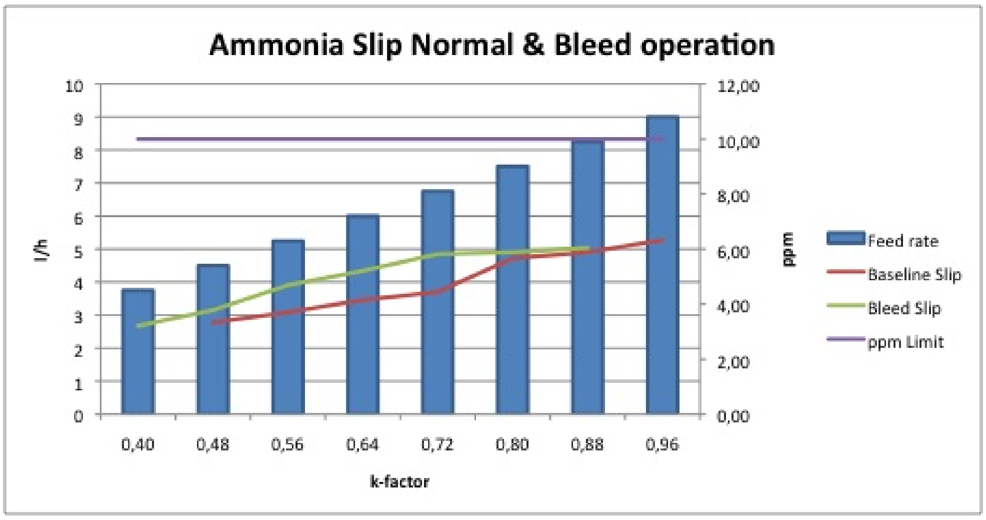


Figure 8.4: Ammonia slip for corresponding k-factors

slip with reference to the figure 8.3 by Argillon. To compare the results it is also interesting to compare the reduction efficiency for the actual k-levels and corrected NO_x values. As we see in figure 8.5 the NO_x values correspond and follow each other for the same actual k-factors. This shows that the temperatures we have for normal operation are sufficient to ensure maximum performance of the catalyst on MGO. Both these result indicates that we have reached the system's maximum performance when it comes to ammonia slip and NO_x conversion. The system are basically not capable of converting more than 95% of the NO_x and still be in compliance with the 10 ppm ammonia slip level. As this tests has only been done at 50% MCR, we should perform the test for loads at 75 and 100% as well in order to fully be able to conclude with this, however the test team find no reason to believe

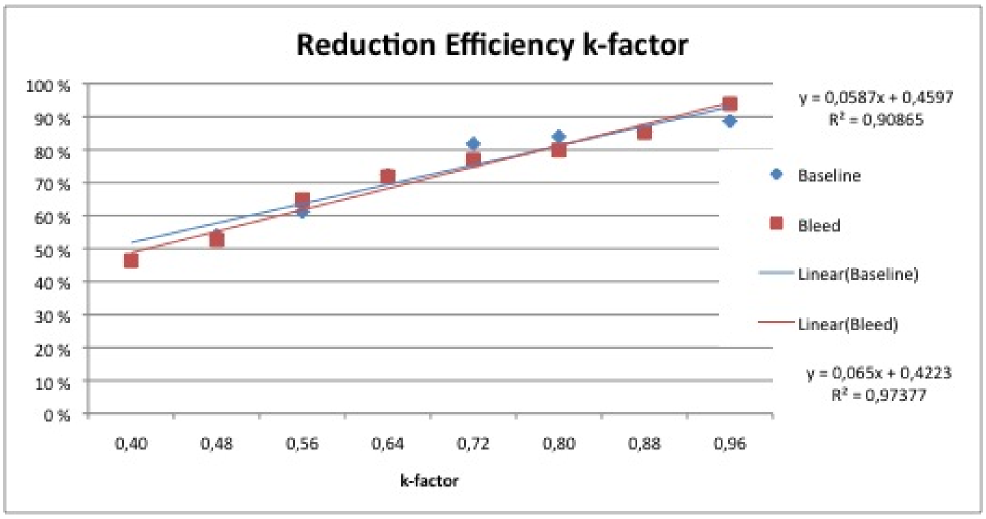


Figure 8.5: Reduction efficiency for corresponding k-factors

that these results should vary significantly for higher load conditions.

8.3.1 NH_3's influence on NO_x measurements

The secondary objective of this laboratory test was to determine the accuracy of the Horiba PG-250 gas sampler. For this I have decided to only compare the two instruments for the normal operation, as the feed rate there is according to the Yarwil standards. The two curves for the PG-250 and FTIR respectively are shown in figure 8.6

As presented in figure 8.6 there are no large differences in the measurements, thus there are nothing that indicates that NH_3 and NO_x are cross-sensitive and that the Horiba PG-250 measurements are reliable with compared to FTIR.

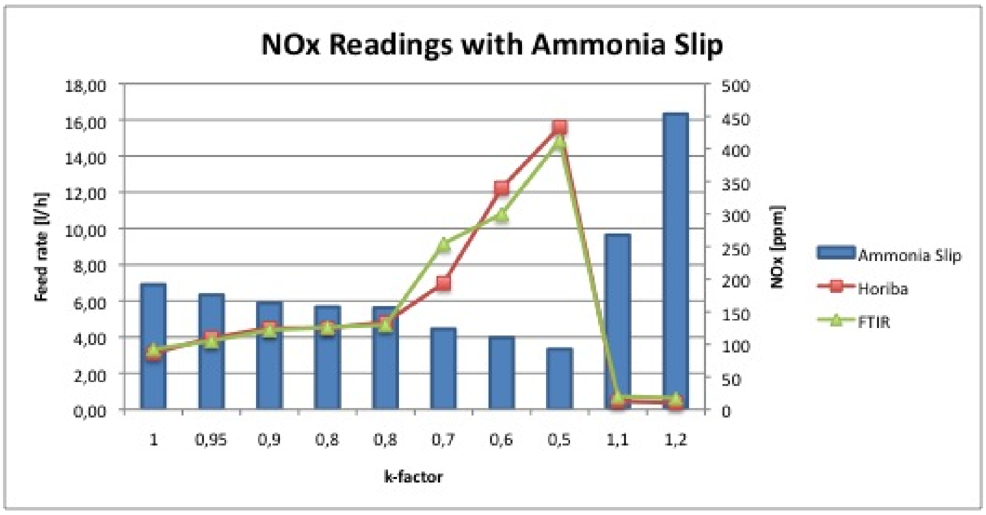


Figure 8.6: NO_x measurements with FTIR and PG-250

Chapter 9

Performance of SCR installed on GDF Suez Neptune

Due to confidentiality this chapter has been placed in appendix E, which is excluded from the published version.

Chapter 10

Conclusion and Discussion

10.1 Degrading

10.1.1 SO_2 to SO_3 Conversion

As explained in section 4.2 the SO_2 to SO_3 conversion rate is one of the key elements that set the basis for degrading of the catalyst. The SO_3 conversion rate is mostly dependent on sulphur content in the fuel and amount of vanadium in the catalyst's honeycombs. It is reason to believe, although not measured, that the SO_3 content in the lab catalyst is limited as we operate on MGO with low sulphur content. This should been tested more thoroughly in the laboratory with the FTIR sampler to see the difference upstream and downstream the catalyst. Teekay listed that their main challenge with the SCR was formation of deposits that eventually clogged the system. As they operated at HFO with a sulphur content most likely above 1,5% I strongly believe that this degrading would have been reduced significantly with operation on low sulphur fuel and reduced SO_3 content.

10.1.2 Fatigue Due to Temperatures Variations

As presented in chapter 5 we investigated if the temperature variations in the catalyst could be significant enough to cause fatigue in of the honeycombs due to thermal load. The temperatures were logged upstream, downstream and centre of the catalyst. A maximum difference of about 10 °C in transient and stationary load conditions was observed. As we know that the honeycombs are calcined and hence has thermodynamic properties much similar to other ceramics the probability of this variations causing any thermal load on the honeycombs is small. However it is in the start-up phase of the system we observe temperature variations significantly higher than during normal operation, but not high enough to cause fatigue. With this we will conclude that it is only due to vibrations we may get fraction of the honeycombs and not from thermal loads.

10.1.3 Temperature as Indicator of Degrading

Based on the findings in the laboratory we certainly see a correlation between the activity and temperature difference ΔT and not the T_{Center} as first assumed. If we then assume that degrading and formation of deposits as ammonia sulphate and ammonia bisulphate, will have reduced activity, we should be able of find indicator of this by logging the ΔT. ΔT is defined as $\Delta T = T_2 - T_1$. From the results we see that the activity is highly dependent on the urea feed rate and we saw clearly that T_1 decreased with increased feed rate due to the heat capacity of the ammonia. This will alone contribute to a rise in ΔT, and as T_2 tend follow more or less the T_{Center} we may wonder whether ΔT are related to the activity or the urea feed rate. Another aspect of the variations in T_2 is that it seems to be closer to T_{Center} as the sulphur content decreases. This is shown in the first experiment with HFO and MGO and in the white diesel lab where we compared MGO to white diesel. This contributes to an increased ΔT. It is difficult to pinpoint the reason for this, as the reason for why T_2 generally is significantly lower than T_{Center} is hard to determine. To verify ΔT as a reliable indicator we must focus further on the development of T_2 as we get deposits in the catalyst and reduced activity, where it should decrease with decreased activity. Even if this should turn out to be the case we still don't know the magnitude of these changes. They may be too small for registration in the lab and onboard operating vessels, together with this the uncertainty of the measurements will increase. The indicator on the other hand, if successful, could have a very positive effect for operation of SCR. If one could be able to find a correlation between temperatures and degrading, e.g. with a factor similar to the thermal efficiency number k, this could ease the work onboard vessels assessing the current status on their SCR. It is reasonable to believe that such a goal is within reach, however the need for empirical data is strong, and the constraints for this achievement is available operating hours of the engine in the lab.

To summarize the results in the degrading part we have sketched correlation between activity, SO_2 to SO_3 conversion rate and formation of deposits with respect to exhaust gas temperature displayed in figure 10.1. As we see the activity and formation of deposits have a positive development with increased temperature. Hence we should focus on limiting the SO_2 to SO_3 conversion rate with other measures, and should be a focus for future research in the laboratory at MARINTEK.

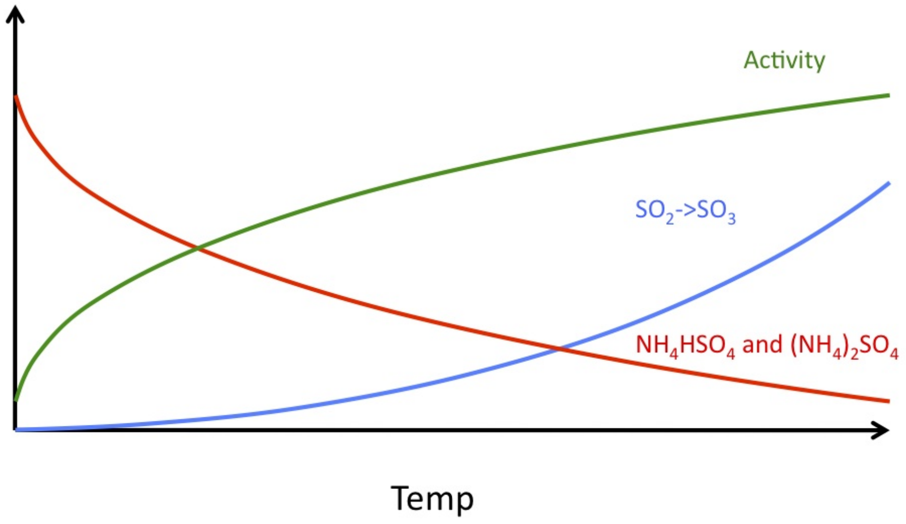


Figure 10.1: Contributors to degrading

10.2 Performance

When discussing the performance of the SCR the main focus was to find the system's maximum reduction efficiency while being in compliance with international regulation with respect to ammonia slip and to see whether this was according to what manufacturers claiming. In the lab we achieved an impressive reduction of 95% with an ammonia slip of 9,64 ppm, which is within the 10 ppm restriction. For a higher feed rate, we have much higher ammonia slip that seems to have an exponential development as in figure 10.2. While investigating the performance we also wanted to check whether an increased exhaust gas temperature would increase the reduction. With reference to figure 5.1 we should already be well within the temperature window for operation on MGO. As we increased the exhaust temperature we did not achieve higher reduction efficiency, but with somewhat higher slip after the recalculation had been done. As we did not change the amount of ammonia per

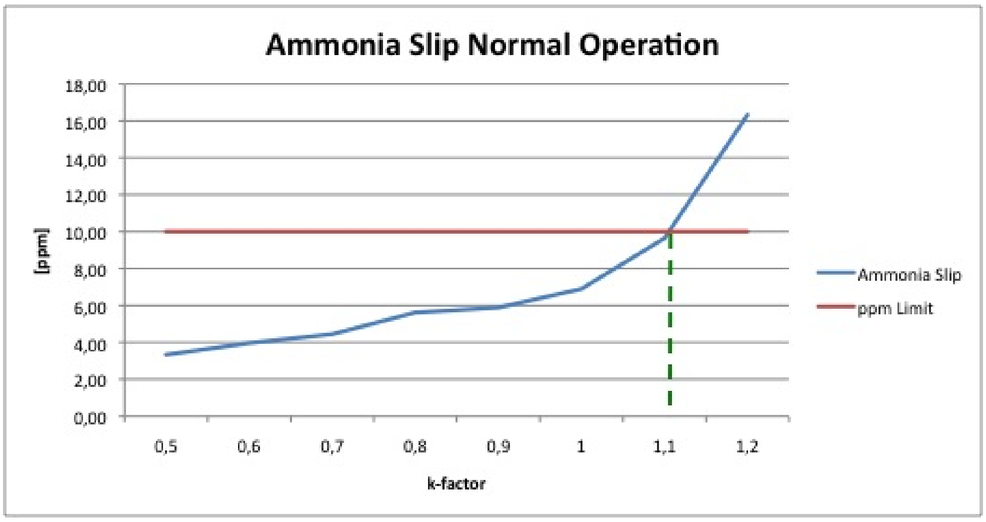


Figure 10.2: Development of Ammonia Slip - Normal Operation

NO_x, this indicates that with the current settings and design of the SCR we have reached the system's maximum capable performance.

Chapter 11

Further Work

There is still a lot of research that should be conducted in the area around selective catalytic reduction related to degrading and performance. With respect to the degrading part of this thesis, I would like to continue the research around using temperatures as indicators for degrading. Further research should include an experiment where we actively intend to degrade the catalyst by operating it in undesirable conditions. My suggestion for experiment was to intentionally operate the engine at low load with high feed rate of urea into the catalyst. This will when operating on HFO give formation of ammonia sulphate and ammonia bisulphate in the catalyst due to the presence of SO_3. We would on the other hand have higher SO_3 content if we increased the engine load and hence the flue gas temperature, but there will be less formation of deposits. When performing this experiment one should be able to see a reduction in activity as the catalyst has been degraded. When comparing this with the baseline reference values one should hopefully be able to establish a degrading rate with interpolation. Simultaneously one should log the temperatures in order to track the development of T_2 as the catalyst gets degraded and search for a connection between degrading and ΔT. This experiment is however costly as it will spoil the honeycombs for future testing.

It should also be conducted an experiment for temperature logging where operation is done at all possible ISO loads and for HFO. With the HFO in mind one should also test the influence on introducing magnesium oxide into the exhaust gas flow in order to reduce the oxidation of SO_2 into SO_3.

When it comes to the performance part we have successfully proved a 95% reduction at 50% load within the allowed ammonia slip limits. Future work should involve performing similar tests also for the two higher ISO loads 75 and 100%. I don't see any reason for why we should see better or worse performance at these loads, but documentation is useful. In my opinion further work with respect to performance should be centred on the catalyst's ability to reduce other types of emissions as PM and HC. PM is probably the main focus for the research on emissions related to SCR at MARINTEK, and there are conducted little research within the area.

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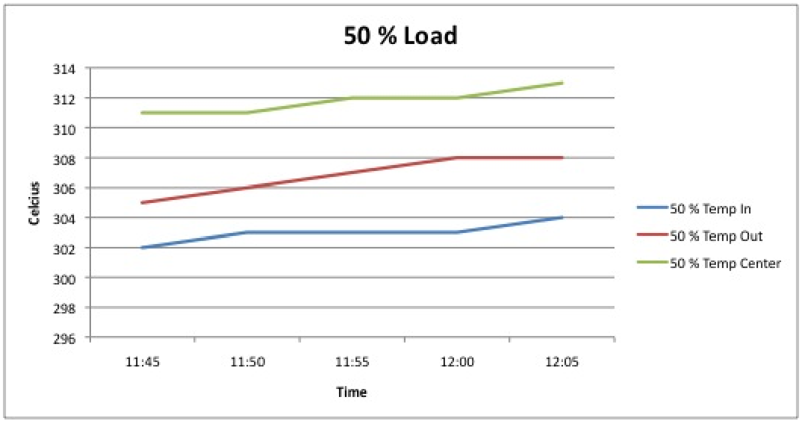
Appendices

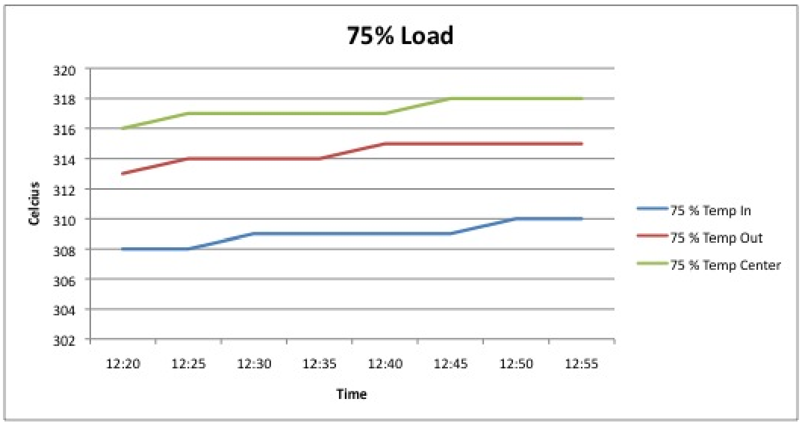
Appendix A

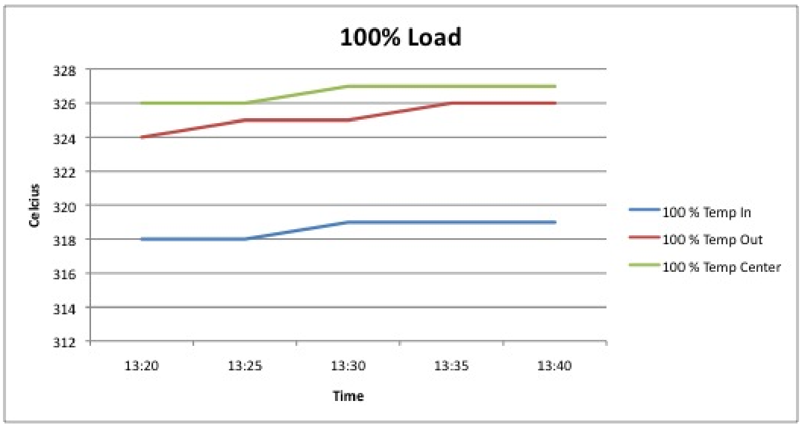
Results First Experiment 18.02.2010

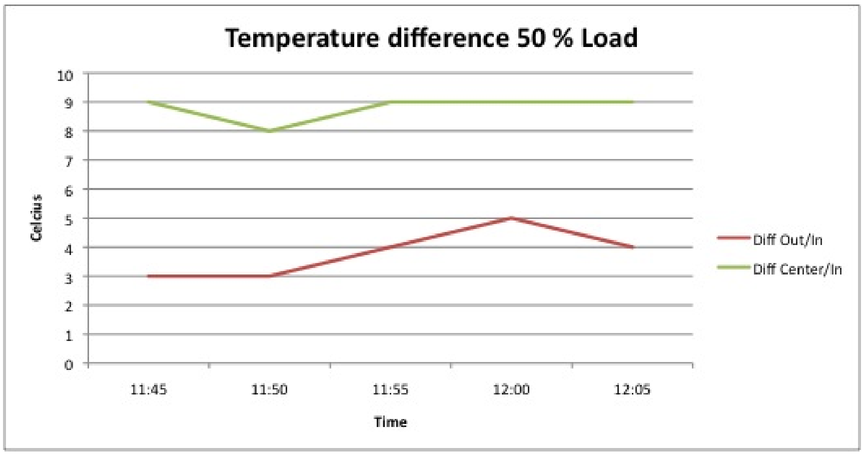
MGO

Stationary Load





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8
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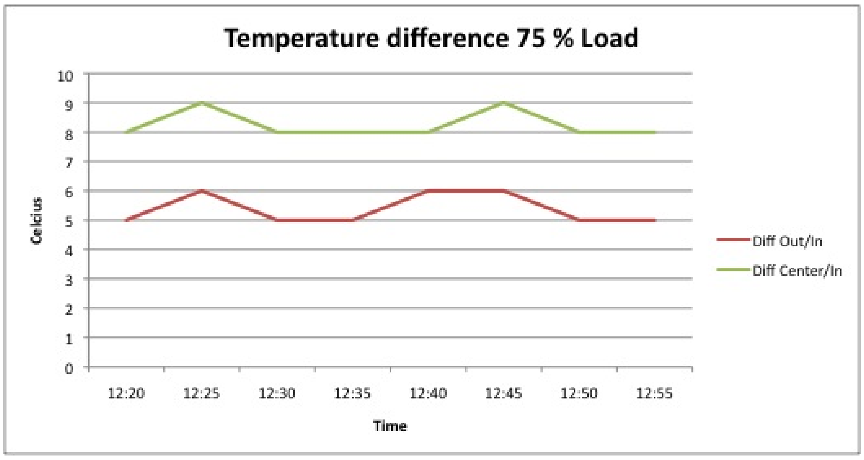
12:05
Time
Diff Out/In
Diff Center/In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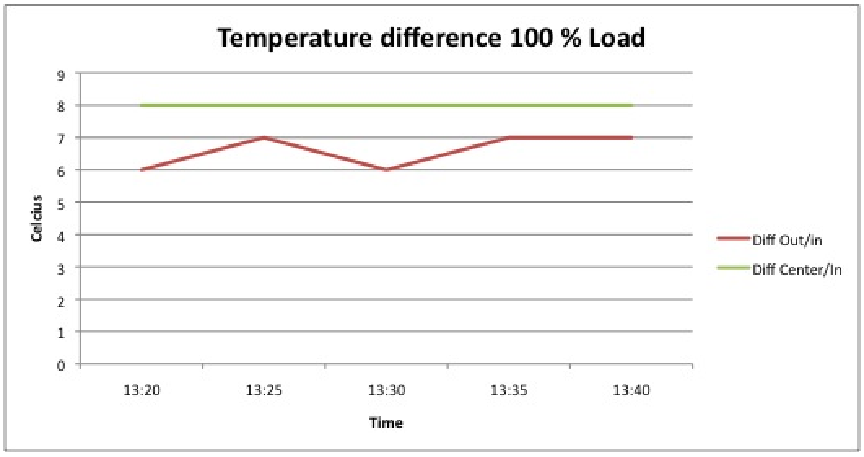
Time
Diff Out/In
Diff Center/In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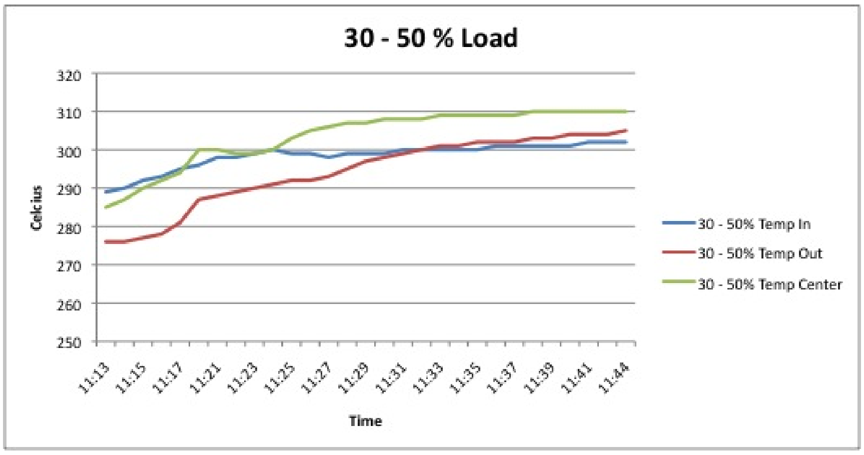
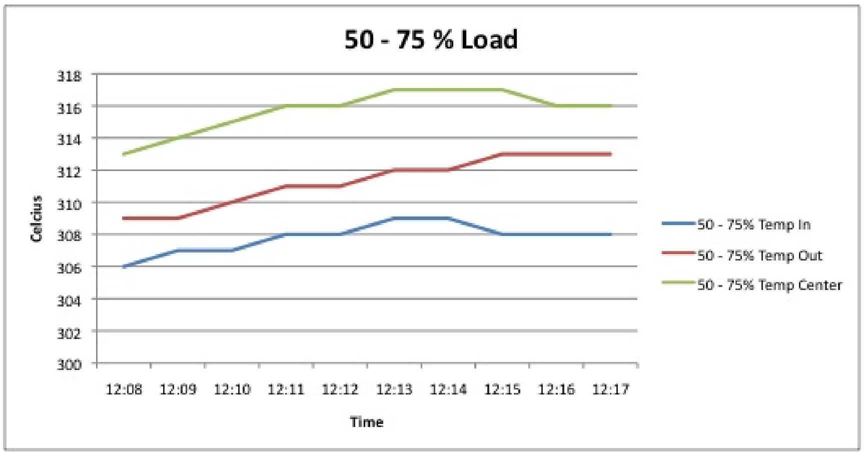
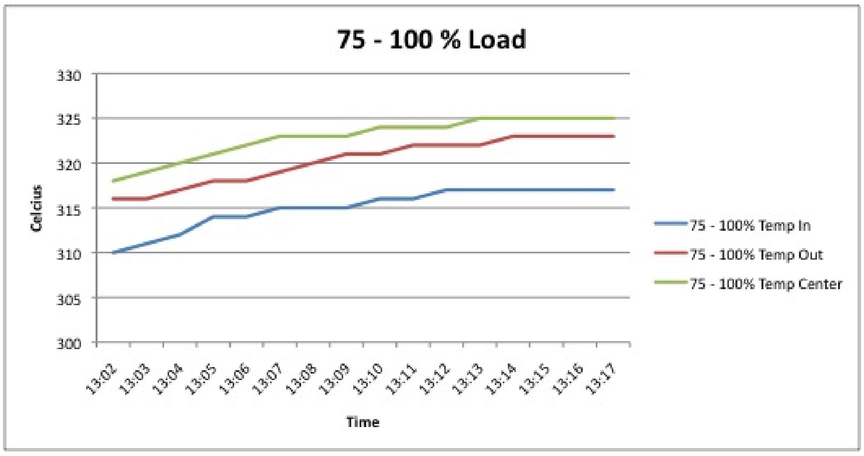
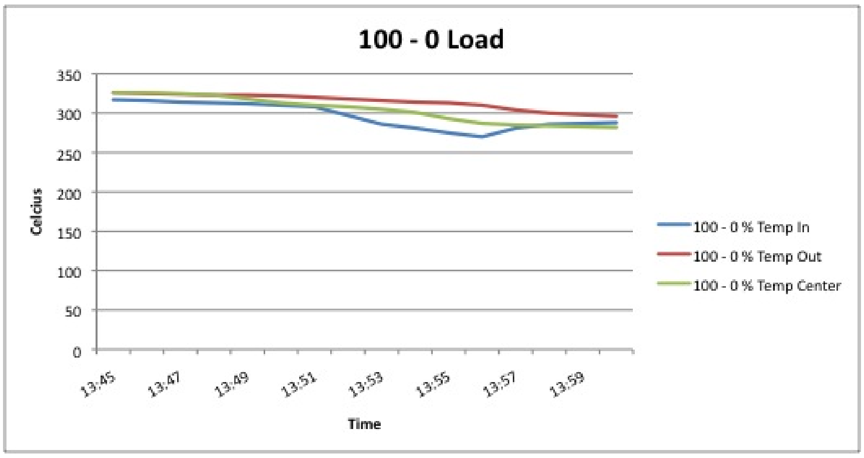
Time
Diff Out/In
Diff Center/In

Transient Load





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50
0
Celcius
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13:57
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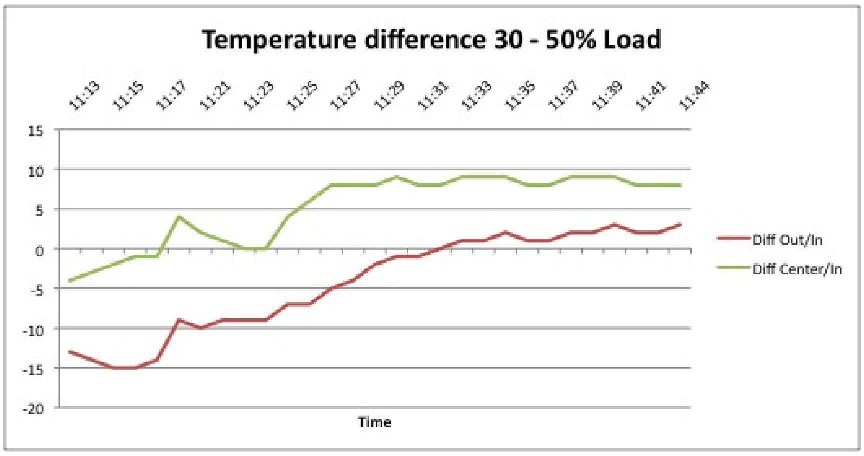
Time
100 - 0 % Temp In
100 - 0 % Temp Out
100 - 0 % Temp Center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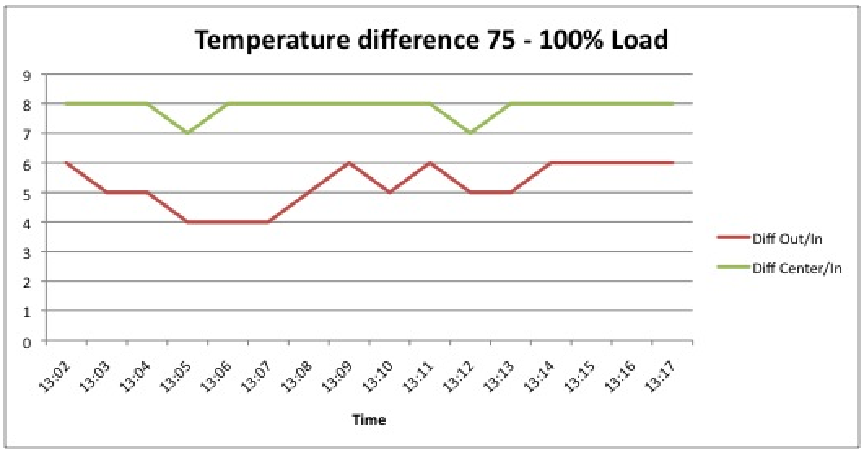
Time
Diff Out/In
Diff Center/In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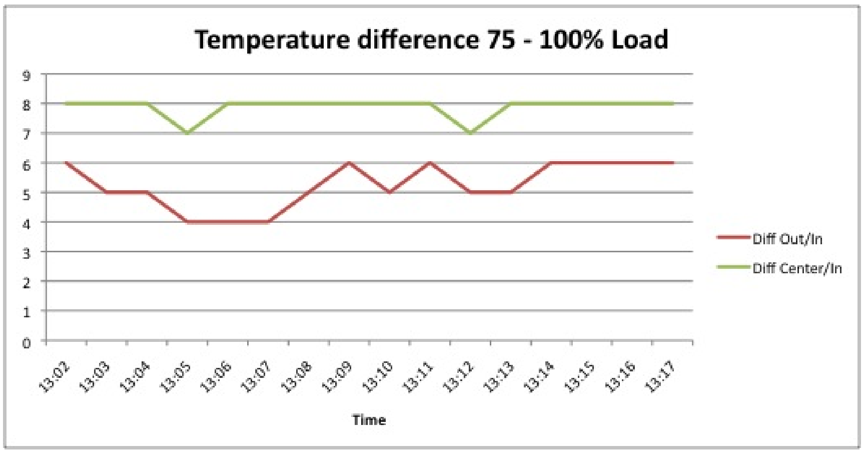
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Diff Out/In
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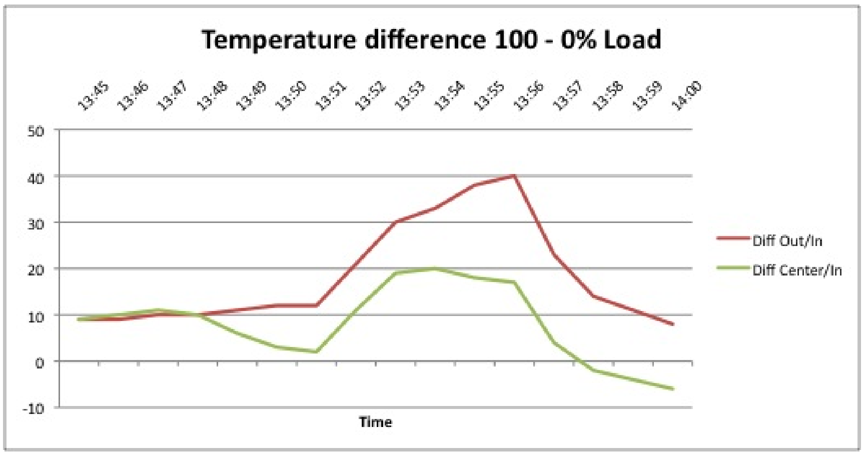
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13:55
13:56
13:57
13:58
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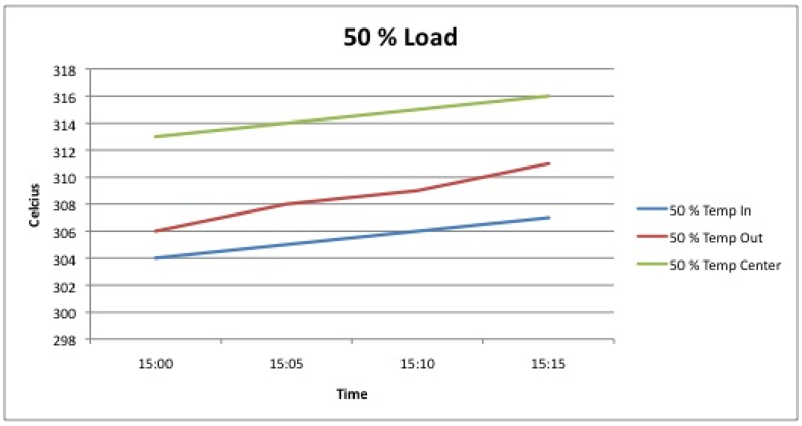
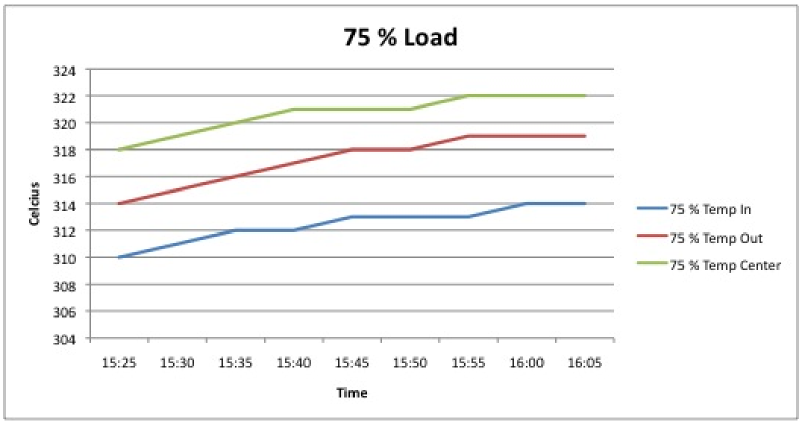
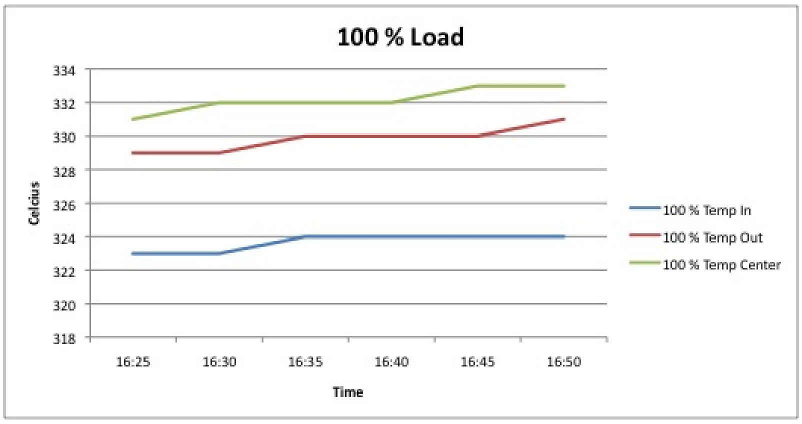
14:00
50
40
30
20
10
0
-10
Time
Diff Out/In
Diff Center/In

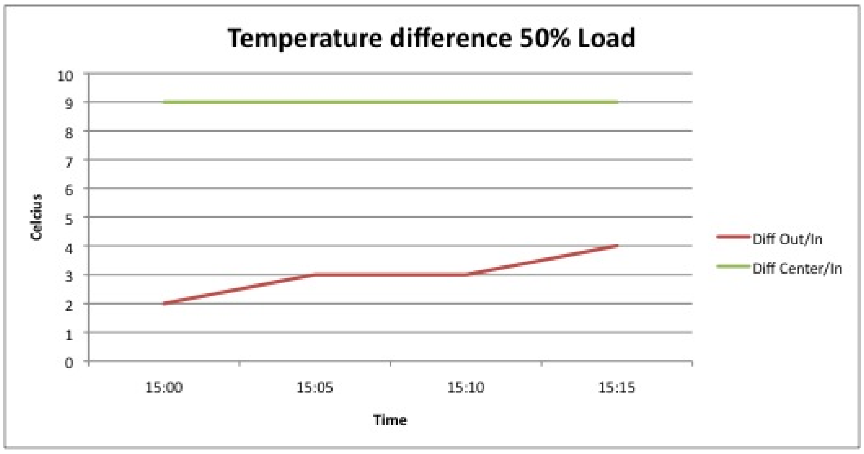
HFO

Stationary Load





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8
7
6
5
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3
2
1
0
15:00
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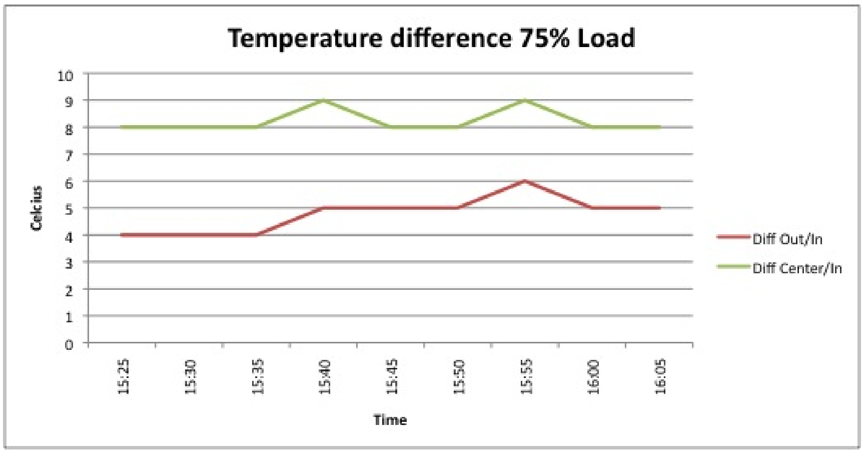
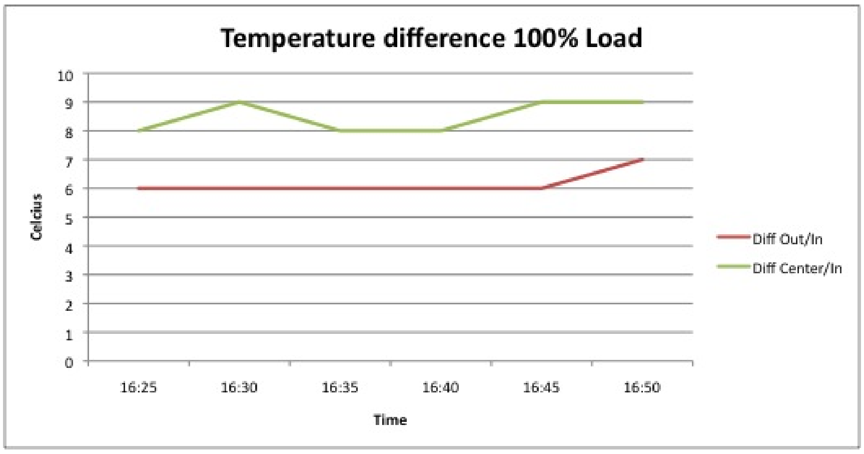
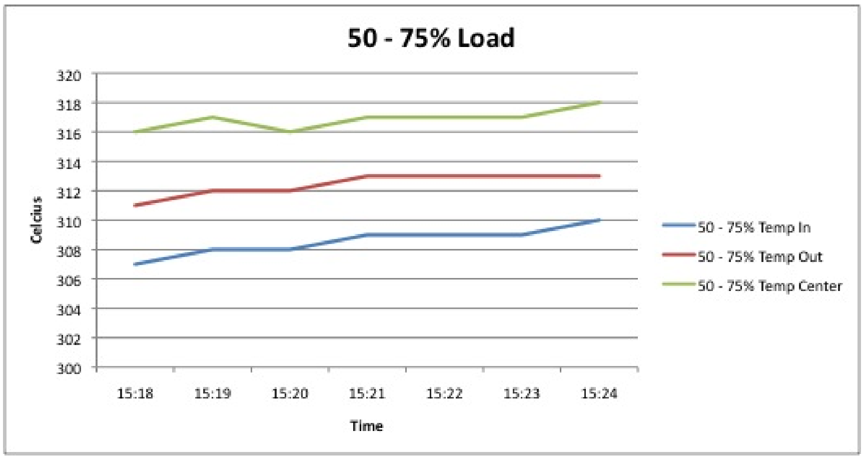
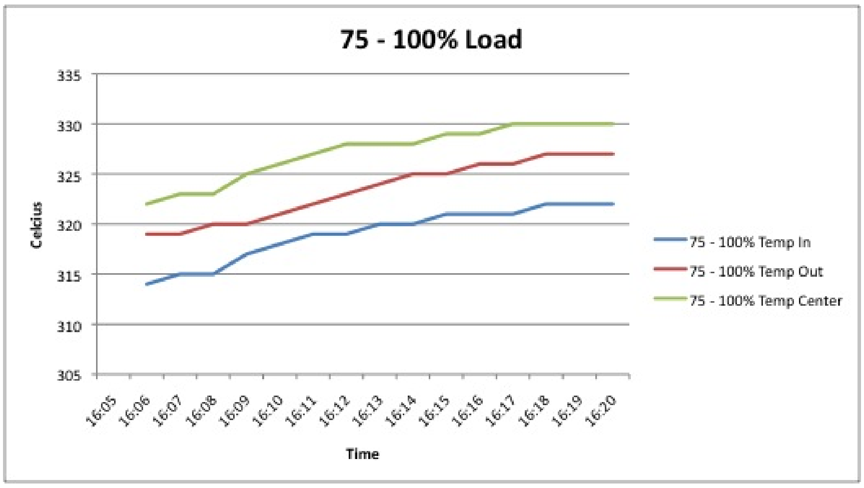
15:15
Time
Diff Out/In
Diff Center/In

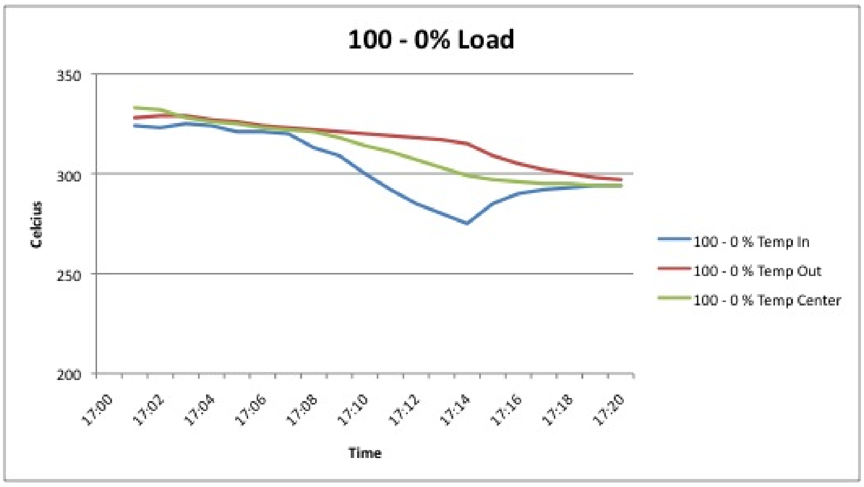

Temperature difference 75% Load
Celcius
10
9
8
7
6
5
4
3
2
1
0
15:25
15:30
15:35
15:40
15:45
15:50
15:55
16:00
16:05
Time
Diff Out/In
Diff Center/In

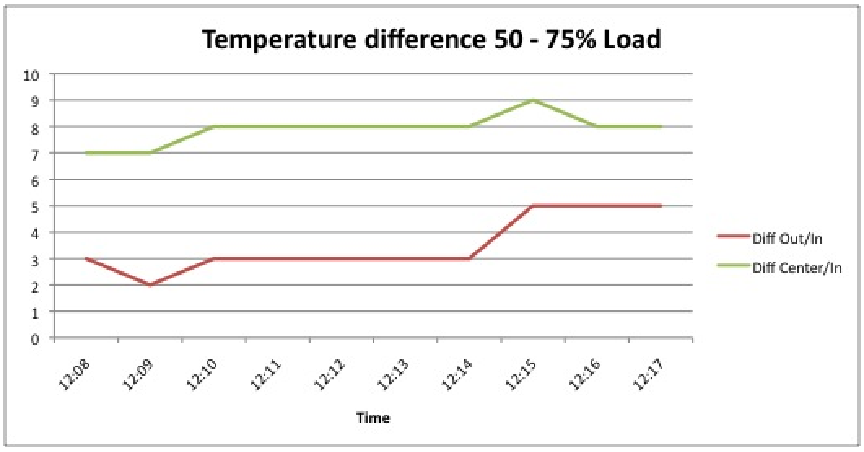

Temperature difference 100% Load
Celcius
10
9
8
7
6
5
4
3
2
1
0
16:25
16:30
16:35
16:40
16:45
16:50
Time
Diff Out/In
Diff Center/In

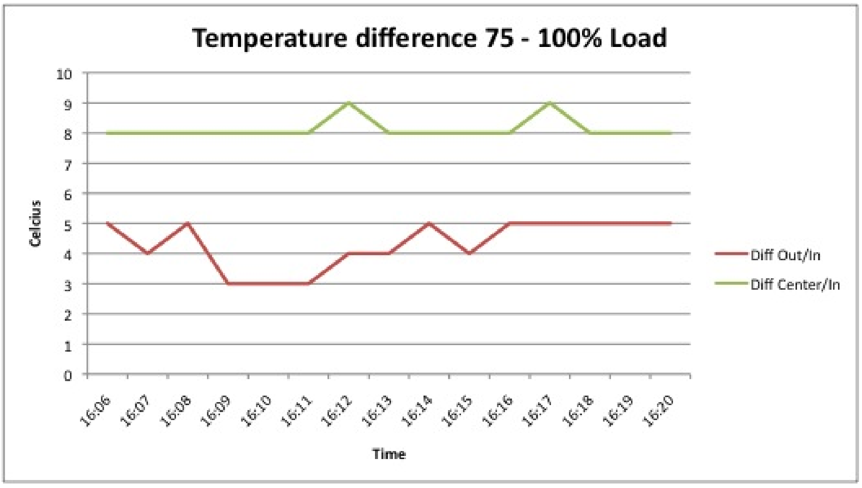
Transient Load

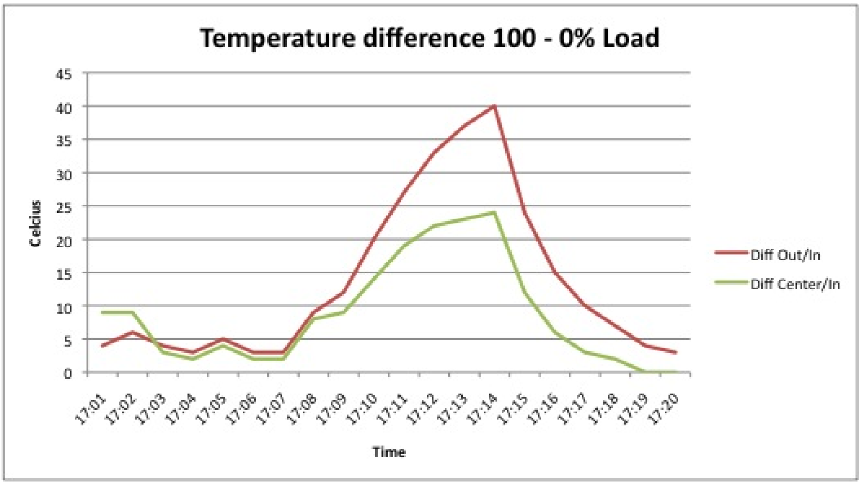







Temperature difference 50 - 75% Load
10
9
8
7
6
5
4
3
2
1
0
12:08
12:09
12:10
12:11
12:12
12:13
12:14
12:15
12:16
12:17
Time
Diff Out/In
Diff Center/In

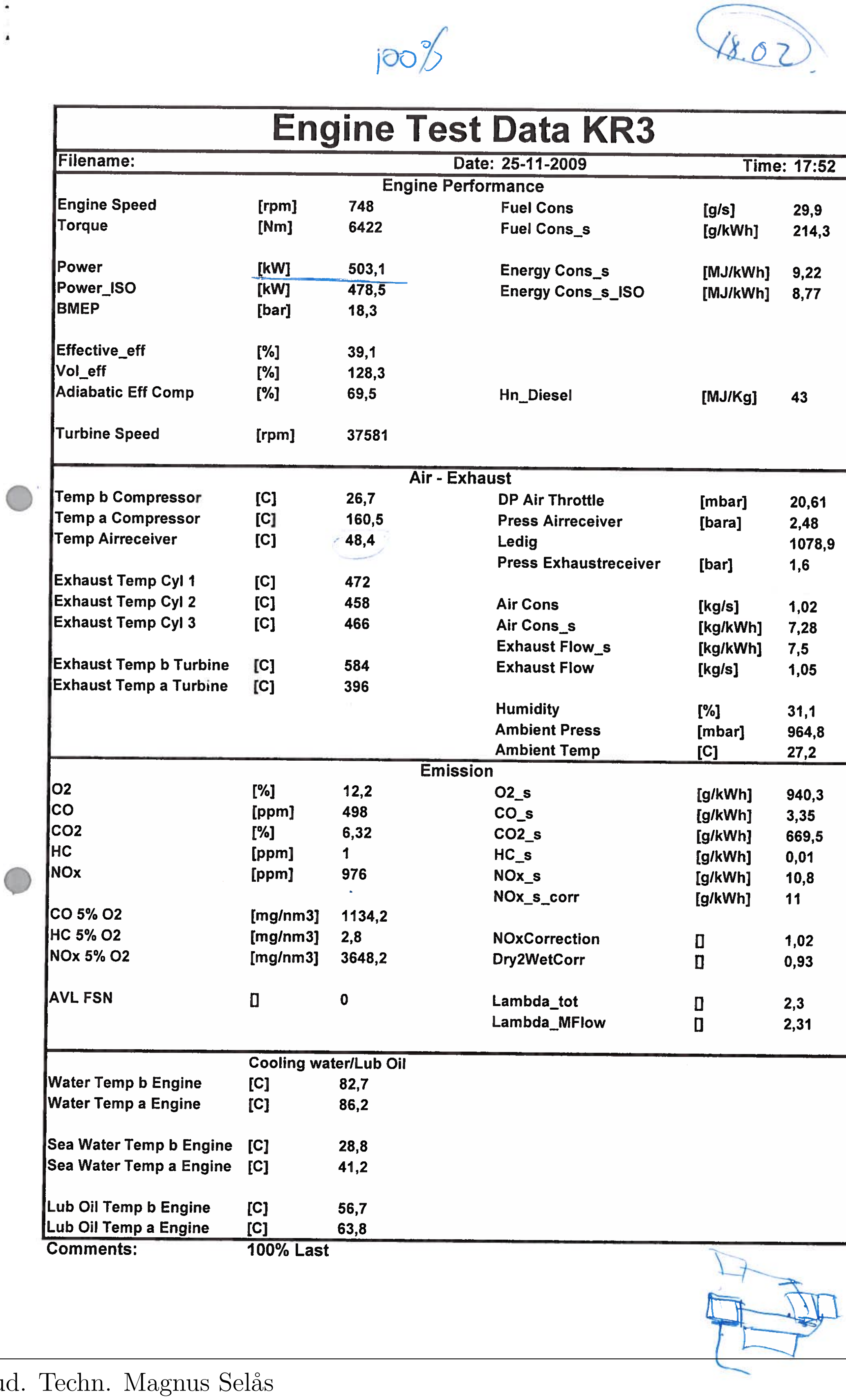

Temperature difference 75 - 100% Load
Celcius
10
9
8
7
6
5
4
3
2
1
0
16:06
16:07
16:08
16:09
16:10
16:11
16:12
16:13
16:14
16:15
16:16
16:17
16:18
16:19
16:20
Time
Diff Out/In
Diff Center/In


Temperature difference 100 - 0% Load
Celcius
45
40
35
30
25
20
15
10
5
0
17:01
17:02
17:03
17:04
17:05
17:06
17:07
17:08
17:09
17:10
17:11
17:12
17:13
17:14
17:15
17:16
17:17
17:18
17:19
17:20
Time
Diff Out/In
Diff Center/In

Appendix B

Rolls Royce KR3 Test Data

Before T/C Refitting - 25.11.2010



100%

18.02

Engine Test Data KR3

Filename:			Date: 25-11-2009		Time: 17:52

Engine Performance

Engine Speed	[rpm]	748	Fuel Cons	[g/s]	29,9
Torque	[Nm]	6422	Fuel Cons_s	[g/kWh]	214,3
Power	[kW]	503,1	Energy Cons_s	[MJ/kWh]	9,22
Power_ISO	[kW]	478,5	Energy Cons_s_ISO	[MJ/kWh]	8,77
BMEP	[bar]	18,3			
Effective_eff	[%]	39,1			
Vol_eff	[%]	128,3			
Adiabatic Eff Comp	[%]	69,5	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	37581			

Air - Exhaust

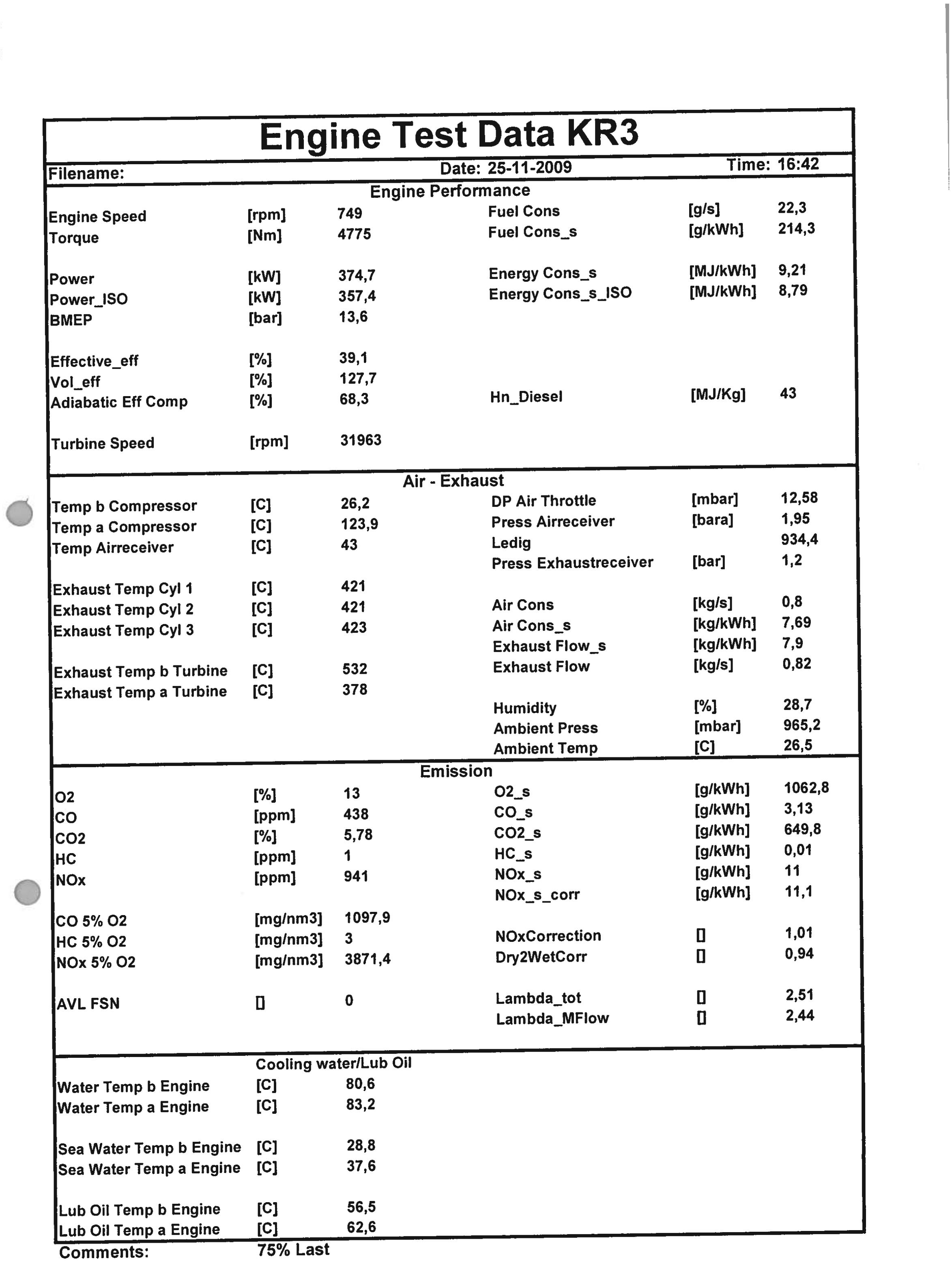
Temp b Compressor	[C]	26,7	DP Air Throttle	[mbar]	20,61
Temp a Compressor	[C]	160,5	Press Airreceiver	[bara]	2,48
Temp Airreceiver	[C]	48,4	Ledig		1078,9
			Press Exhaustreceiver	[bar]	1,6
Exhaust Temp Cyl 1	[C]	472			
Exhaust Temp Cyl 2	[C]	458	Air Cons	[kg/s]	1,02
Exhaust Temp Cyl 3	[C]	466	Air Cons_s	[kg/kWh]	7,28
			Exhaust Flow_s	[kg/kWh]	7,5
Exhaust Temp b Turbine	[C]	584	Exhaust Flow	[kg/s]	1,05
Exhaust Temp a Turbine	[C]	396			
			Humidity	[%]	31,1
			Ambient Press	[mbar]	964,8
			Ambient Temp	[C]	27,2

Emission

O2	[%]	12,2	O2_s	[g/kWh]	940,3
CO	[ppm]	498	CO_s	[g/kWh]	3,35
CO2	[%]	6,32	CO2_s	[g/kWh]	669,5
HC	[ppm]	1	HC_s	[g/kWh]	0,01
NOx	[ppm]	976	NOx_s	[g/kWh]	10,8
			NOx_s_corr	[g/kWh]	11
CO 5% O2	[mg/nm3]	1134,2			
HC 5% O2	[mg/nm3]	2,8	NOxCorrection	▯	1,02
NOx 5% O2	[mg/nm3]	3648,2	Dry2WetCorr	▯	0,93
AVL FSN	▯	0	Lambda_tot	▯	2,3
			Lambda_MFlow	▯	2,31

Cooling water/Lub Oil

Water Temp b Engine	[C]	82,7
Water Temp a Engine	[C]	86,2
Sea Water Temp b Engine	[C]	28,8
Sea Water Temp a Engine	[C]	41,2
Lub Oil Temp b Engine	[C]	56,7
Lub Oil Temp a Engine	[C]	63,8
Comments:	100% Last	



Engine Test Data KR3

Filename: Date: 25-11-2009 Time: 16:42

Engine Performance

Engine Speed	[rpm]	749	Fuel Cons	[g/s]	22,3
Torque	[Nm]	4775	Fuel Cons_s	[g/kWh]	214,3
Power	[kW]	374,7	Energy Cons_s	[MJ/kWh]	9,21
Power_ISO	[kW]	357,4	Energy Cons_s_ISO	[MJ/kWh]	8,79
BMEP	[bar]	13,6			
Effective_eff	[%]	39,1			
Vol_eff	[%]	127,7			
Adiabatic Eff Comp	[%]	68,3	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	31963			

Air - Exhaust

Temp b Compressor	[C]	26,2	DP Air Throttle	[mbar]	12,58
Temp a Compressor	[C]	123,9	Press Airreceiver	[bara]	1,95
Temp Airreceiver	[C]	43	Ledig		934,4
			Press Exhaustreceiver	[bar]	1,2
Exhaust Temp Cyl 1	[C]	421			
Exhaust Temp Cyl 2	[C]	421	Air Cons	[kg/s]	0,8
Exhaust Temp Cyl 3	[C]	423	Air Cons_s	[kg/kWh]	7,69
			Exhaust Flow_s	[kg/kWh]	7,9
Exhaust Temp b Turbine	[C]	532	Exhaust Flow	[kg/s]	0,82
Exhaust Temp a Turbine	[C]	378			
			Humidity	[%]	28,7
			Ambient Press	[mbar]	965,2
			Ambient Temp	[C]	26,5

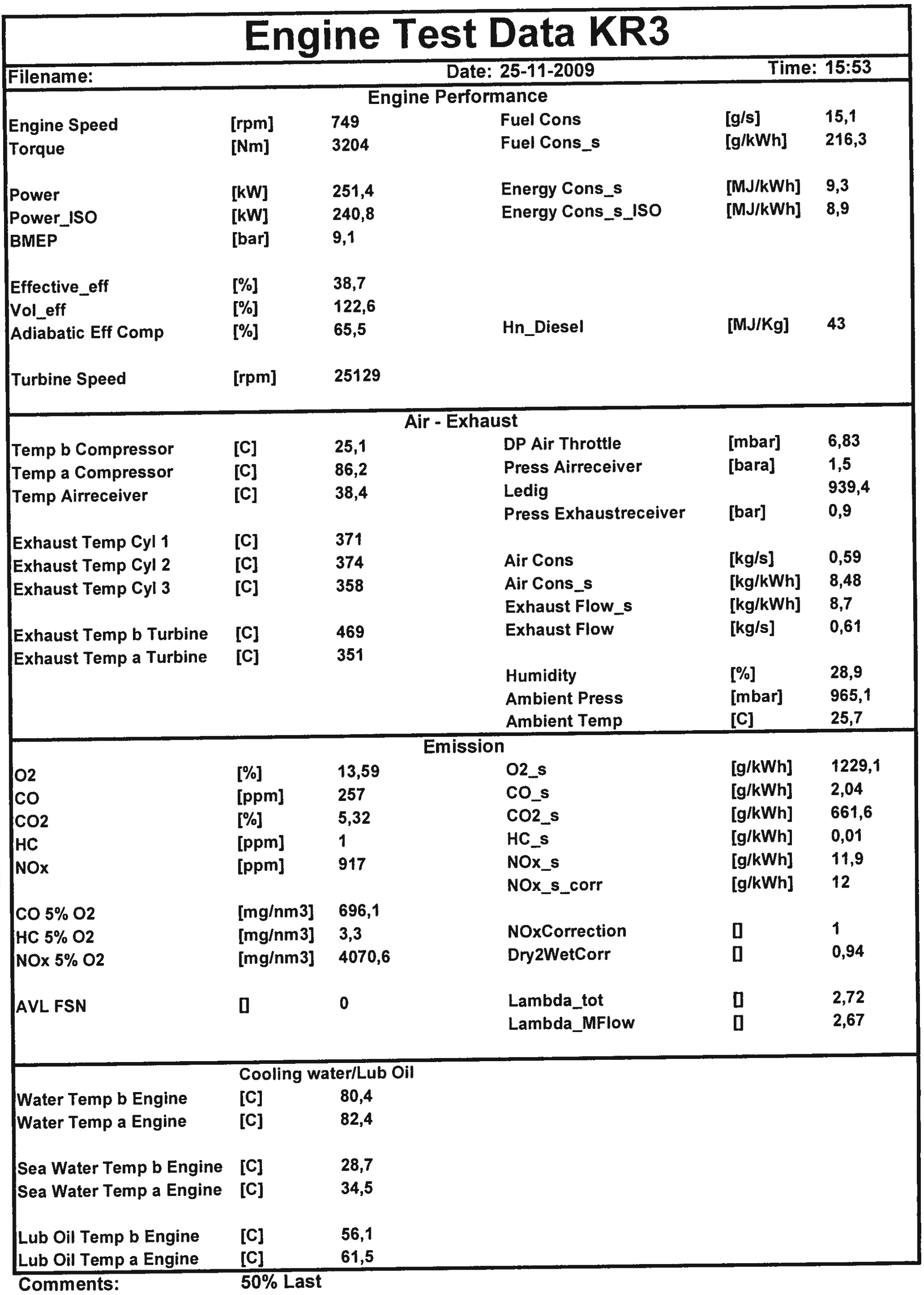
Emission

O2	[%]	13	O2_s	[g/kWh]	1062,8
CO	[ppm]	438	CO_s	[g/kWh]	3,13
CO2	[%]	5,78	CO2_s	[g/kWh]	649,8
HC	[ppm]	1	HC_s	[g/kWh]	0,01
NOx	[ppm]	941	NOx_s	[g/kWh]	11
			NOx_s_corr	[g/kWh]	11,1
CO 5% O2	[mg/nm3]	1097,9			
HC 5% O2	[mg/nm3]	3	NOxCorrection	[]	1,01
NOx 5% O2	[mg/nm3]	3871,4	Dry2WetCorr	[]	0,94
AVL FSN	[]	0	Lambda_tot	[]	2,51
			Lambda_MFlow	[]	2,44

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,6
Water Temp a Engine	[C]	83,2
Sea Water Temp b Engine	[C]	28,8
Sea Water Temp a Engine	[C]	37,6
Lub Oil Temp b Engine	[C]	56,5
Lub Oil Temp a Engine	[C]	62,6

Comments: 75% Last



Engine Test Data KR3

Filename: **Date: 25-11-2009** **Time: 15:53**

Engine Performance

Engine Speed	[rpm]	749	Fuel Cons	[g/s]	15,1
Torque	[Nm]	3204	Fuel Cons_s	[g/kWh]	216,3
Power	[kW]	251,4	Energy Cons_s	[MJ/kWh]	9,3
Power_ISO	[kW]	240,8	Energy Cons_s_ISO	[MJ/kWh]	8,9
BMEP	[bar]	9,1			
Effective_eff	[%]	38,7			
Vol_eff	[%]	122,6			
Adiabatic Eff Comp	[%]	65,5	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	25129			

Air - Exhaust

Temp b Compressor	[C]	25,1	DP Air Throttle	[mbar]	6,83
Temp a Compressor	[C]	86,2	Press Airreceiver	[bara]	1,5
Temp Airreceiver	[C]	38,4	Ledig		939,4
			Press Exhaustreceiver	[bar]	0,9
Exhaust Temp Cyl 1	[C]	371			
Exhaust Temp Cyl 2	[C]	374	Air Cons	[kg/s]	0,59
Exhaust Temp Cyl 3	[C]	358	Air Cons_s	[kg/kWh]	8,48
			Exhaust Flow_s	[kg/kWh]	8,7
Exhaust Temp b Turbine	[C]	469	Exhaust Flow	[kg/s]	0,61
Exhaust Temp a Turbine	[C]	351			
			Humidity	[%]	28,9
			Ambient Press	[mbar]	965,1
			Ambient Temp	[C]	25,7

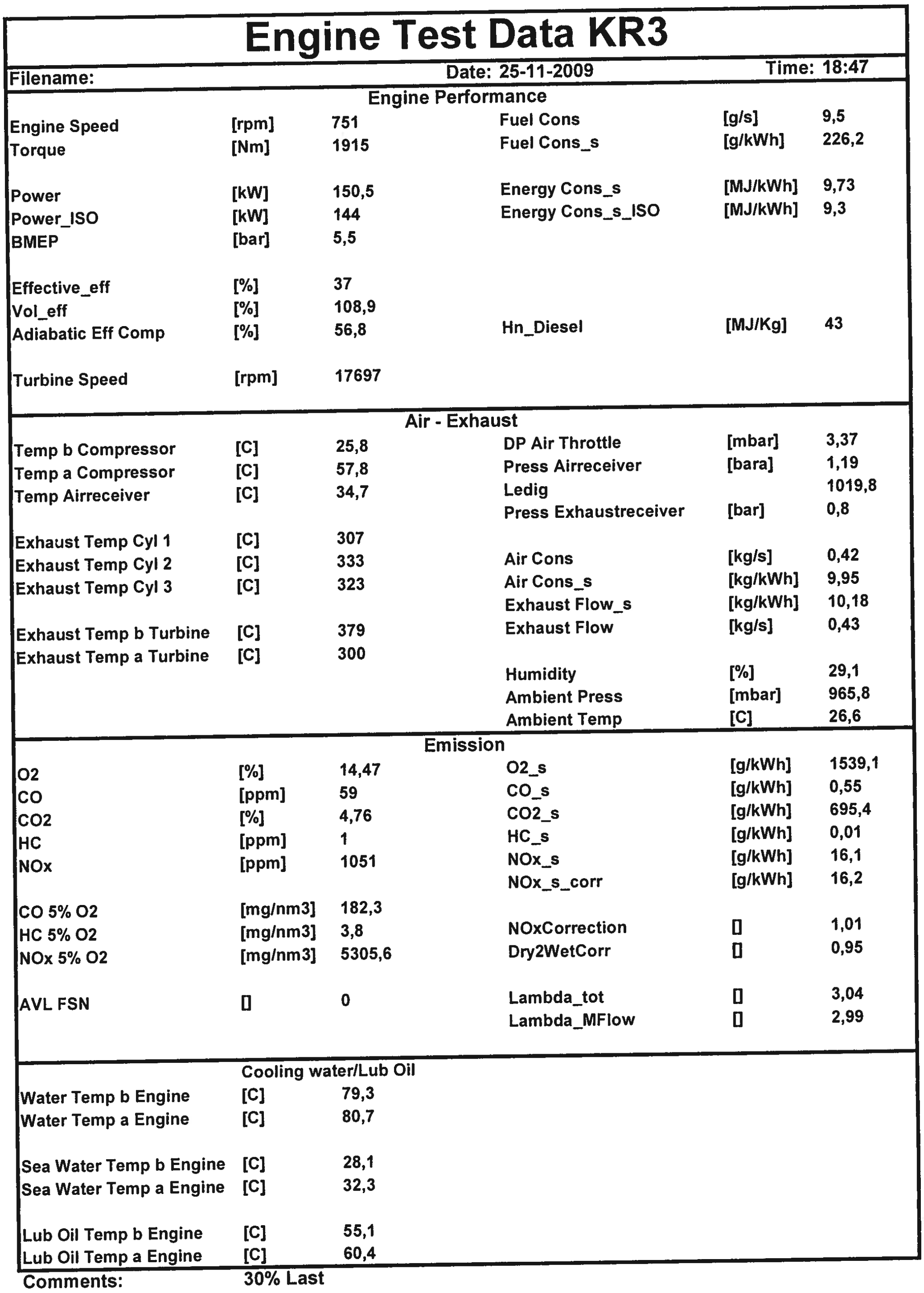
Emission

O2	[%]	13,59	O2_s	[g/kWh]	1229,1
CO	[ppm]	257	CO_s	[g/kWh]	2,04
CO2	[%]	5,32	CO2_s	[g/kWh]	661,6
HC	[ppm]	1	HC_s	[g/kWh]	0,01
NOx	[ppm]	917	NOx_s	[g/kWh]	11,9
			NOx_s_corr	[g/kWh]	12
CO 5% O2	[mg/nm3]	696,1			
HC 5% O2	[mg/nm3]	3,3	NOxCorrection	[]	1
NOx 5% O2	[mg/nm3]	4070,6	Dry2WetCorr	[]	0,94
AVL FSN	[]	0	Lambda_tot	[]	2,72
			Lambda_MFlow	[]	2,67

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,4
Water Temp a Engine	[C]	82,4
Sea Water Temp b Engine	[C]	28,7
Sea Water Temp a Engine	[C]	34,5
Lub Oil Temp b Engine	[C]	56,1
Lub Oil Temp a Engine	[C]	61,5

Comments: **50% Last**



Engine Test Data KR3

Filename: Date: 25-11-2009 Time: 18:47

Engine Performance

Engine Speed	[rpm]	751	Fuel Cons	[g/s]	9,5
Torque	[Nm]	1915	Fuel Cons_s	[g/kWh]	226,2
Power	[kW]	150,5	Energy Cons_s	[MJ/kWh]	9,73
Power_ISO	[kW]	144	Energy Cons_s_ISO	[MJ/kWh]	9,3
BMEP	[bar]	5,5			
Effective_eff	[%]	37			
Vol_eff	[%]	108,9			
Adiabatic Eff Comp	[%]	56,8	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	17697			

Air - Exhaust

Temp b Compressor	[C]	25,8	DP Air Throttle	[mbar]	3,37
Temp a Compressor	[C]	57,8	Press Airreceiver	[bara]	1,19
Temp Airreceiver	[C]	34,7	Ledig		1019,8
			Press Exhaustreceiver	[bar]	0,8
Exhaust Temp Cyl 1	[C]	307			
Exhaust Temp Cyl 2	[C]	333	Air Cons	[kg/s]	0,42
Exhaust Temp Cyl 3	[C]	323	Air Cons_s	[kg/kWh]	9,95
			Exhaust Flow_s	[kg/kWh]	10,18
Exhaust Temp b Turbine	[C]	379	Exhaust Flow	[kg/s]	0,43
Exhaust Temp a Turbine	[C]	300			
			Humidity	[%]	29,1
			Ambient Press	[mbar]	965,8
			Ambient Temp	[C]	26,6

Emission

O2	[%]	14,47	O2_s	[g/kWh]	1539,1
CO	[ppm]	59	CO_s	[g/kWh]	0,55
CO2	[%]	4,76	CO2_s	[g/kWh]	695,4
HC	[ppm]	1	HC_s	[g/kWh]	0,01
NOx	[ppm]	1051	NOx_s	[g/kWh]	16,1
			NOx_s_corr	[g/kWh]	16,2
CO 5% O2	[mg/nm3]	182,3			
HC 5% O2	[mg/nm3]	3,8	NOxCorrection	[]	1,01
NOx 5% O2	[mg/nm3]	5305,6	Dry2WetCorr	[]	0,95
AVL FSN	[]	0	Lambda_tot	[]	3,04
			Lambda_MFlow	[]	2,99

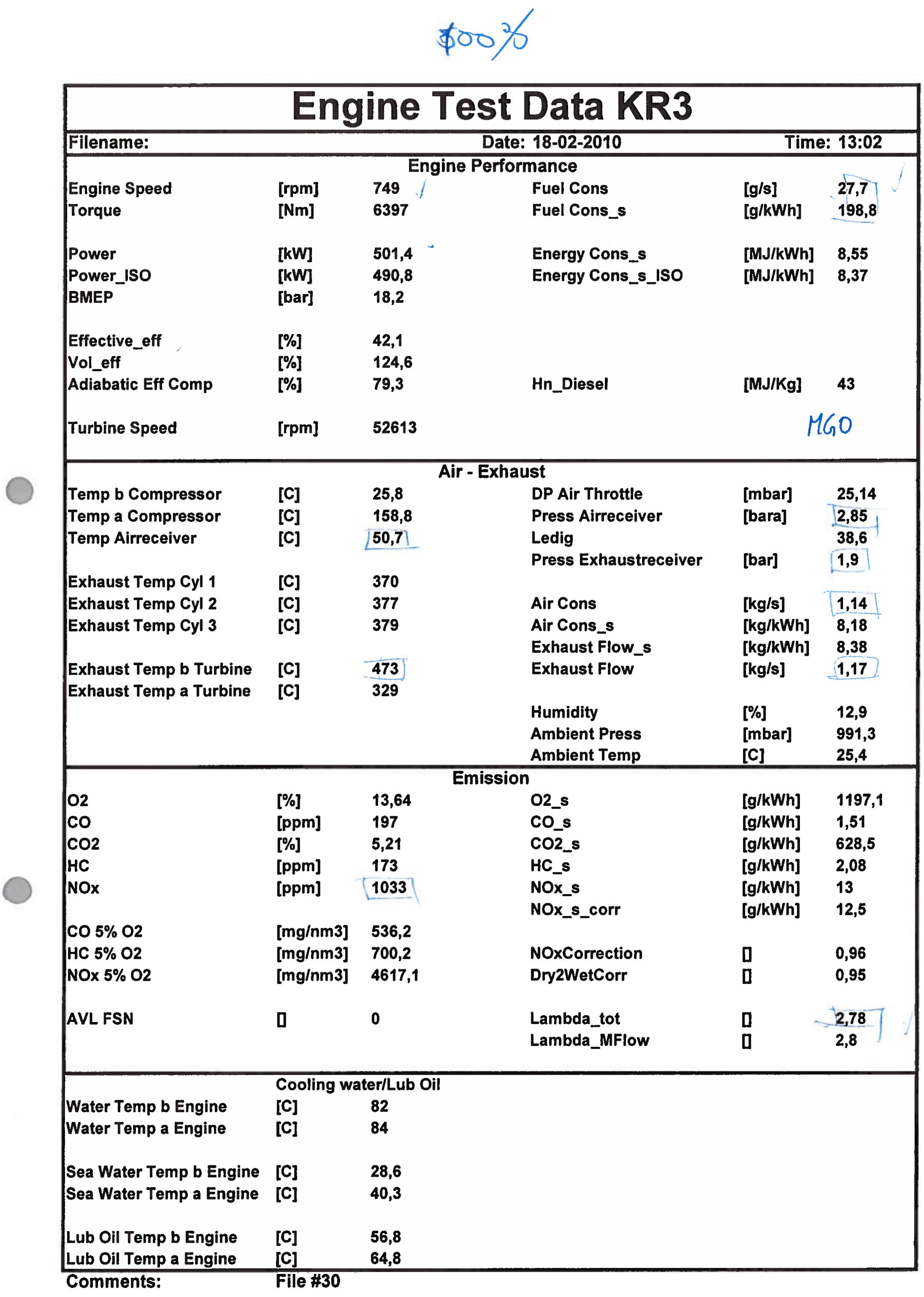
Cooling water/Lub Oil

Water Temp b Engine	[C]	79,3
Water Temp a Engine	[C]	80,7
Sea Water Temp b Engine	[C]	28,1
Sea Water Temp a Engine	[C]	32,3
Lub Oil Temp b Engine	[C]	55,1
Lub Oil Temp a Engine	[C]	60,4

Comments: 30% Last

After T/C Refitting, Before Calibration - 18.02.2010

MGO



100%

Engine Test Data KR3

Filename: Date: 18-02-2010 Time: 13:02

Engine Performance

Engine Speed	[rpm]	749	Fuel Cons	[g/s]	27,7
Torque	[Nm]	6397	Fuel Cons_s	[g/kWh]	198,8
Power	[kW]	501,4	Energy Cons_s	[MJ/kWh]	8,55
Power_ISO	[kW]	490,8	Energy Cons_s_ISO	[MJ/kWh]	8,37
BMEP	[bar]	18,2			
Effective_eff	[%]	42,1			
Vol_eff	[%]	124,6			
Adiabatic Eff Comp	[%]	79,3	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	52613			MGO

Air - Exhaust

Temp b Compressor	[C]	25,8	DP Air Throttle	[mbar]	25,14
Temp a Compressor	[C]	158,8	Press Airreceiver	[bara]	2,85
Temp Airreceiver	[C]	50,7	Ledig		38,6
			Press Exhaustreceiver	[bar]	1,9
Exhaust Temp Cyl 1	[C]	370			
Exhaust Temp Cyl 2	[C]	377	Air Cons	[kg/s]	1,14
Exhaust Temp Cyl 3	[C]	379	Air Cons_s	[kg/kWh]	8,18
			Exhaust Flow_s	[kg/kWh]	8,38
Exhaust Temp b Turbine	[C]	473	Exhaust Flow	[kg/s]	1,17
Exhaust Temp a Turbine	[C]	329			
			Humidity	[%]	12,9
			Ambient Press	[mbar]	991,3
			Ambient Temp	[C]	25,4

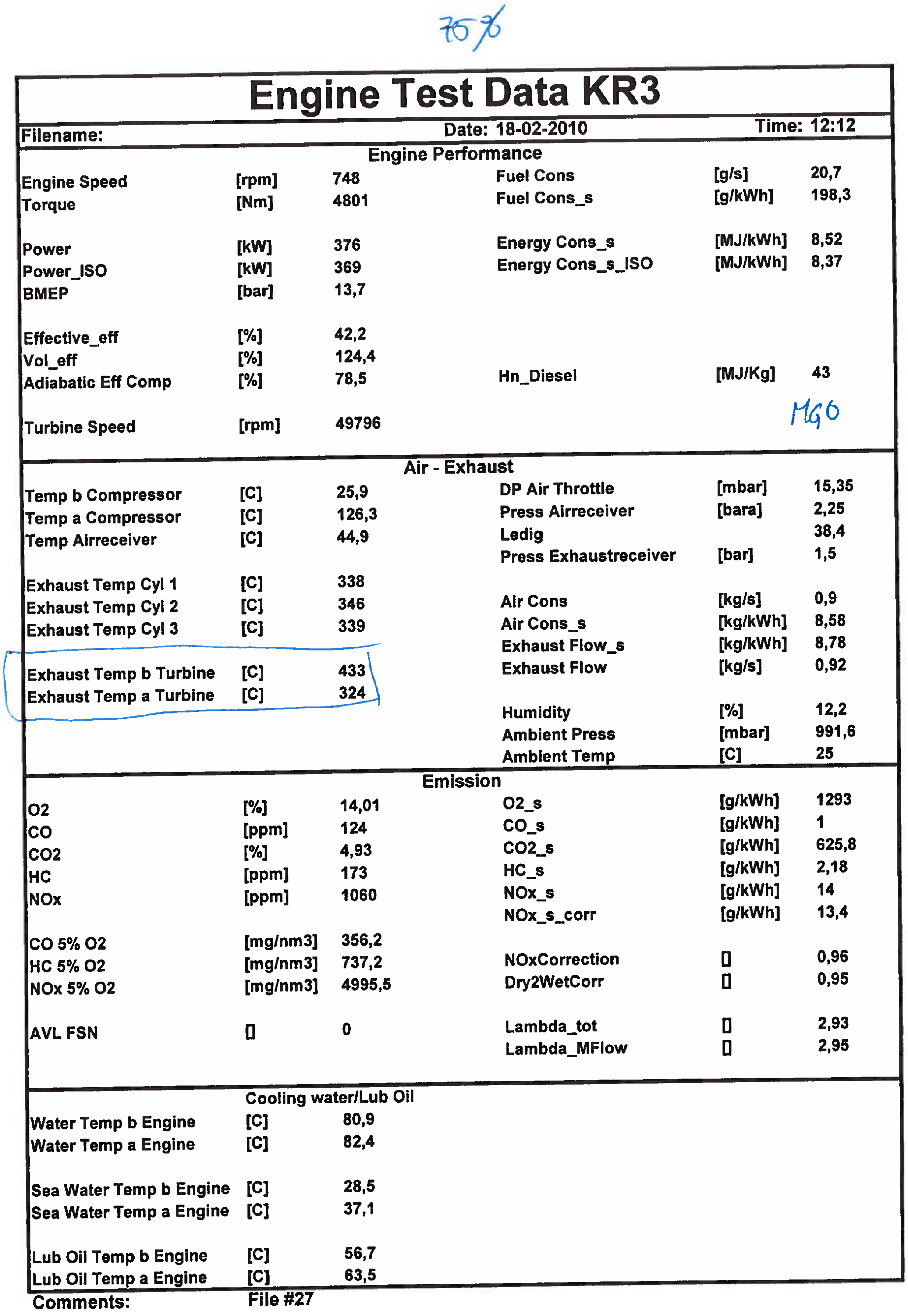
Emission

O2	[%]	13,64	O2_s	[g/kWh]	1197,1
CO	[ppm]	197	CO_s	[g/kWh]	1,51
CO2	[%]	5,21	CO2_s	[g/kWh]	628,5
HC	[ppm]	173	HC_s	[g/kWh]	2,08
NOx	[ppm]	1033	NOx_s	[g/kWh]	13
			NOx_s_corr	[g/kWh]	12,5
CO 5% O2	[mg/nm3]	536,2			
HC 5% O2	[mg/nm3]	700,2	NOxCorrection	▯	0,96
NOx 5% O2	[mg/nm3]	4617,1	Dry2WetCorr	▯	0,95
AVL FSN	▯	0	Lambda_tot	▯	2,78
			Lambda_MFlow	▯	2,8

Cooling water/Lub Oil

Water Temp b Engine	[C]	82
Water Temp a Engine	[C]	84
Sea Water Temp b Engine	[C]	28,6
Sea Water Temp a Engine	[C]	40,3
Lub Oil Temp b Engine	[C]	56,8
Lub Oil Temp a Engine	[C]	64,8

Comments: File #30



75%

Engine Test Data KR3

Filename: **Date: 18-02-2010** **Time: 12:12**

Engine Performance

Engine Speed	[rpm]	748	Fuel Cons	[g/s]	20,7
Torque	[Nm]	4801	Fuel Cons_s	[g/kWh]	198,3
Power	[kW]	376	Energy Cons_s	[MJ/kWh]	8,52
Power_ISO	[kW]	369	Energy Cons_s_ISO	[MJ/kWh]	8,37
BMEP	[bar]	13,7			
Effective_eff	[%]	42,2			
Vol_eff	[%]	124,4			
Adiabatic Eff Comp	[%]	78,5	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	49796			MGO

Air - Exhaust

Temp b Compressor	[C]	25,9	DP Air Throttle	[mbar]	15,35
Temp a Compressor	[C]	126,3	Press Airreceiver	[bara]	2,25
Temp Airreceiver	[C]	44,9	Ledig		38,4
			Press Exhaustreceiver	[bar]	1,5
Exhaust Temp Cyl 1	[C]	338	Air Cons	[kg/s]	0,9
Exhaust Temp Cyl 2	[C]	346	Air Cons_s	[kg/kWh]	8,58
Exhaust Temp Cyl 3	[C]	339	Exhaust Flow_s	[kg/kWh]	8,78
Exhaust Temp b Turbine	[C]	433	Exhaust Flow	[kg/s]	0,92
Exhaust Temp a Turbine	[C]	324			
			Humidity	[%]	12,2
			Ambient Press	[mbar]	991,6
			Ambient Temp	[C]	25

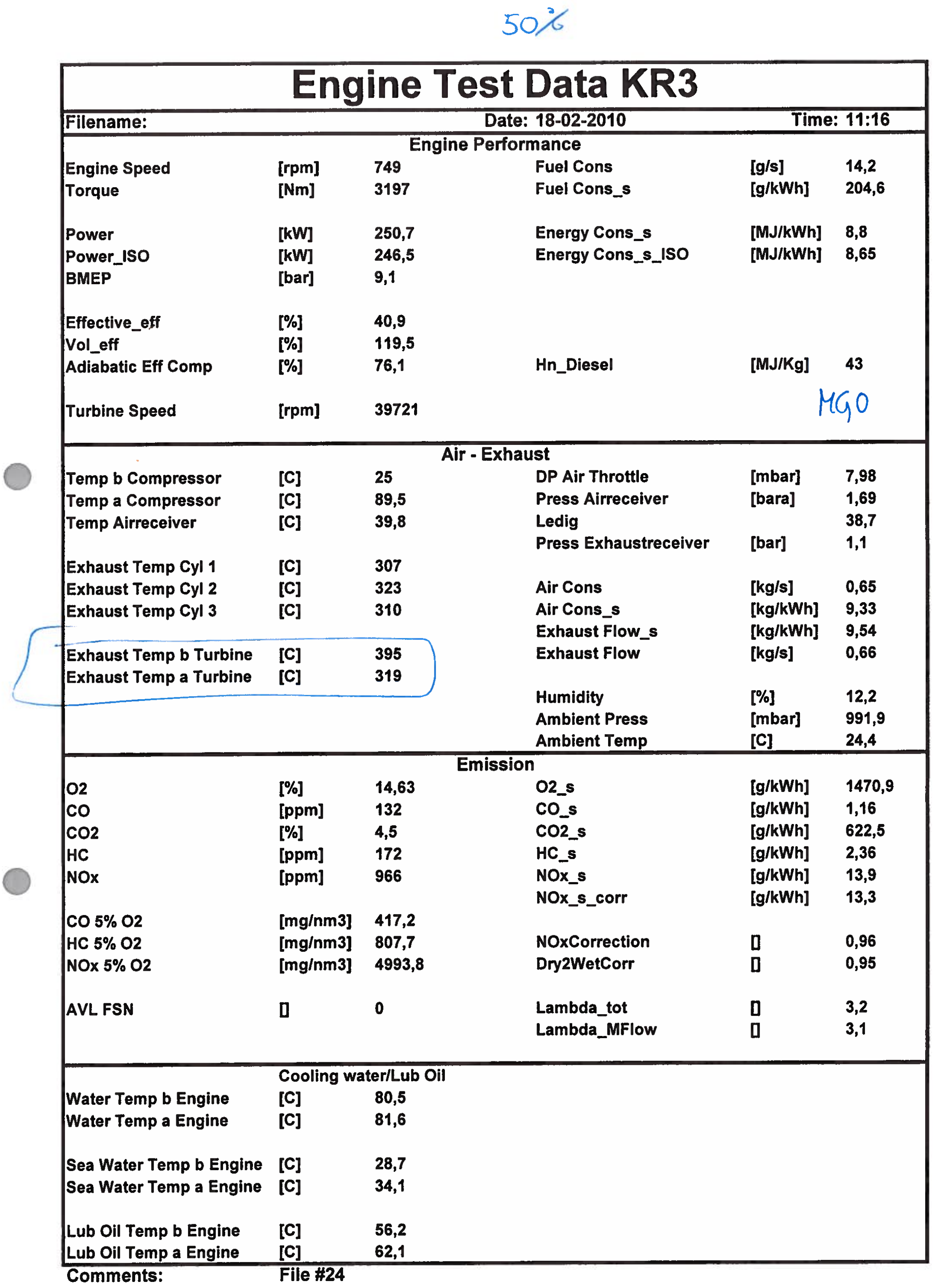
Emission

O2	[%]	14,01	O2_s	[g/kWh]	1293
CO	[ppm]	124	CO_s	[g/kWh]	1
CO2	[%]	4,93	CO2_s	[g/kWh]	625,8
HC	[ppm]	173	HC_s	[g/kWh]	2,18
NOx	[ppm]	1060	NOx_s	[g/kWh]	14
			NOx_s_corr	[g/kWh]	13,4
CO 5% O2	[mg/nm3]	356,2			
HC 5% O2	[mg/nm3]	737,2	NOxCorrection	▯	0,96
NOx 5% O2	[mg/nm3]	4995,5	Dry2WetCorr	▯	0,95
AVL FSN	▯	0	Lambda_tot	▯	2,93
			Lambda_MFlow	▯	2,95

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,9
Water Temp a Engine	[C]	82,4
Sea Water Temp b Engine	[C]	28,5
Sea Water Temp a Engine	[C]	37,1
Lub Oil Temp b Engine	[C]	56,7
Lub Oil Temp a Engine	[C]	63,5

Comments: File #27



50%

Engine Test Data KR3

Filename: **Date: 18-02-2010** **Time: 11:16**

Engine Performance

Engine Speed	[rpm]	749	Fuel Cons	[g/s]	14,2
Torque	[Nm]	3197	Fuel Cons_s	[g/kWh]	204,6
Power	[kW]	250,7	Energy Cons_s	[MJ/kWh]	8,8
Power_ISO	[kW]	246,5	Energy Cons_s_ISO	[MJ/kWh]	8,65
BMEP	[bar]	9,1			
Effective_eff	[%]	40,9			
Vol_eff	[%]	119,5			
Adiabatic Eff Comp	[%]	76,1	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	39721			MGO

Air - Exhaust

Temp b Compressor	[C]	25	DP Air Throttle	[mbar]	7,98
Temp a Compressor	[C]	89,5	Press Airreceiver	[bara]	1,69
Temp Airreceiver	[C]	39,8	Ledig		38,7
			Press Exhaustreceiver	[bar]	1,1
Exhaust Temp Cyl 1	[C]	307			
Exhaust Temp Cyl 2	[C]	323	Air Cons	[kg/s]	0,65
Exhaust Temp Cyl 3	[C]	310	Air Cons_s	[kg/kWh]	9,33
			Exhaust Flow_s	[kg/kWh]	9,54
Exhaust Temp b Turbine	[C]	395	Exhaust Flow	[kg/s]	0,66
Exhaust Temp a Turbine	[C]	319			
			Humidity	[%]	12,2
			Ambient Press	[mbar]	991,9
			Ambient Temp	[C]	24,4

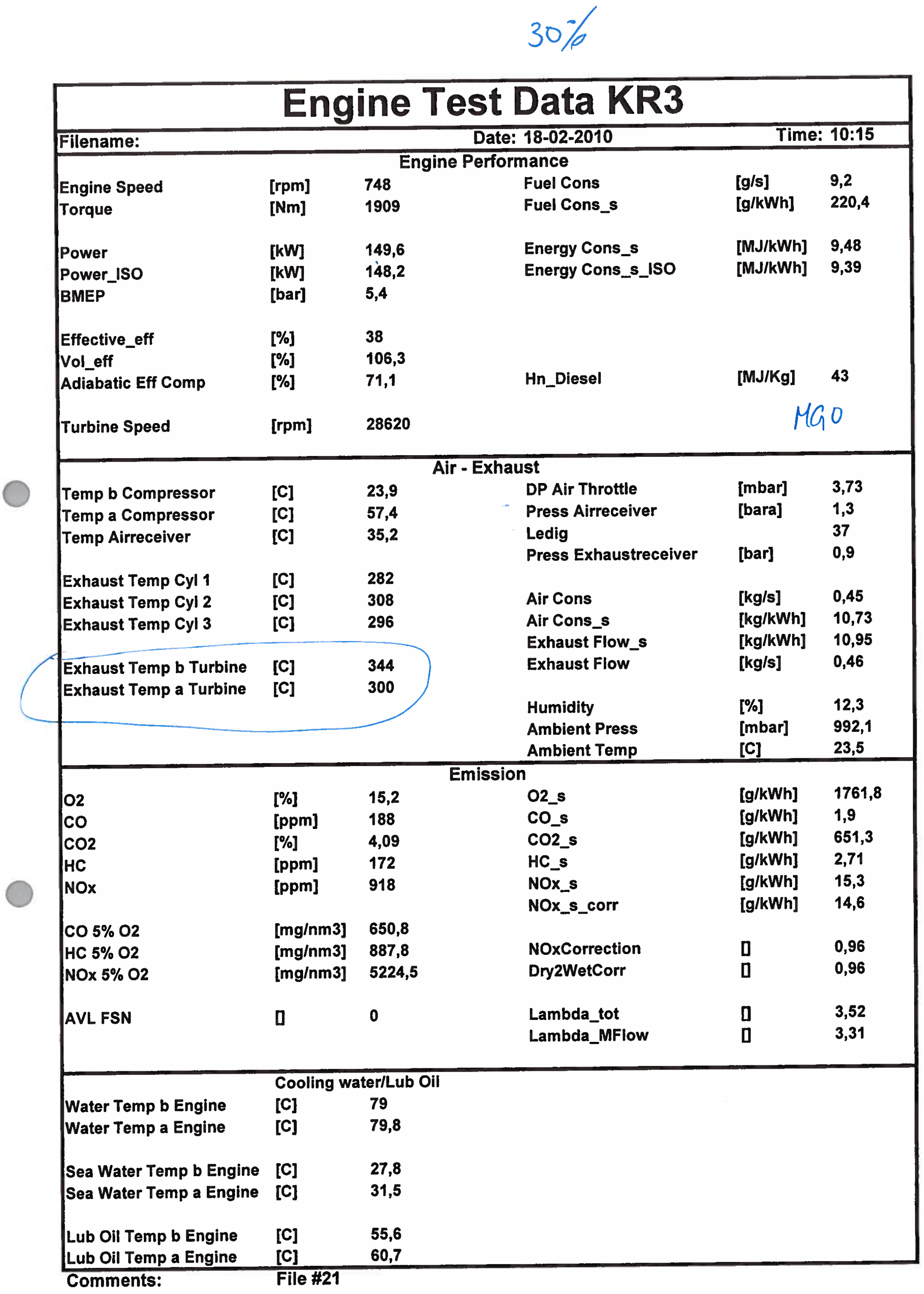
Emission

O2	[%]	14,63	O2_s	[g/kWh]	1470,9
CO	[ppm]	132	CO_s	[g/kWh]	1,16
CO2	[%]	4,5	CO2_s	[g/kWh]	622,5
HC	[ppm]	172	HC_s	[g/kWh]	2,36
NOx	[ppm]	966	NOx_s	[g/kWh]	13,9
			NOx_s_corr	[g/kWh]	13,3
CO 5% O2	[mg/nm3]	417,2			
HC 5% O2	[mg/nm3]	807,7	NOxCorrection	[]	0,96
NOx 5% O2	[mg/nm3]	4993,8	Dry2WetCorr	[]	0,95
AVL FSN	[]	0	Lambda_tot	[]	3,2
			Lambda_MFlow	[]	3,1

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,5
Water Temp a Engine	[C]	81,6
Sea Water Temp b Engine	[C]	28,7
Sea Water Temp a Engine	[C]	34,1
Lub Oil Temp b Engine	[C]	56,2
Lub Oil Temp a Engine	[C]	62,1

Comments: **File #24**



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Engine Test Data KR3

Filename: Date: 18-02-2010 Time: 10:15

Engine Performance

Engine Speed	[rpm]	748	Fuel Cons	[g/s]	9,2
Torque	[Nm]	1909	Fuel Cons_s	[g/kWh]	220,4
Power	[kW]	149,6	Energy Cons_s	[MJ/kWh]	9,48
Power_ISO	[kW]	148,2	Energy Cons_s_ISO	[MJ/kWh]	9,39
BMEP	[bar]	5,4			
Effective_eff	[%]	38			
Vol_eff	[%]	106,3			
Adiabatic Eff Comp	[%]	71,1	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	28620		MGO	

Air - Exhaust

Temp b Compressor	[C]	23,9	DP Air Throttle	[mbar]	3,73
Temp a Compressor	[C]	57,4	Press Airreceiver	[bara]	1,3
Temp Airreceiver	[C]	35,2	Ledig		37
			Press Exhaustreceiver	[bar]	0,9
Exhaust Temp Cyl 1	[C]	282			
Exhaust Temp Cyl 2	[C]	308	Air Cons	[kg/s]	0,45
Exhaust Temp Cyl 3	[C]	296	Air Cons_s	[kg/kWh]	10,73
			Exhaust Flow_s	[kg/kWh]	10,95
Exhaust Temp b Turbine	[C]	344	Exhaust Flow	[kg/s]	0,46
Exhaust Temp a Turbine	[C]	300			
			Humidity	[%]	12,3
			Ambient Press	[mbar]	992,1
			Ambient Temp	[C]	23,5

Emission

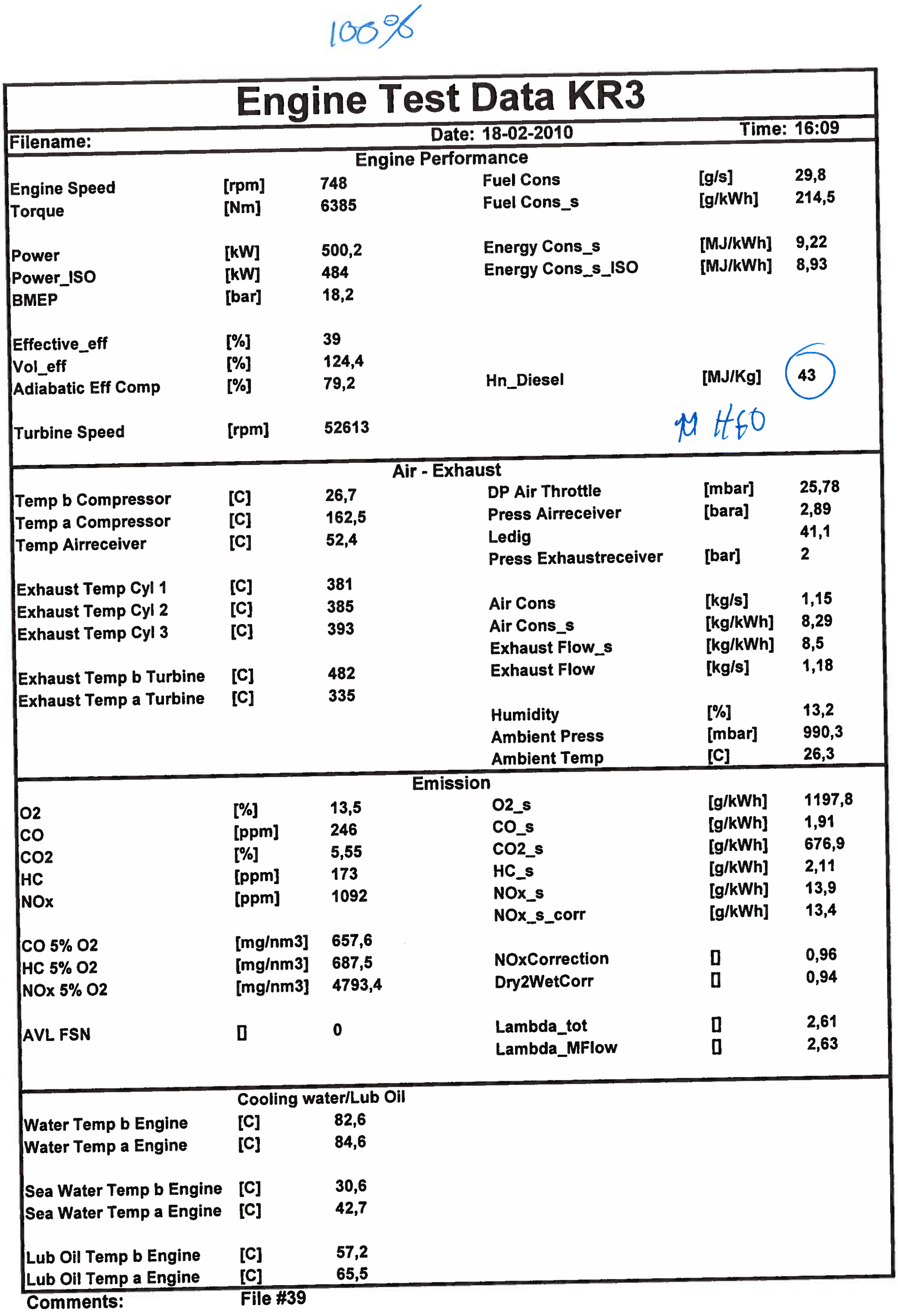
O2	[%]	15,2	O2_s	[g/kWh]	1761,8
CO	[ppm]	188	CO_s	[g/kWh]	1,9
CO2	[%]	4,09	CO2_s	[g/kWh]	651,3
HC	[ppm]	172	HC_s	[g/kWh]	2,71
NOx	[ppm]	918	NOx_s	[g/kWh]	15,3
			NOx_s_corr	[g/kWh]	14,6
CO 5% O2	[mg/nm3]	650,8			
HC 5% O2	[mg/nm3]	887,8	NOxCorrection	[]	0,96
NOx 5% O2	[mg/nm3]	5224,5	Dry2WetCorr	[]	0,96
AVL FSN	[]	0	Lambda_tot	[]	3,52
			Lambda_MFlow	[]	3,31

Cooling water/Lub Oil

Water Temp b Engine	[C]	79
Water Temp a Engine	[C]	79,8
Sea Water Temp b Engine	[C]	27,8
Sea Water Temp a Engine	[C]	31,5
Lub Oil Temp b Engine	[C]	55,6
Lub Oil Temp a Engine	[C]	60,7

Comments: File #21

HFO



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Engine Test Data KR3

Filename: Date: 18-02-2010 Time: 16:09

Engine Performance

Engine Speed	[rpm]	748	Fuel Cons	[g/s]	29,8
Torque	[Nm]	6385	Fuel Cons_s	[g/kWh]	214,5
Power	[kW]	500,2	Energy Cons_s	[MJ/kWh]	9,22
Power_ISO	[kW]	484	Energy Cons_s_ISO	[MJ/kWh]	8,93
BMEP	[bar]	18,2			
Effective_eff	[%]	39			
Vol_eff	[%]	124,4			
Adiabatic Eff Comp	[%]	79,2	Hn_Diesel	[MJ/Kg]	⓸⓷ 43
Turbine Speed	[rpm]	52613	M H60		

Air - Exhaust

Temp b Compressor	[C]	26,7	DP Air Throttle	[mbar]	25,78
Temp a Compressor	[C]	162,5	Press Airreceiver	[bara]	2,89
Temp Airreceiver	[C]	52,4	Ledig		41,1
			Press Exhaustreceiver	[bar]	2
Exhaust Temp Cyl 1	[C]	381	Air Cons	[kg/s]	1,15
Exhaust Temp Cyl 2	[C]	385	Air Cons_s	[kg/kWh]	8,29
Exhaust Temp Cyl 3	[C]	393	Exhaust Flow_s	[kg/kWh]	8,5
Exhaust Temp b Turbine	[C]	482	Exhaust Flow	[kg/s]	1,18
Exhaust Temp a Turbine	[C]	335			
			Humidity	[%]	13,2
			Ambient Press	[mbar]	990,3
			Ambient Temp	[C]	26,3

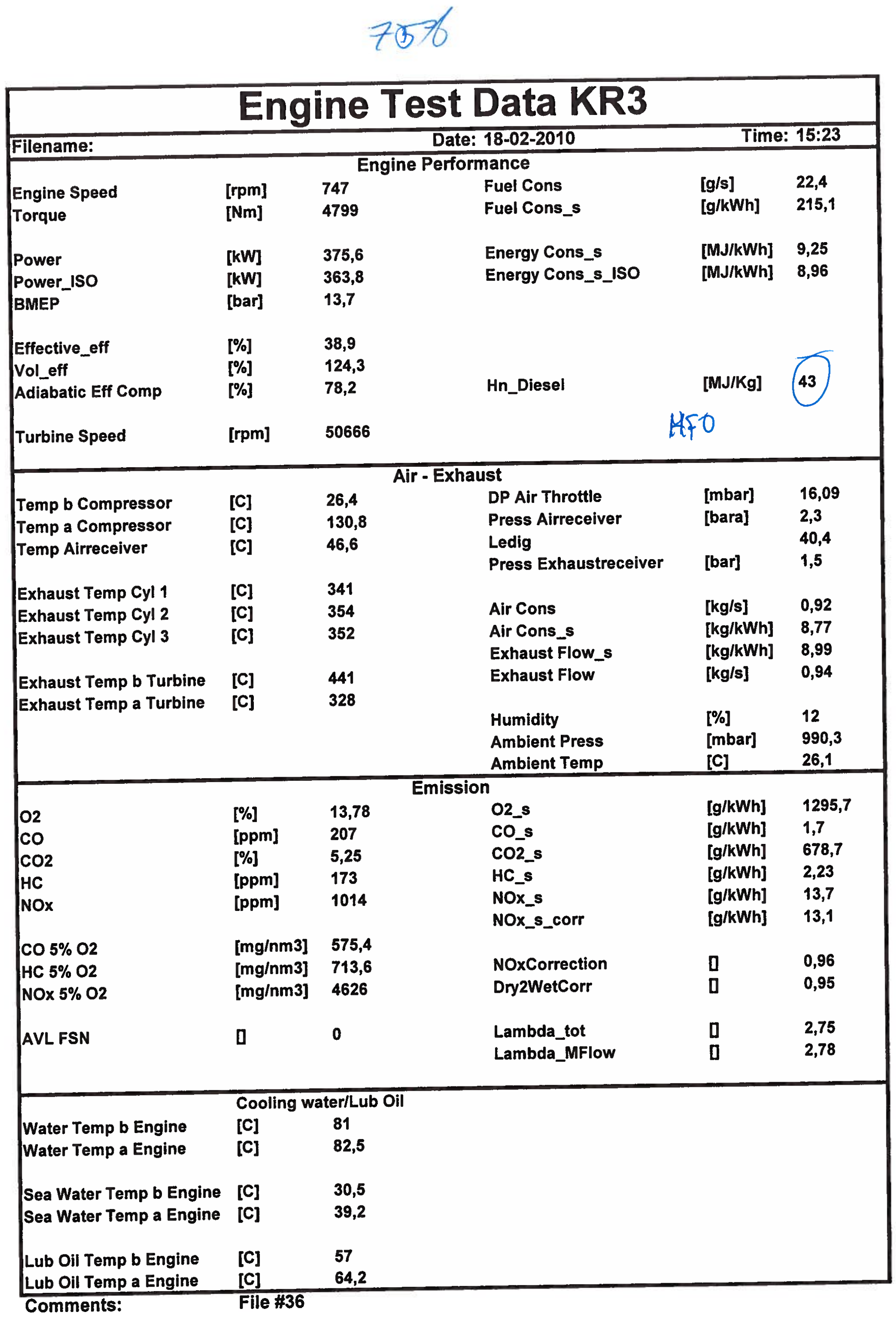
Emission

O2	[%]	13,5	O2_s	[g/kWh]	1197,8
CO	[ppm]	246	CO_s	[g/kWh]	1,91
CO2	[%]	5,55	CO2_s	[g/kWh]	676,9
HC	[ppm]	173	HC_s	[g/kWh]	2,11
NOx	[ppm]	1092	NOx_s	[g/kWh]	13,9
			NOx_s_corr	[g/kWh]	13,4
CO 5% O2	[mg/nm3]	657,6			
HC 5% O2	[mg/nm3]	687,5	NOxCorrection	▯	0,96
NOx 5% O2	[mg/nm3]	4793,4	Dry2WetCorr	▯	0,94
AVL FSN	▯	0	Lambda_tot	▯	2,61
			Lambda_MFlow	▯	2,63

Cooling water/Lub Oil

Water Temp b Engine	[C]	82,6
Water Temp a Engine	[C]	84,6
Sea Water Temp b Engine	[C]	30,6
Sea Water Temp a Engine	[C]	42,7
Lub Oil Temp b Engine	[C]	57,2
Lub Oil Temp a Engine	[C]	65,5

Comments: File #39



7576

Engine Test Data KR3

Filename: Date: 18-02-2010 Time: 15:23

Engine Performance

Engine Speed	[rpm]	747	Fuel Cons	[g/s]	22,4
Torque	[Nm]	4799	Fuel Cons_s	[g/kWh]	215,1
Power	[kW]	375,6	Energy Cons_s	[MJ/kWh]	9,25
Power_ISO	[kW]	363,8	Energy Cons_s_ISO	[MJ/kWh]	8,96
BMEP	[bar]	13,7			
Effective_eff	[%]	38,9			
Vol_eff	[%]	124,3			
Adiabatic Eff Comp	[%]	78,2	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	50666		HFO	

Air - Exhaust

Temp b Compressor	[C]	26,4	DP Air Throttle	[mbar]	16,09
Temp a Compressor	[C]	130,8	Press Airreceiver	[bara]	2,3
Temp Airreceiver	[C]	46,6	Ledig		40,4
			Press Exhaustreceiver	[bar]	1,5
Exhaust Temp Cyl 1	[C]	341	Air Cons	[kg/s]	0,92
Exhaust Temp Cyl 2	[C]	354	Air Cons_s	[kg/kWh]	8,77
Exhaust Temp Cyl 3	[C]	352	Exhaust Flow_s	[kg/kWh]	8,99
Exhaust Temp b Turbine	[C]	441	Exhaust Flow	[kg/s]	0,94
Exhaust Temp a Turbine	[C]	328			
			Humidity	[%]	12
			Ambient Press	[mbar]	990,3
			Ambient Temp	[C]	26,1

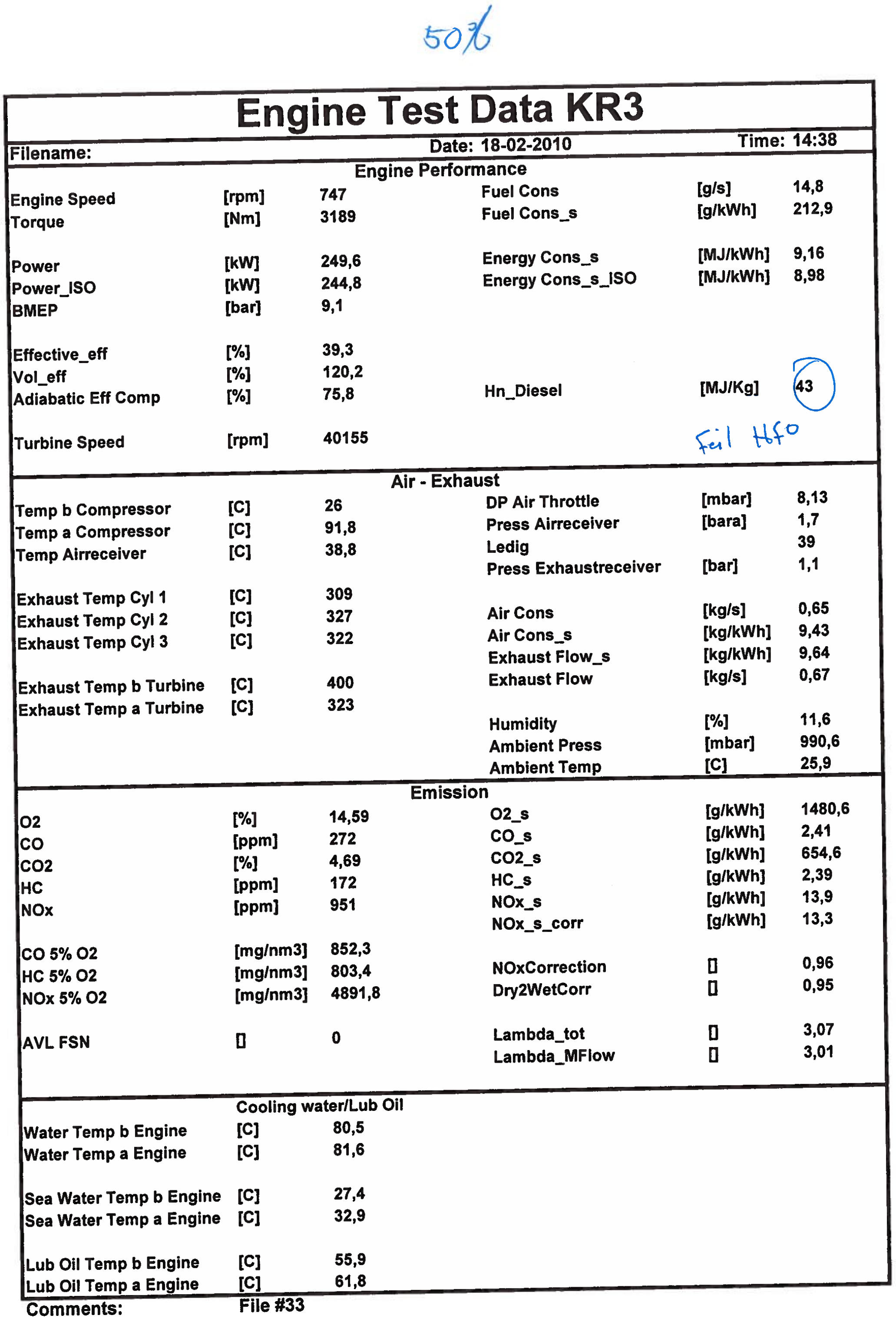
Emission

O2	[%]	13,78	O2_s	[g/kWh]	1295,7
CO	[ppm]	207	CO_s	[g/kWh]	1,7
CO2	[%]	5,25	CO2_s	[g/kWh]	678,7
HC	[ppm]	173	HC_s	[g/kWh]	2,23
NOx	[ppm]	1014	NOx_s	[g/kWh]	13,7
			NOx_s_corr	[g/kWh]	13,1
CO 5% O2	[mg/nm3]	575,4			
HC 5% O2	[mg/nm3]	713,6	NOxCorrection	▯	0,96
NOx 5% O2	[mg/nm3]	4626	Dry2WetCorr	▯	0,95
AVL FSN	▯	0	Lambda_tot	▯	2,75
			Lambda_MFlow	▯	2,78

Cooling water/Lub Oil

Water Temp b Engine	[C]	81
Water Temp a Engine	[C]	82,5
Sea Water Temp b Engine	[C]	30,5
Sea Water Temp a Engine	[C]	39,2
Lub Oil Temp b Engine	[C]	57
Lub Oil Temp a Engine	[C]	64,2

Comments: File #36



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Engine Test Data KR3

Filename: Date: 18-02-2010 Time: 14:38

Engine Performance

Engine Speed	[rpm]	747	Fuel Cons	[g/s]	14,8
Torque	[Nm]	3189	Fuel Cons_s	[g/kWh]	212,9
Power	[kW]	249,6	Energy Cons_s	[MJ/kWh]	9,16
Power_ISO	[kW]	244,8	Energy Cons_s_ISO	[MJ/kWh]	8,98
BMEP	[bar]	9,1			
Effective_eff	[%]	39,3			
Vol_eff	[%]	120,2			
Adiabatic Eff Comp	[%]	75,8	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	40155		Feil HFO	

Air - Exhaust

Temp b Compressor	[C]	26	DP Air Throttle	[mbar]	8,13
Temp a Compressor	[C]	91,8	Press Airreceiver	[bara]	1,7
Temp Airreceiver	[C]	38,8	Ledig		39
			Press Exhaustreceiver	[bar]	1,1
Exhaust Temp Cyl 1	[C]	309	Air Cons	[kg/s]	0,65
Exhaust Temp Cyl 2	[C]	327	Air Cons_s	[kg/kWh]	9,43
Exhaust Temp Cyl 3	[C]	322	Exhaust Flow_s	[kg/kWh]	9,64
			Exhaust Flow	[kg/s]	0,67
Exhaust Temp b Turbine	[C]	400			
Exhaust Temp a Turbine	[C]	323			
			Humidity	[%]	11,6
			Ambient Press	[mbar]	990,6
			Ambient Temp	[C]	25,9

Emission

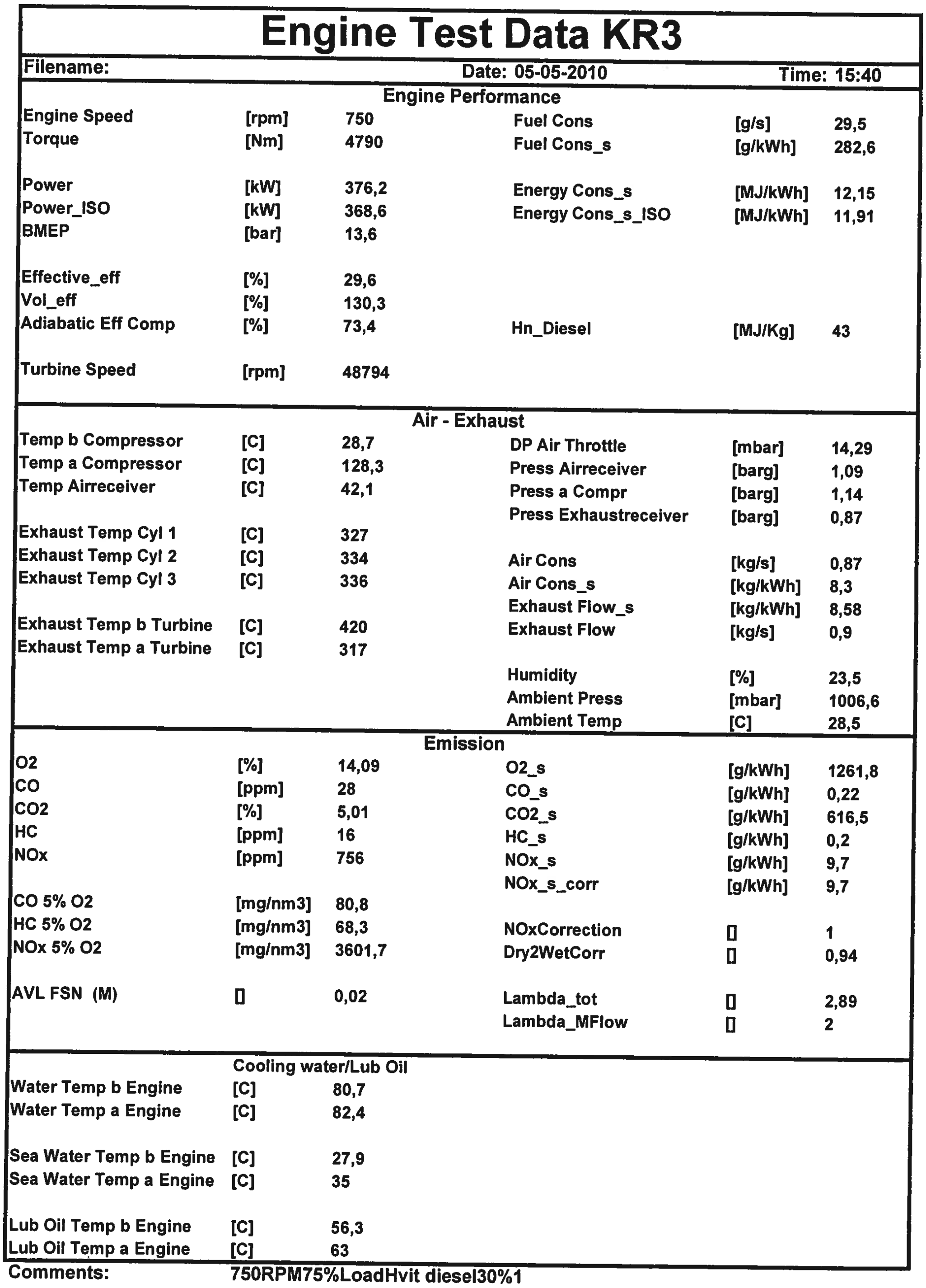
O2	[%]	14,59	O2_s	[g/kWh]	1480,6
CO	[ppm]	272	CO_s	[g/kWh]	2,41
CO2	[%]	4,69	CO2_s	[g/kWh]	654,6
HC	[ppm]	172	HC_s	[g/kWh]	2,39
NOx	[ppm]	951	NOx_s	[g/kWh]	13,9
			NOx_s_corr	[g/kWh]	13,3
CO 5% O2	[mg/nm3]	852,3			
HC 5% O2	[mg/nm3]	803,4	NOxCorrection	[]	0,96
NOx 5% O2	[mg/nm3]	4891,8	Dry2WetCorr	[]	0,95
AVL FSN	[]	0	Lambda_tot	[]	3,07
			Lambda_MFlow	[]	3,01

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,5
Water Temp a Engine	[C]	81,6
Sea Water Temp b Engine	[C]	27,4
Sea Water Temp a Engine	[C]	32,9
Lub Oil Temp b Engine	[C]	55,9
Lub Oil Temp a Engine	[C]	61,8

Comments: File #33

White Diesel Reference - 05.05.2010



Engine Test Data KR3

Filename: **Date: 05-05-2010** **Time: 15:40**

Engine Performance

Engine Speed	[rpm]	750	Fuel Cons	[g/s]	29,5
Torque	[Nm]	4790	Fuel Cons_s	[g/kWh]	282,6
Power	[kW]	376,2	Energy Cons_s	[MJ/kWh]	12,15
Power_ISO	[kW]	368,6	Energy Cons_s_ISO	[MJ/kWh]	11,91
BMEP	[bar]	13,6			
Effective_eff	[%]	29,6			
Vol_eff	[%]	130,3			
Adiabatic Eff Comp	[%]	73,4	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	48794			

Air - Exhaust

Temp b Compressor	[C]	28,7	DP Air Throttle	[mbar]	14,29
Temp a Compressor	[C]	128,3	Press Airreceiver	[barg]	1,09
Temp Airreceiver	[C]	42,1	Press a Compr	[barg]	1,14
			Press Exhaustreceiver	[barg]	0,87
Exhaust Temp Cyl 1	[C]	327			
Exhaust Temp Cyl 2	[C]	334	Air Cons	[kg/s]	0,87
Exhaust Temp Cyl 3	[C]	336	Air Cons_s	[kg/kWh]	8,3
			Exhaust Flow_s	[kg/kWh]	8,58
Exhaust Temp b Turbine	[C]	420	Exhaust Flow	[kg/s]	0,9
Exhaust Temp a Turbine	[C]	317			
			Humidity	[%]	23,5
			Ambient Press	[mbar]	1006,6
			Ambient Temp	[C]	28,5

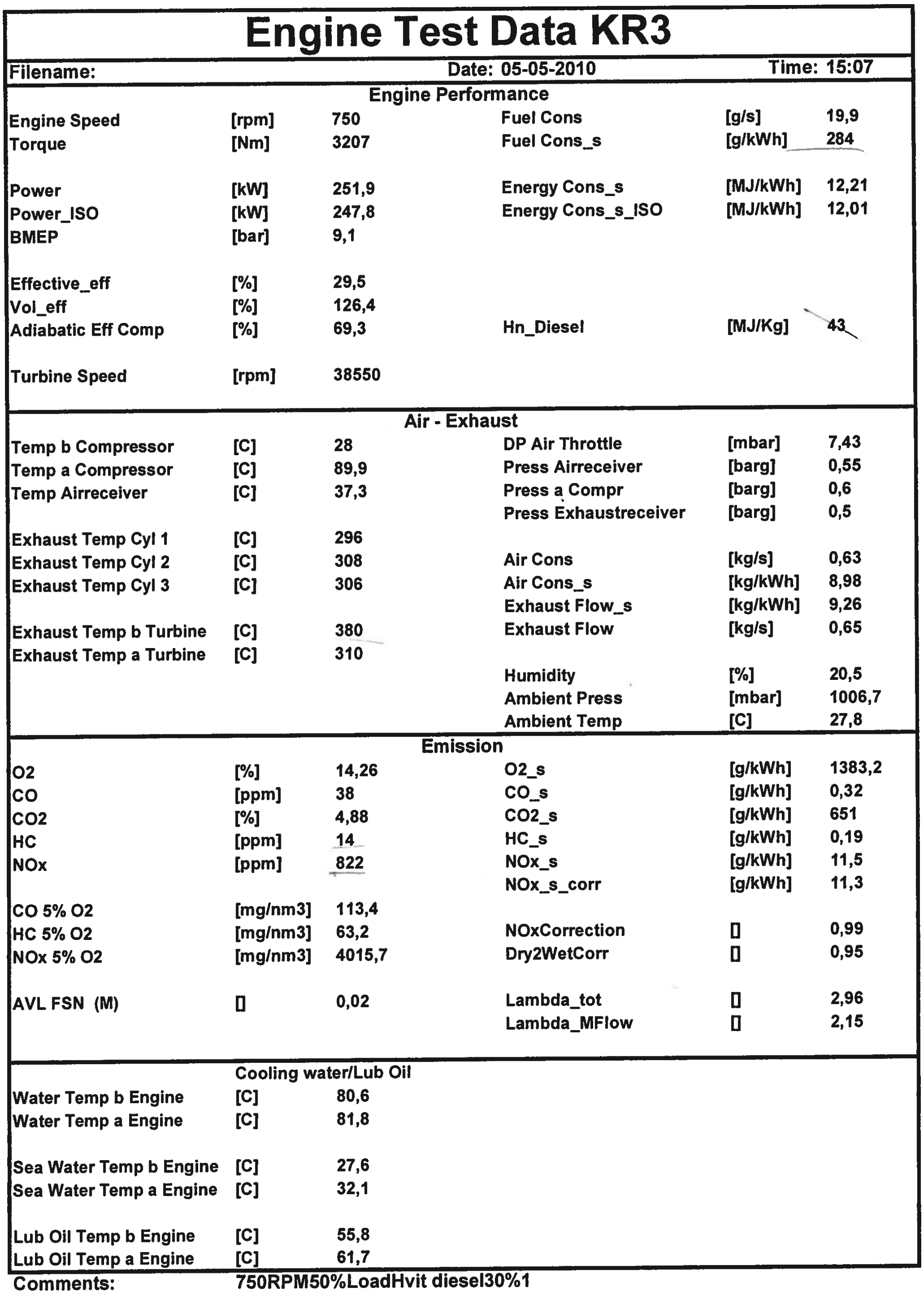
Emission

O2	[%]	14,09	O2_s	[g/kWh]	1261,8
CO	[ppm]	28	CO_s	[g/kWh]	0,22
CO2	[%]	5,01	CO2_s	[g/kWh]	616,5
HC	[ppm]	16	HC_s	[g/kWh]	0,2
NOx	[ppm]	756	NOx_s	[g/kWh]	9,7
			NOx_s_corr	[g/kWh]	9,7
CO 5% O2	[mg/nm3]	80,8			
HC 5% O2	[mg/nm3]	68,3	NOxCorrection	[]	1
NOx 5% O2	[mg/nm3]	3601,7	Dry2WetCorr	[]	0,94
AVL FSN (M)	[]	0,02	Lambda_tot	[]	2,89
			Lambda_MFlow	[]	2

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,7
Water Temp a Engine	[C]	82,4
Sea Water Temp b Engine	[C]	27,9
Sea Water Temp a Engine	[C]	35
Lub Oil Temp b Engine	[C]	56,3
Lub Oil Temp a Engine	[C]	63

Comments: **750RPM75%LoadHvit diesel30%1**



Engine Test Data KR3

Filename: **Date: 05-05-2010** **Time: 15:07**

Engine Performance

Engine Speed	[rpm]	750	Fuel Cons	[g/s]	19,9
Torque	[Nm]	3207	Fuel Cons_s	[g/kWh]	284
Power	[kW]	251,9	Energy Cons_s	[MJ/kWh]	12,21
Power_ISO	[kW]	247,8	Energy Cons_s_ISO	[MJ/kWh]	12,01
BMEP	[bar]	9,1			
Effective_eff	[%]	29,5			
Vol_eff	[%]	126,4			
Adiabatic Eff Comp	[%]	69,3	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	38550			

Air - Exhaust

Temp b Compressor	[C]	28	DP Air Throttle	[mbar]	7,43
Temp a Compressor	[C]	89,9	Press Airreceiver	[barg]	0,55
Temp Airreceiver	[C]	37,3	Press a Compr	[barg]	0,6
			Press Exhaustreceiver	[barg]	0,5
Exhaust Temp Cyl 1	[C]	296			
Exhaust Temp Cyl 2	[C]	308	Air Cons	[kg/s]	0,63
Exhaust Temp Cyl 3	[C]	306	Air Cons_s	[kg/kWh]	8,98
			Exhaust Flow_s	[kg/kWh]	9,26
Exhaust Temp b Turbine	[C]	380	Exhaust Flow	[kg/s]	0,65
Exhaust Temp a Turbine	[C]	310			
			Humidity	[%]	20,5
			Ambient Press	[mbar]	1006,7
			Ambient Temp	[C]	27,8

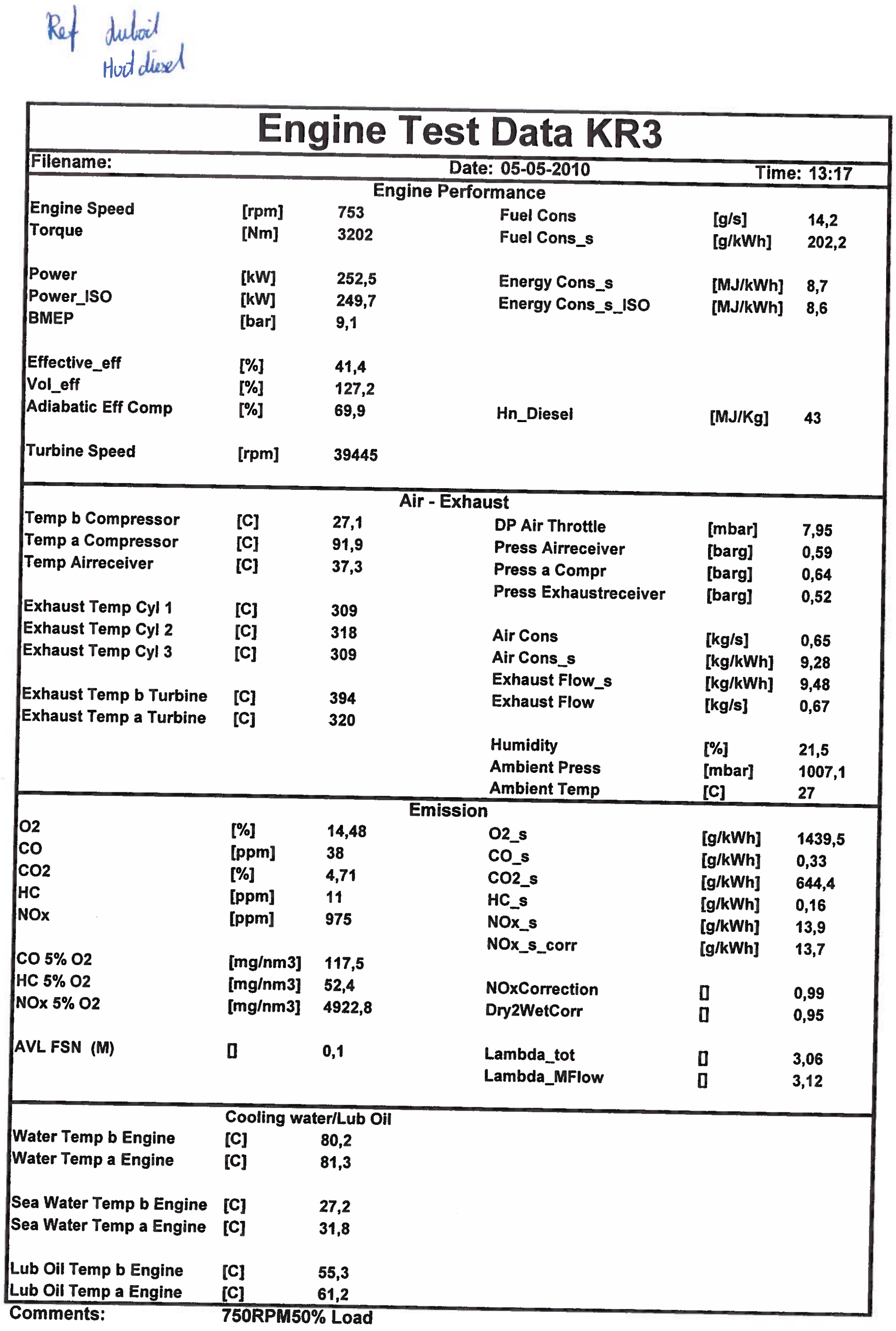
Emission

O2	[%]	14,26	O2_s	[g/kWh]	1383,2
CO	[ppm]	38	CO_s	[g/kWh]	0,32
CO2	[%]	4,88	CO2_s	[g/kWh]	651
HC	[ppm]	14	HC_s	[g/kWh]	0,19
NOx	[ppm]	822	NOx_s	[g/kWh]	11,5
			NOx_s_corr	[g/kWh]	11,3
CO 5% O2	[mg/nm3]	113,4			
HC 5% O2	[mg/nm3]	63,2	NOxCorrection	[]	0,99
NOx 5% O2	[mg/nm3]	4015,7	Dry2WetCorr	[]	0,95
AVL FSN (M)	[]	0,02	Lambda_tot	[]	2,96
			Lambda_MFlow	[]	2,15

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,6
Water Temp a Engine	[C]	81,8
Sea Water Temp b Engine	[C]	27,6
Sea Water Temp a Engine	[C]	32,1
Lub Oil Temp b Engine	[C]	55,8
Lub Oil Temp a Engine	[C]	61,7

Comments: **750RPM50%LoadHvit diesel30%1**



Ref duboil
Hud diesel

Engine Test Data KR3

Filename:

Date: 05-05-2010

Time: 13:17

Engine Performance

Engine Speed	[rpm]	753	Fuel Cons	[g/s]	14,2
Torque	[Nm]	3202	Fuel Cons_s	[g/kWh]	202,2
Power	[kW]	252,5	Energy Cons_s	[MJ/kWh]	8,7
Power_ISO	[kW]	249,7	Energy Cons_s_ISO	[MJ/kWh]	8,6
BMEP	[bar]	9,1			
Effective_eff	[%]	41,4			
Vol_eff	[%]	127,2			
Adiabatic Eff Comp	[%]	69,9	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	39445			

Air - Exhaust

Temp b Compressor	[C]	27,1	DP Air Throttle	[mbar]	7,95
Temp a Compressor	[C]	91,9	Press Airreceiver	[barg]	0,59
Temp Airreceiver	[C]	37,3	Press a Compr	[barg]	0,64
			Press Exhaustreceiver	[barg]	0,52
Exhaust Temp Cyl 1	[C]	309			
Exhaust Temp Cyl 2	[C]	318	Air Cons	[kg/s]	0,65
Exhaust Temp Cyl 3	[C]	309	Air Cons_s	[kg/kWh]	9,28
			Exhaust Flow_s	[kg/kWh]	9,48
Exhaust Temp b Turbine	[C]	394	Exhaust Flow	[kg/s]	0,67
Exhaust Temp a Turbine	[C]	320			
			Humidity	[%]	21,5
			Ambient Press	[mbar]	1007,1
			Ambient Temp	[C]	27

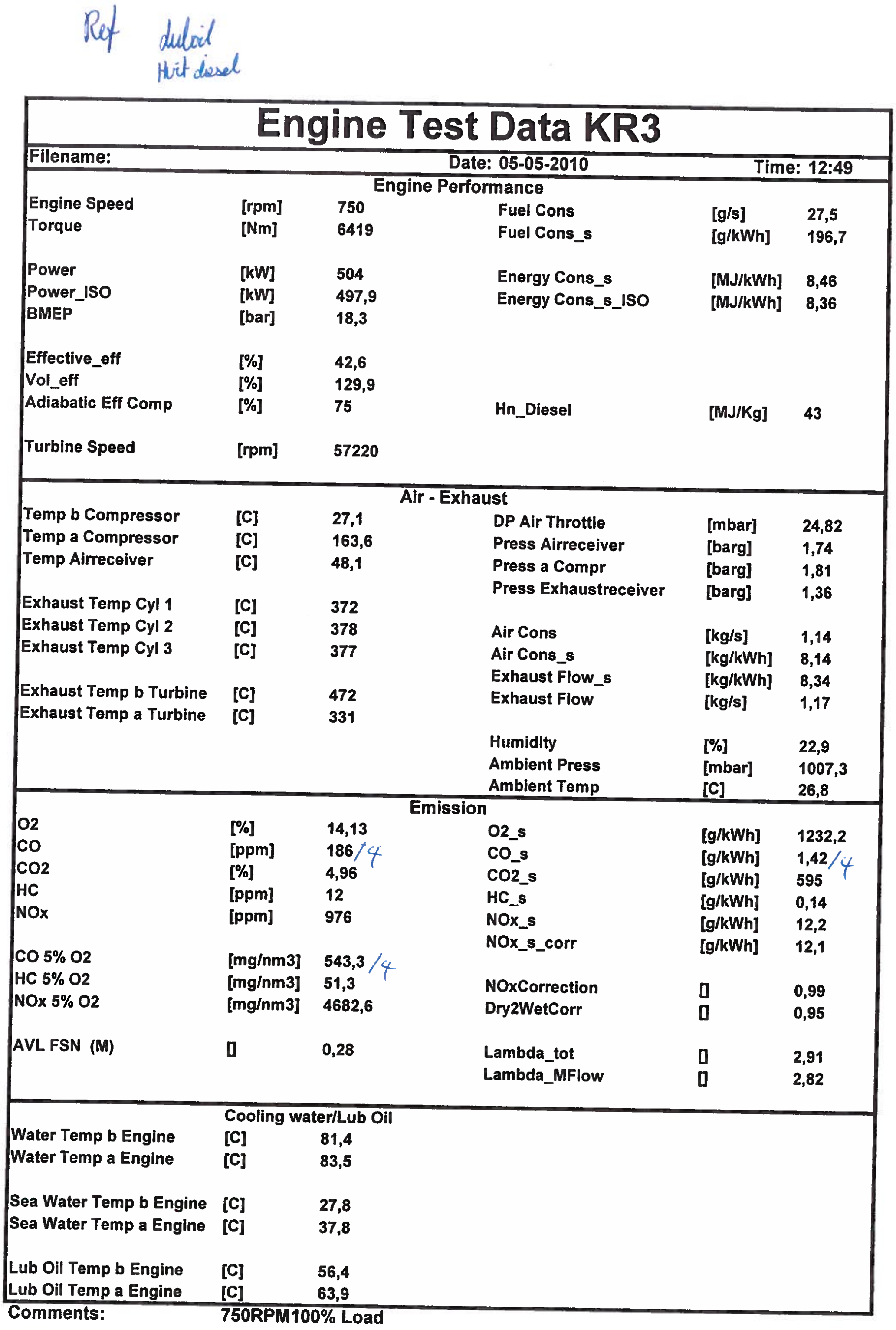
Emission

O2	[%]	14,48	O2_s	[g/kWh]	1439,5
CO	[ppm]	38	CO_s	[g/kWh]	0,33
CO2	[%]	4,71	CO2_s	[g/kWh]	644,4
HC	[ppm]	11	HC_s	[g/kWh]	0,16
NOx	[ppm]	975	NOx_s	[g/kWh]	13,9
			NOx_s_corr	[g/kWh]	13,7
CO 5% O2	[mg/nm3]	117,5			
HC 5% O2	[mg/nm3]	52,4	NOxCorrection	▯	0,99
NOx 5% O2	[mg/nm3]	4922,8	Dry2WetCorr	▯	0,95
AVL FSN (M)	▯	0,1	Lambda_tot	▯	3,06
			Lambda_MFlow	▯	3,12

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,2
Water Temp a Engine	[C]	81,3
Sea Water Temp b Engine	[C]	27,2
Sea Water Temp a Engine	[C]	31,8
Lub Oil Temp b Engine	[C]	55,3
Lub Oil Temp a Engine	[C]	61,2

Comments: 750RPM50% Load



Ref

duloil
Hvit diesel

Engine Test Data KR3

Filename:

Date: 05-05-2010 Time: 12:49

Engine Performance

Engine Speed	[rpm]	750	Fuel Cons	[g/s]	27,5
Torque	[Nm]	6419	Fuel Cons_s	[g/kWh]	196,7
Power	[kW]	504	Energy Cons_s	[MJ/kWh]	8,46
Power_ISO	[kW]	497,9	Energy Cons_s_ISO	[MJ/kWh]	8,36
BMEP	[bar]	18,3			
Effective_eff	[%]	42,6			
Vol_eff	[%]	129,9			
Adiabatic Eff Comp	[%]	75	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	57220			

Air - Exhaust

Temp b Compressor	[C]	27,1	DP Air Throttle	[mbar]	24,82
Temp a Compressor	[C]	163,6	Press Airreceiver	[barg]	1,74
Temp Airreceiver	[C]	48,1	Press a Compr	[barg]	1,81
			Press Exhaustreceiver	[barg]	1,36
Exhaust Temp Cyl 1	[C]	372			
Exhaust Temp Cyl 2	[C]	378	Air Cons	[kg/s]	1,14
Exhaust Temp Cyl 3	[C]	377	Air Cons_s	[kg/kWh]	8,14
			Exhaust Flow_s	[kg/kWh]	8,34
Exhaust Temp b Turbine	[C]	472	Exhaust Flow	[kg/s]	1,17
Exhaust Temp a Turbine	[C]	331			
			Humidity	[%]	22,9
			Ambient Press	[mbar]	1007,3
			Ambient Temp	[C]	26,8

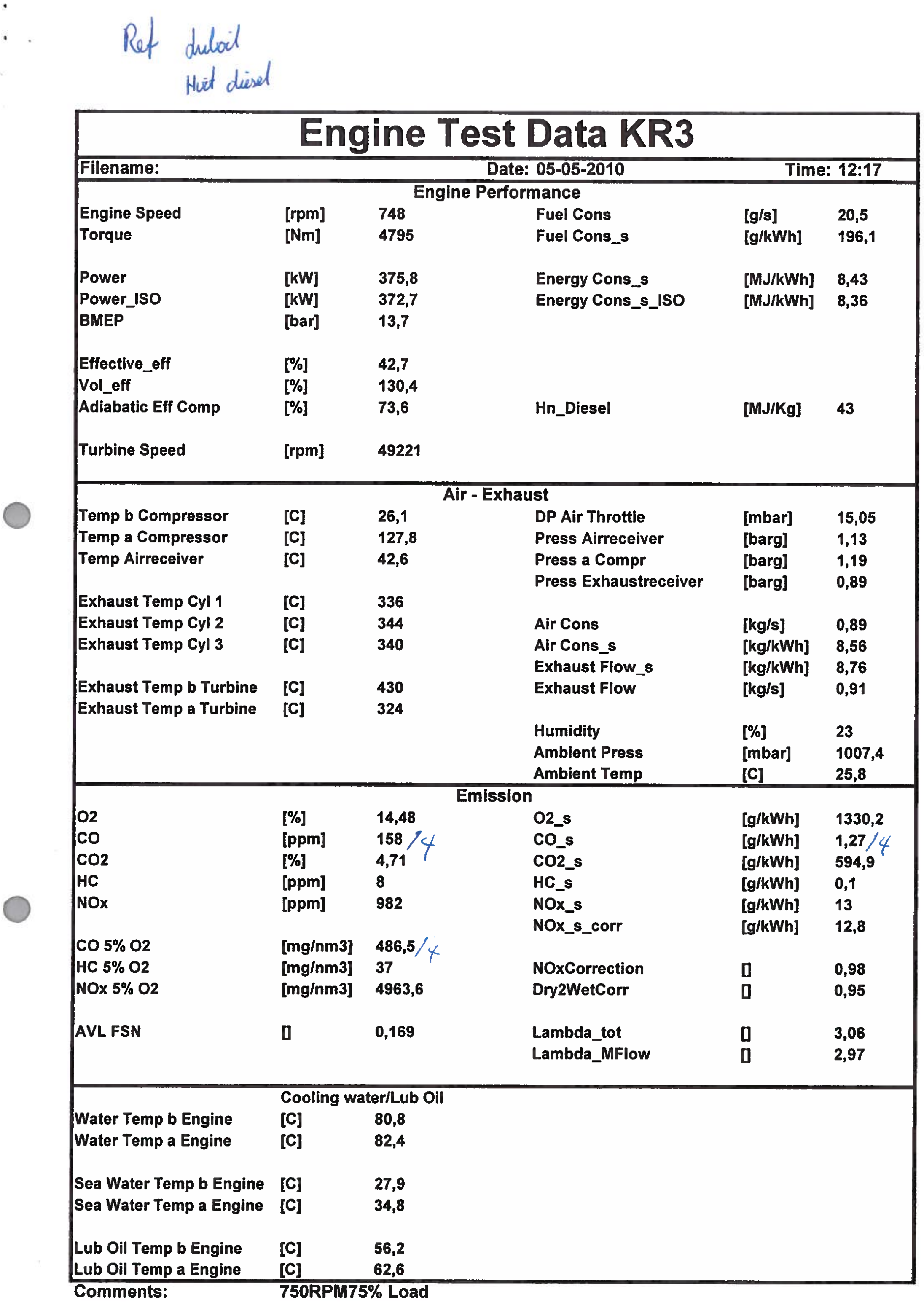
Emission

O2	[%]	14,13	O2_s	[g/kWh]	1232,2
CO	[ppm]	186/4	CO_s	[g/kWh]	1,42/4
CO2	[%]	4,96	CO2_s	[g/kWh]	595
HC	[ppm]	12	HC_s	[g/kWh]	0,14
NOx	[ppm]	976	NOx_s	[g/kWh]	12,2
			NOx_s_corr	[g/kWh]	12,1
CO 5% O2	[mg/nm3]	543,3/4			
HC 5% O2	[mg/nm3]	51,3	NOxCorrection	[]	0,99
NOx 5% O2	[mg/nm3]	4682,6	Dry2WetCorr	[]	0,95
AVL FSN (M)	[]	0,28	Lambda_tot	[]	2,91
			Lambda_MFlow	[]	2,82

Cooling water/Lub Oil

Water Temp b Engine	[C]	81,4
Water Temp a Engine	[C]	83,5
Sea Water Temp b Engine	[C]	27,8
Sea Water Temp a Engine	[C]	37,8
Lub Oil Temp b Engine	[C]	56,4
Lub Oil Temp a Engine	[C]	63,9

Comments: 750RPM100% Load



Ref duloil
Hvit diesel

Engine Test Data KR3

Filename:	Date: 05-05-2010	Time: 12:17

Engine Performance

Engine Speed	[rpm]	748	Fuel Cons	[g/s]	20,5
Torque	[Nm]	4795	Fuel Cons_s	[g/kWh]	196,1
Power	[kW]	375,8	Energy Cons_s	[MJ/kWh]	8,43
Power_ISO	[kW]	372,7	Energy Cons_s_ISO	[MJ/kWh]	8,36
BMEP	[bar]	13,7			
Effective_eff	[%]	42,7			
Vol_eff	[%]	130,4			
Adiabatic Eff Comp	[%]	73,6	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	49221			

Air - Exhaust

Temp b Compressor	[C]	26,1	DP Air Throttle	[mbar]	15,05
Temp a Compressor	[C]	127,8	Press Airreceiver	[barg]	1,13
Temp Airreceiver	[C]	42,6	Press a Compr	[barg]	1,19
			Press Exhaustreceiver	[barg]	0,89
Exhaust Temp Cyl 1	[C]	336			
Exhaust Temp Cyl 2	[C]	344	Air Cons	[kg/s]	0,89
Exhaust Temp Cyl 3	[C]	340	Air Cons_s	[kg/kWh]	8,56
			Exhaust Flow_s	[kg/kWh]	8,76
Exhaust Temp b Turbine	[C]	430	Exhaust Flow	[kg/s]	0,91
Exhaust Temp a Turbine	[C]	324			
			Humidity	[%]	23
			Ambient Press	[mbar]	1007,4
			Ambient Temp	[C]	25,8

Emission

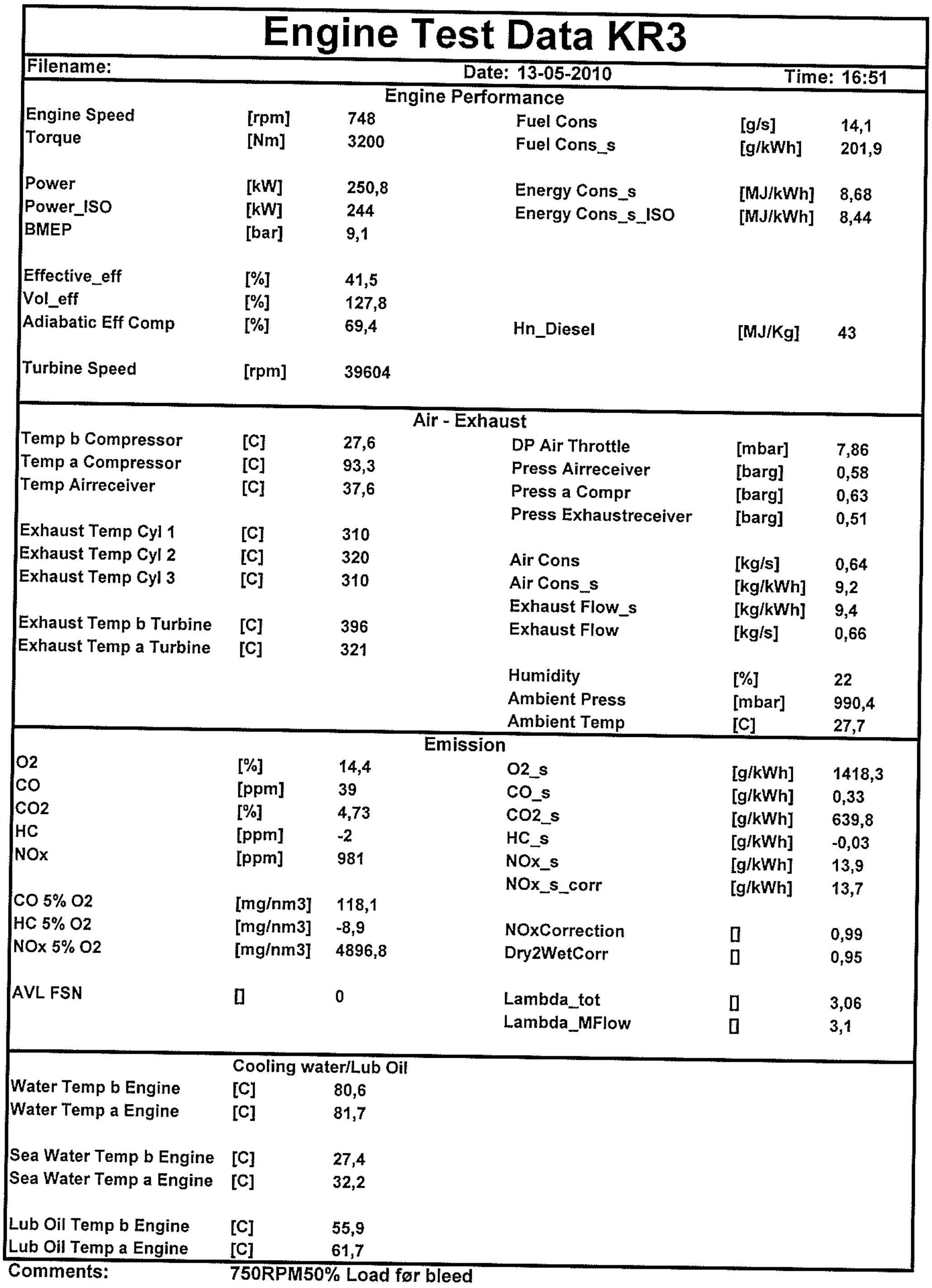
O2	[%]	14,48	O2_s	[g/kWh]	1330,2
CO	[ppm]	158 /4	CO_s	[g/kWh]	1,27 /4
CO2	[%]	4,71	CO2_s	[g/kWh]	594,9
HC	[ppm]	8	HC_s	[g/kWh]	0,1
NOx	[ppm]	982	NOx_s	[g/kWh]	13
			NOx_s_corr	[g/kWh]	12,8
CO 5% O2	[mg/nm3]	486,5 /4			
HC 5% O2	[mg/nm3]	37	NOxCorrection	[]	0,98
NOx 5% O2	[mg/nm3]	4963,6	Dry2WetCorr	[]	0,95
AVL FSN	[]	0,169	Lambda_tot	[]	3,06
			Lambda_MFlow	[]	2,97

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,8
Water Temp a Engine	[C]	82,4
Sea Water Temp b Engine	[C]	27,9
Sea Water Temp a Engine	[C]	34,8
Lub Oil Temp b Engine	[C]	56,2
Lub Oil Temp a Engine	[C]	62,6

Comments: 750RPM75% Load

After Refitting and Calibration - 10.10.2010



Engine Test Data KR3

Filename: **Date: 13-05-2010** **Time: 16:51**

Engine Performance

Engine Speed	[rpm]	748	Fuel Cons	[g/s]	14,1
Torque	[Nm]	3200	Fuel Cons_s	[g/kWh]	201,9
Power	[kW]	250,8	Energy Cons_s	[MJ/kWh]	8,68
Power_ISO	[kW]	244	Energy Cons_s_ISO	[MJ/kWh]	8,44
BMEP	[bar]	9,1			
Effective_eff	[%]	41,5			
Vol_eff	[%]	127,8			
Adiabatic Eff Comp	[%]	69,4	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	39604			

Air - Exhaust

Temp b Compressor	[C]	27,6	DP Air Throttle	[mbar]	7,86
Temp a Compressor	[C]	93,3	Press Airreceiver	[barg]	0,58
Temp Airreceiver	[C]	37,6	Press a Compr	[barg]	0,63
			Press Exhaustreceiver	[barg]	0,51
Exhaust Temp Cyl 1	[C]	310			
Exhaust Temp Cyl 2	[C]	320	Air Cons	[kg/s]	0,64
Exhaust Temp Cyl 3	[C]	310	Air Cons_s	[kg/kWh]	9,2
			Exhaust Flow_s	[kg/kWh]	9,4
Exhaust Temp b Turbine	[C]	396	Exhaust Flow	[kg/s]	0,66
Exhaust Temp a Turbine	[C]	321			
			Humidity	[%]	22
			Ambient Press	[mbar]	990,4
			Ambient Temp	[C]	27,7

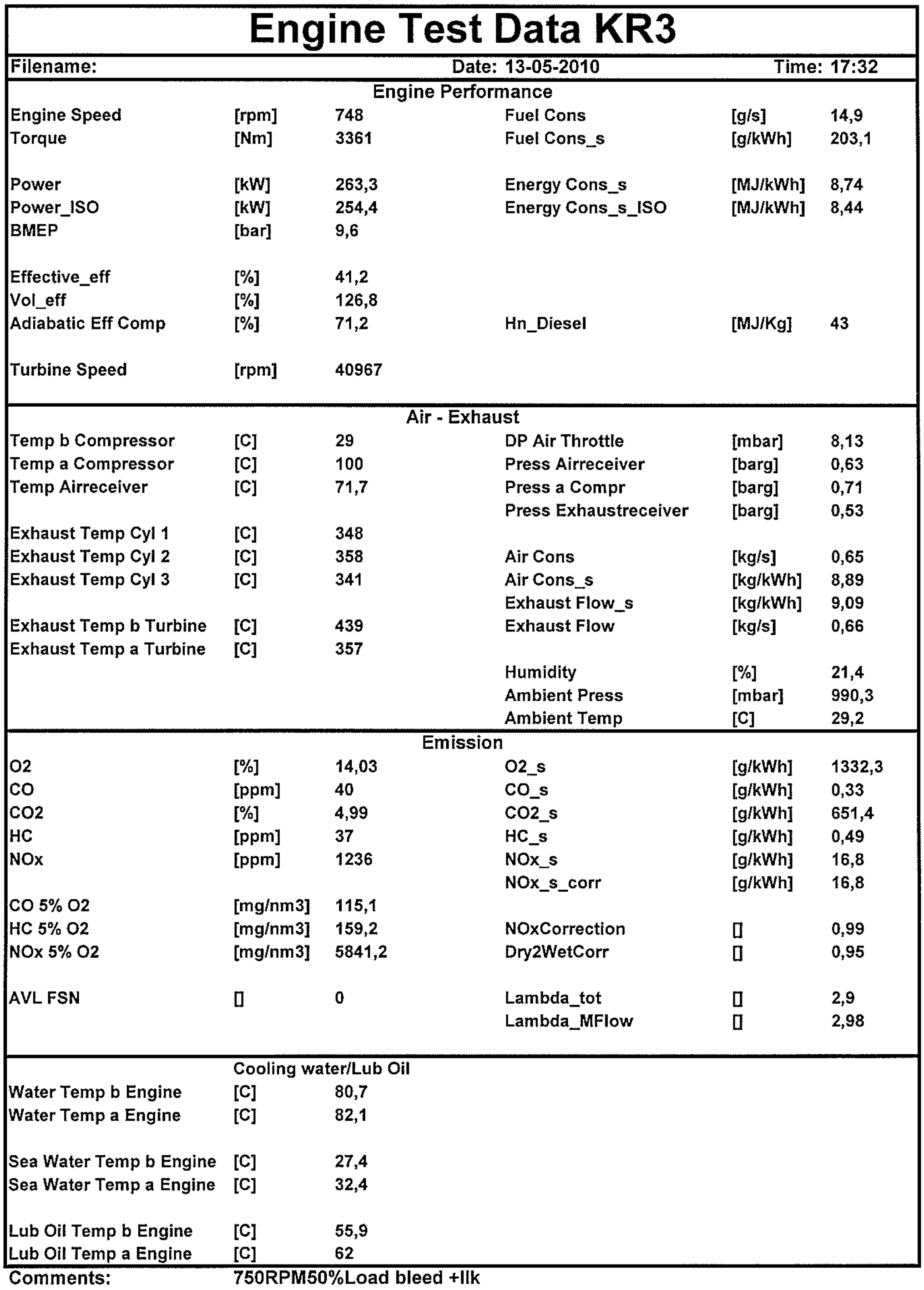
Emission

O2	[%]	14,4	O2_s	[g/kWh]	1418,3
CO	[ppm]	39	CO_s	[g/kWh]	0,33
CO2	[%]	4,73	CO2_s	[g/kWh]	639,8
HC	[ppm]	-2	HC_s	[g/kWh]	-0,03
NOx	[ppm]	981	NOx_s	[g/kWh]	13,9
			NOx_s_corr	[g/kWh]	13,7
CO 5% O2	[mg/nm3]	118,1			
HC 5% O2	[mg/nm3]	-8,9	NOxCorrection	[]	0,99
NOx 5% O2	[mg/nm3]	4896,8	Dry2WetCorr	[]	0,95
AVL FSN	[]	0	Lambda_tot	[]	3,06
			Lambda_MFlow	[]	3,1

Cooling water/Lub Oil

Water Temp b Engine	[C]	80,6
Water Temp a Engine	[C]	81,7
Sea Water Temp b Engine	[C]	27,4
Sea Water Temp a Engine	[C]	32,2
Lub Oil Temp b Engine	[C]	55,9
Lub Oil Temp a Engine	[C]	61,7

Comments: **750RPM50% Load før bleed**

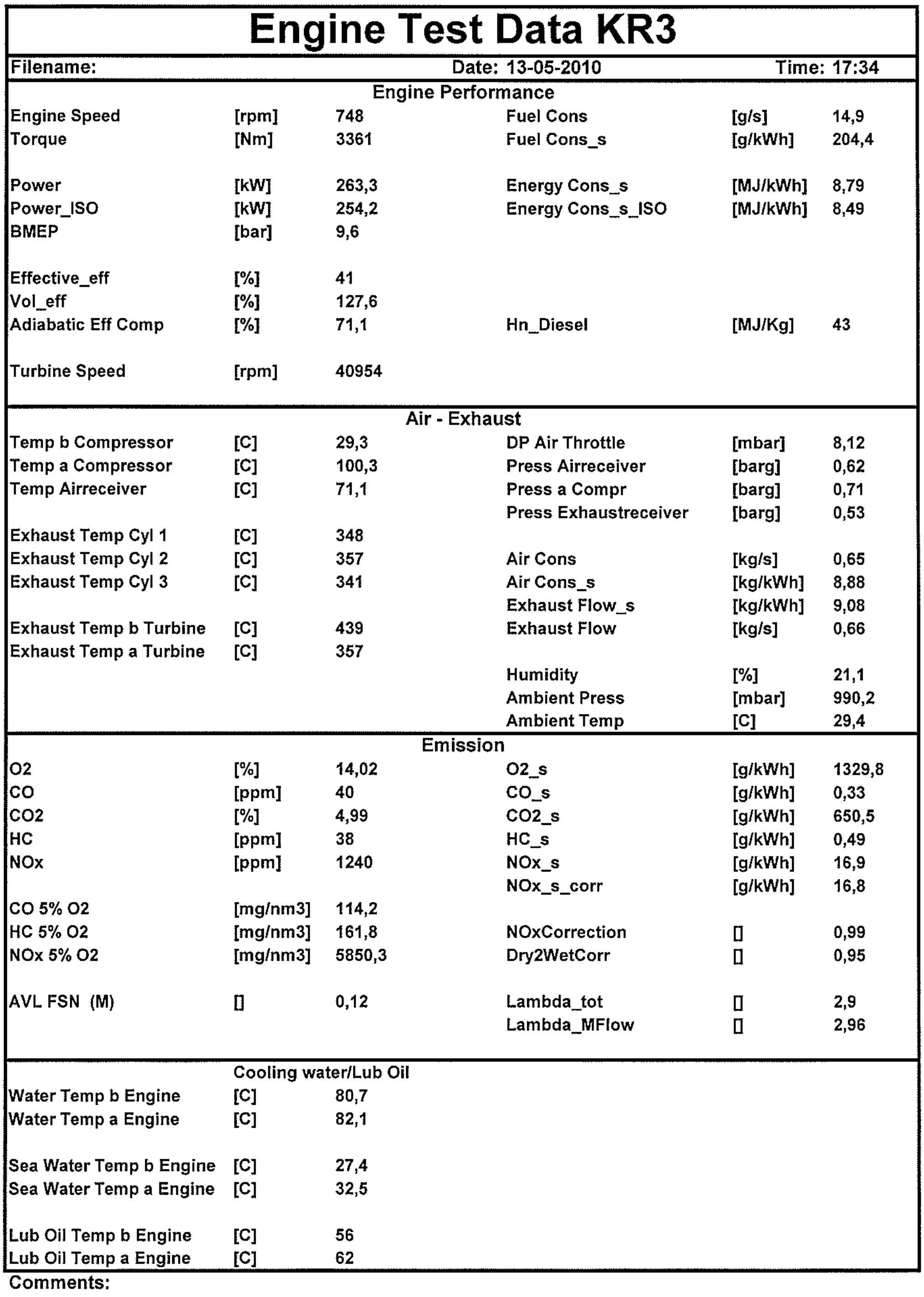


Engine Test Data KR3

Filename: **Date: 13-05-2010** **Time: 17:32**

		Engine Performance			
Engine Speed	[rpm]	748	Fuel Cons	[g/s]	14,9
Torque	[Nm]	3361	Fuel Cons_s	[g/kWh]	203,1
Power	[kW]	263,3	Energy Cons_s	[MJ/kWh]	8,74
Power_ISO	[kW]	254,4	Energy Cons_s_ISO	[MJ/kWh]	8,44
BMEP	[bar]	9,6			
Effective_eff	[%]	41,2			
Vol_eff	[%]	126,8			
Adiabatic Eff Comp	[%]	71,2	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	40967			
		Air - Exhaust			
Temp b Compressor	[C]	29	DP Air Throttle	[mbar]	8,13
Temp a Compressor	[C]	100	Press Airreceiver	[barg]	0,63
Temp Airreceiver	[C]	71,7	Press a Compr	[barg]	0,71
			Press Exhaustreceiver	[barg]	0,53
Exhaust Temp Cyl 1	[C]	348			
Exhaust Temp Cyl 2	[C]	358	Air Cons	[kg/s]	0,65
Exhaust Temp Cyl 3	[C]	341	Air Cons_s	[kg/kWh]	8,89
			Exhaust Flow_s	[kg/kWh]	9,09
Exhaust Temp b Turbine	[C]	439	Exhaust Flow	[kg/s]	0,66
Exhaust Temp a Turbine	[C]	357			
			Humidity	[%]	21,4
			Ambient Press	[mbar]	990,3
			Ambient Temp	[C]	29,2
		Emission			
O2	[%]	14,03	O2_s	[g/kWh]	1332,3
CO	[ppm]	40	CO_s	[g/kWh]	0,33
CO2	[%]	4,99	CO2_s	[g/kWh]	651,4
HC	[ppm]	37	HC_s	[g/kWh]	0,49
NOx	[ppm]	1236	NOx_s	[g/kWh]	16,8
			NOx_s_corr	[g/kWh]	16,8
CO 5% O2	[mg/nm3]	115,1			
HC 5% O2	[mg/nm3]	159,2	NOxCorrection	[]	0,99
NOx 5% O2	[mg/nm3]	5841,2	Dry2WetCorr	[]	0,95
AVL FSN	[]	0	Lambda_tot	[]	2,9
			Lambda_MFlow	[]	2,98
	Cooling water/Lub Oil				
Water Temp b Engine	[C]	80,7			
Water Temp a Engine	[C]	82,1			
Sea Water Temp b Engine	[C]	27,4			
Sea Water Temp a Engine	[C]	32,4			
Lub Oil Temp b Engine	[C]	55,9			
Lub Oil Temp a Engine	[C]	62			

Comments: 750RPM50%Load bleed +llk



Engine Test Data KR3

Filename: Date: 13-05-2010 Time: 17:34

		Engine Performance			
Engine Speed	[rpm]	748	Fuel Cons	[g/s]	14,9
Torque	[Nm]	3361	Fuel Cons_s	[g/kWh]	204,4
Power	[kW]	263,3	Energy Cons_s	[MJ/kWh]	8,79
Power_ISO	[kW]	254,2	Energy Cons_s_ISO	[MJ/kWh]	8,49
BMEP	[bar]	9,6			
Effective_eff	[%]	41			
Vol_eff	[%]	127,6			
Adiabatic Eff Comp	[%]	71,1	Hn_Diesel	[MJ/Kg]	43
Turbine Speed	[rpm]	40954			
		Air - Exhaust			
Temp b Compressor	[C]	29,3	DP Air Throttle	[mbar]	8,12
Temp a Compressor	[C]	100,3	Press Airreceiver	[barg]	0,62
Temp Airreceiver	[C]	71,1	Press a Compr	[barg]	0,71
			Press Exhaustreceiver	[barg]	0,53
Exhaust Temp Cyl 1	[C]	348			
Exhaust Temp Cyl 2	[C]	357	Air Cons	[kg/s]	0,65
Exhaust Temp Cyl 3	[C]	341	Air Cons_s	[kg/kWh]	8,88
			Exhaust Flow_s	[kg/kWh]	9,08
Exhaust Temp b Turbine	[C]	439	Exhaust Flow	[kg/s]	0,66
Exhaust Temp a Turbine	[C]	357			
			Humidity	[%]	21,1
			Ambient Press	[mbar]	990,2
			Ambient Temp	[C]	29,4
		Emission			
O2	[%]	14,02	O2_s	[g/kWh]	1329,8
CO	[ppm]	40	CO_s	[g/kWh]	0,33
CO2	[%]	4,99	CO2_s	[g/kWh]	650,5
HC	[ppm]	38	HC_s	[g/kWh]	0,49
NOx	[ppm]	1240	NOx_s	[g/kWh]	16,9
			NOx_s_corr	[g/kWh]	16,8
CO 5% O2	[mg/nm3]	114,2			
HC 5% O2	[mg/nm3]	161,8	NOxCorrection	[]	0,99
NOx 5% O2	[mg/nm3]	5850,3	Dry2WetCorr	[]	0,95
AVL FSN (M)	[]	0,12	Lambda_tot	[]	2,9
			Lambda_MFlow	[]	2,96
	Cooling water/Lub Oil				
Water Temp b Engine	[C]	80,7			
Water Temp a Engine	[C]	82,1			
Sea Water Temp b Engine	[C]	27,4			
Sea Water Temp a Engine	[C]	32,5			
Lub Oil Temp b Engine	[C]	56			
Lub Oil Temp a Engine	[C]	62			

Comments:

Appendix C

Shipping Companies - Survey

Survey – Selective Catalytic Reduction (SCR) - Eidesvik

Magnus Selås MSc Candidate selas@stud.ntnu.no 4797560844

Introduction

Last semester I wrote a project thesis with the topic *"Exhaust Gas Cleaning with Selective Catalytic Reduction (SCR)"*. This project thesis's goal is for the candidate to get related with a topic for further research in the master thesis. The master thesis will be divided into two main areas for future studies, performance and degrading mechanisms of a SCR system. The degrading mechanisms are understood as *"what makes the system loose efficiency in operation?"* The thesis will be based on data from a SCR system installed at the machinery test facilities at MARINTEK, and hopefully with your help from SCR systems in operation. This data together with your overall experience will be of great value to this thesis as you have more operational experience than I will be able to get in this short period of time conducting the MSc thesis.

About my background:

I'm currently a 5th year MSc student at NTNU department of Marine Technology, within the line of Marine Systems Design. My specialization lies within the field of maritime operation and maintenance. This MSc thesis is within the field of marine machinery and is in the borderland to maritime operation.

General Information

* I've tried to make this survey as easy as possible for you to answer within a reasonable period of time.
* In total, I've sent this to 6 shipping companies included yours, all with SCR experience.
* The paper will be open to the public reader at NTNU's archives and can be sent to you on request.
* Any information that you regard as sensitive, please let me know and I will add this to an appendix that will be marked as confidential and not open to the public.

Thank you for your great cooperation!

1	How many vessels in your fleet are equipped with SCR?	Ans:	*Write the number here*
2	What type of vessels are these? (AHTS, PSV, FSV, LNG/LPG, Tanker etc)	Ans:	AHTS PSV FSV LNG/LPG Oil Tanker
3	What type of SCR system is installed? (Maker)	Ans:	*Write name of the maker here* **Argillon GmbH**
4	On what type of engine are the SCR installed?	Ans:	Maker: **MaK M25** Output: **2540Kw**
5	On what fuel quality do you operate the engines?	Ans:	HFO MDO MGO **MDO 161** Sulphur content: **0,05 %**
6	Are ceramic stones in the catalyst washcoated or homogenously extruded?	Ans:	Washcoat Homogenously Exstruded **Meshcoated**
7	What is the pitch of the catalyst material?	Ans:	4mm 5mm 6mm
8	What is the Urea quality supplied from your vendor?	Ans:	% Urea solution in water (e.g. 40%) **40 %**
9	What type of instruments do you have for exhaust gas measurements?	Ans:	**NIL**
10	What is the measured reduction of NOx from the SCR on your vessels?	Ans:	**NOx after SCR < 6,5 g/kWh**
11	What is the real reduction if you consider effect loss due to changes in the operational profile?	Ans:	
12	Do you have equipment for measurement of methanol slip?	Ans:	***NO***
13	Does your SCR system have a unit for dust/soot blowing installed?	Ans:	***NO***
14	IF YES in 13: What is ususally the interval used to perform a dust/soot blowing?	Ans:	
15	If no fixed interval is used in 14, what parameters do you use to identify when a dust/soot blowin is needed, and what are their limits?	Ans:	**No equipment for measurement**
16	What is the expected life time on the catalyst material on your SCR units?	Ans:	
17	How often do you change the catalyst material, and what parameters and limits are set in order to do so?	Ans:	
18	Do you see a drop in the reduction efficiency after 1000 operational hours?	Ans:	**No equipment for measurement**
19	Does the dozing unit (urea dozing control) get signals from the engine alone, or is it linked to a continously NOx monitoring system?	Ans:	**Get signals from the engine alone**
20	Do you change the setting on the dozing unit during the life time in order to increase the urea dozing and compensate for a drop in the reduction efficiency?	Ans:	**No equipment for measurement**
21	What are the temperature limits on the exhast gas flow in order to activate the urea dozing?	Ans:	Temperature before catalyst Temperature after catalyst **290 C**
22	What is the pressure drop over the catalyst in new condition?	Ans:	at 25% MCR 50% MCR 75% MCR 100% MCR Specify unit (e.g. Bar, Pa) **No equipment for measurement**
23	What is the current pressure drop over the catalyst?	Ans:	Current operatioal hours 25% MCR 50% MCR 75% MCR 100% MCR **No equipment for measurement**
24	What do you consider as the main challenges operating a SCR system, and what are your main concerns today?	Ans:	
25	How do a operation profile for one of your vessels look like, and could you please attach it to this document?	Ans:	**operation profile - 80% on DP**
26	Are there in any of your operational states that you have considered shutting down the SCR system?	Ans:	***NO***

Survey – Selective Catalytic Reduction (SCR) - Havila Offshore

Magnus Selås MSc Candidate selas@stud.ntnu.no 4797560844

Introduction

Last semester I wrote a project thesis with the topic *"Exhaust Gas Cleaning with Selective Catalytic Reduction (SCR)"*. This project thesis's goal is for the candidate to get related with a topic for further research in the master thesis. The master thesis will be divided into two main areas for future studies, performance and degrading mechanisms of a SCR system. The degrading mechanisms are understood as *"what makes the system loose efficiency in operation?"* The thesis will be based on data from a SCR system installed at the machinery test facilities at MARINTEK, and hopefully with your help from SCR systems in operation. This data together with your overall experience will be of great value to this thesis as you have more operational experience than I will be able to get in this short period of time conducting the MSc thesis.

About my background:

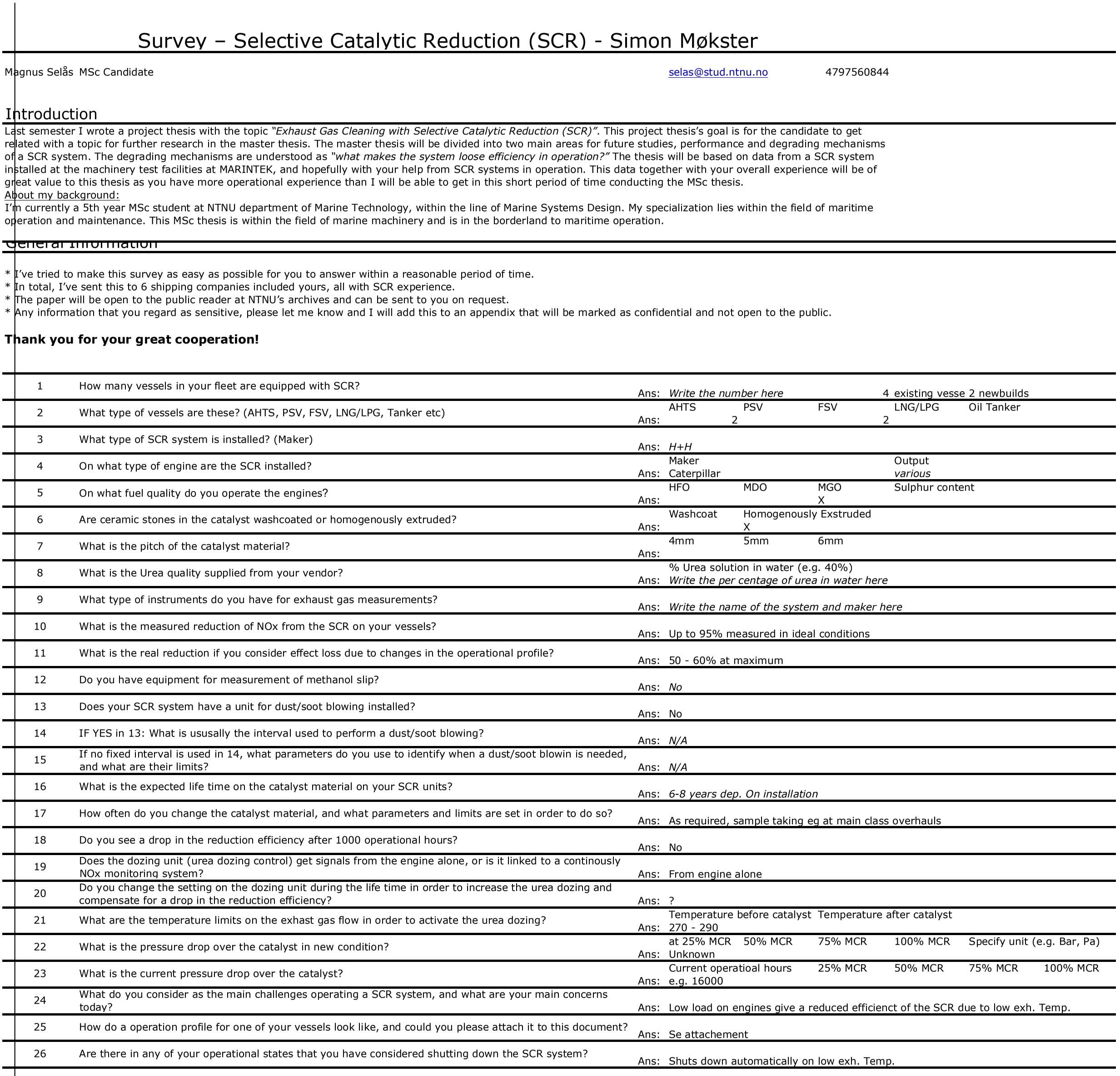
I'm currently a 5th year MSc student at NTNU department of Marine Technology, within the line of Marine Systems Design. My specialization lies within the field of maritime operation and maintenance. This MSc thesis is within the field of marine machinery and is in the borderland to maritime operation.

General Information

* I've tried to make this survey as easy as possible for you to answer within a reasonable period of time.
* In total, I've sent this to 6 shipping companies included yours, all with SCR experience.
* The paper will be open to the public reader at NTNU's archives and can be sent to you on request.
* Any information that you regard as sensitive, please let me know and I will add this to an appendix that will be marked as confidential and not open to the public.

Thank you for your great cooperation!

1	How many vessels in your fleet are equipped with SCR?	Ans:	*Write the number here*					
2	What type of vessels are these? (AHTS, PSV, FSV, LNG/LPG, Tanker etc)		AHTS	PSV	FSV	LNG/LPG	Oil Tanker	
		Ans:	6	6	2			
3	What type of SCR system is installed? (Maker)	Ans:	*Write name of the maker here*			Munters , H&H , Argilon		
4	On what type of engine are the SCR installed?		Maker	MAK , Caterpillar, MTU, Cumr		Output	1800 kw - 6000 kw	
		Ans:	Write name of the maker here			*Write the rated power of the engine here*		
5	On what fuel quality do you operate the engines?		HFO	MDO	MGO	Sulphur content		
		Ans:			x			
6	Are ceramic stones in the catalyst washcoated or homogenously extruded?		Washcoat	Homogenously Exstruded				
		Ans:	x	x				
7	What is the pitch of the catalyst material?		4mm	5mm	6mm			
		Ans:	x	x	x			
8	What is the Urea quality supplied from your vendor?		% Urea solution in water (e.g. 40%)				Technical Urea 40%	
		Ans:	*Write the per centage of urea in water here*					
9	What type of instruments do you have for exhaust gas measurements?	Ans:	*Write the name of the system and maker here*				NA	
10	What is the measured reduction of NOx from the SCR on your vessels?	Ans:		84 - 90 % were SCR is installed.				
11	What is the real reduction if you consider effect loss due to changes in the operational profile?	Ans:				Depends of output		
12	Do you have equipment for measurement of methanol slip?	Ans:	*Yes/No*			No		
13	Does your SCR system have a unit for dust/soot blowing installed?	Ans:	Yes/No			Munters yes , H&H No		
14	IF YES in 13: What is ususally the interval used to perform a dust/soot blowing?	Ans:				Montly		
15	If no fixed interval is used in 14, what parameters do you use to identify when a dust/soot blowin is needed, and what are their limits?	Ans:						
16	What is the expected life time on the catalyst material on your SCR units?	Ans:				*24000 hour*		
17	How often do you change the catalyst material, and what parameters and limits are set in order to do so?	Ans:				5 - 7 year		
18	Do you see a drop in the reduction efficiency after 1000 operational hours?	Ans:				No		
19	Does the dozing unit (urea dozing control) get signals from the engine alone, or is it linked to a continously NOx monitoring system?	Ans:				both		
20	Do you change the setting on the dozing unit during the life time in order to increase the urea dozing and compensate for a drop in the reduction efficiency?	Ans:				yes		
21	What are the temperature limits on the exhast gas flow in order to activate the urea dozing?		Temperature before catalyst		Temperature after catalyst			
		Ans:					Down to 280 deg.	
22	What is the pressure drop over the catalyst in new condition?		at 25% MCR	50% MCR	75% MCR	100% MCR	Specify unit (e.g. Bar, Pa)	
		Ans:	8 - 12 bar , linar					
23	What is the current pressure drop over the catalyst?		Current operatioal hours		25% MCR	50% MCR	75% MCR	100% MCR
		Ans:	e.g. 16000					
24	What do you consider as the main challenges operating a SCR system, and what are your main concerns today?	Ans:		Corrosion				
25	How do a operation profile for one of your vessels look like, and could you please attach it to this document?	Ans:		1/3 20 - 40 % 1/3 40 - 60 % 1/3 over 60 %				
26	Are there in any of your operational states that you have considered shutting down the SCR system?	Ans:		Out of Norwegian Waters				



Survey – Selective Catalytic Reduction (SCR) - Simon Møkster

Magnus Selås MSc Candidate selas@stud.ntnu.no 4797560844

Introduction

Last semester I wrote a project thesis with the topic *"Exhaust Gas Cleaning with Selective Catalytic Reduction (SCR)"*. This project thesis's goal is for the candidate to get related with a topic for further research in the master thesis. The master thesis will be divided into two main areas for future studies, performance and degrading mechanisms of a SCR system. The degrading mechanisms are understood as *"what makes the system loose efficiency in operation?"* The thesis will be based on data from a SCR system installed at the machinery test facilities at MARINTEK, and hopefully with your help from SCR systems in operation. This data together with your overall experience will be of great value to this thesis as you have more operational experience than I will be able to get in this short period of time conducting the MSc thesis.

About my background:

I'm currently a 5th year MSc student at NTNU department of Marine Technology, within the line of Marine Systems Design. My specialization lies within the field of maritime operation and maintenance. This MSc thesis is within the field of marine machinery and is in the borderland to maritime operation.

General Information

* I've tried to make this survey as easy as possible for you to answer within a reasonable period of time.
* In total, I've sent this to 6 shipping companies included yours, all with SCR experience.
* The paper will be open to the public reader at NTNU's archives and can be sent to you on request.
* Any information that you regard as sensitive, please let me know and I will add this to an appendix that will be marked as confidential and not open to the public.

Thank you for your great cooperation!

1	How many vessels in your fleet are equipped with SCR?	Ans:	*Write the number here* 4 existing vesse 2 newbuilds
2	What type of vessels are these? (AHTS, PSV, FSV, LNG/LPG, Tanker etc)	Ans:	AHTS PSV FSV LNG/LPG Oil Tanker 2 2
3	What type of SCR system is installed? (Maker)	Ans:	*H+H*
4	On what type of engine are the SCR installed?	Ans:	Maker Output Caterpillar *various*
5	On what fuel quality do you operate the engines?	Ans:	HFO MDO MGO Sulphur content X
6	Are ceramic stones in the catalyst washcoated or homogenously extruded?	Ans:	Washcoat Homogenously Exstruded X
7	What is the pitch of the catalyst material?	Ans:	4mm 5mm 6mm
8	What is the Urea quality supplied from your vendor?	Ans:	% Urea solution in water (e.g. 40%) *Write the per centage of urea in water here*
9	What type of instruments do you have for exhaust gas measurements?	Ans:	*Write the name of the system and maker here*
10	What is the measured reduction of NOx from the SCR on your vessels?	Ans:	Up to 95% measured in ideal conditions
11	What is the real reduction if you consider effect loss due to changes in the operational profile?	Ans:	50 - 60% at maximum
12	Do you have equipment for measurement of methanol slip?	Ans:	*No*
13	Does your SCR system have a unit for dust/soot blowing installed?	Ans:	No
14	IF YES in 13: What is ususally the interval used to perform a dust/soot blowing?	Ans:	*N/A*
15	If no fixed interval is used in 14, what parameters do you use to identify when a dust/soot blowin is needed, and what are their limits?	Ans:	*N/A*
16	What is the expected life time on the catalyst material on your SCR units?	Ans:	*6-8 years dep. On installation*
17	How often do you change the catalyst material, and what parameters and limits are set in order to do so?	Ans:	As required, sample taking eg at main class overhauls
18	Do you see a drop in the reduction efficiency after 1000 operational hours?	Ans:	No
19	Does the dozing unit (urea dozing control) get signals from the engine alone, or is it linked to a continously NOx monitoring system?	Ans:	From engine alone
20	Do you change the setting on the dozing unit during the life time in order to increase the urea dozing and compensate for a drop in the reduction efficiency?	Ans:	?
21	What are the temperature limits on the exhast gas flow in order to activate the urea dozing?	Ans:	Temperature before catalyst Temperature after catalyst 270 - 290
22	What is the pressure drop over the catalyst in new condition?	Ans:	at 25% MCR 50% MCR 75% MCR 100% MCR Specify unit (e.g. Bar, Pa) Unknown
23	What is the current pressure drop over the catalyst?	Ans:	Current operatioal hours 25% MCR 50% MCR 75% MCR 100% MCR e.g. 16000
24	What do you consider as the main challenges operating a SCR system, and what are your main concerns today?	Ans:	Low load on engines give a reduced efficienct of the SCR due to low exh. Temp.
25	How do a operation profile for one of your vessels look like, and could you please attach it to this document?	Ans:	Se attachement
26	Are there in any of your operational states that you have considered shutting down the SCR system?	Ans:	Shuts down automatically on low exh. Temp.

Survey – Selective Catalytic Reduction (SCR) - Teekay

Magnus Selås MSc Candidate selas@stud.ntnu.no 4797560844

Introduction

Last semester I wrote a project thesis with the topic *"Exhaust Gas Cleaning with Selective Catalytic Reduction (SCR)"*. This project thesis's goal is for the candidate to get related with a topic for further research in the master thesis. The master thesis will be divided into two main areas for future studies, performance and degrading mechanisms of a SCR system. The degrading mechanisms are understood as *"what makes the system loose efficiency in operation?"* The thesis will be based on data from a SCR system installed at the machinery test facilities at MARINTEK, and hopefully with your help from SCR systems in operation. This data together with your overall experience will be of great value to this thesis as you have more operational experience than I will be able to get in this short period of time conducting the MSc thesis.

About my background:

I'm currently a 5th year MSc student at NTNU department of Marine Technology, within the line of Marine Systems Design. My specialization lies within the field of maritime operation and maintenance. This MSc thesis is within the field of marine machinery and is in the borderland to maritime operation.

General Information

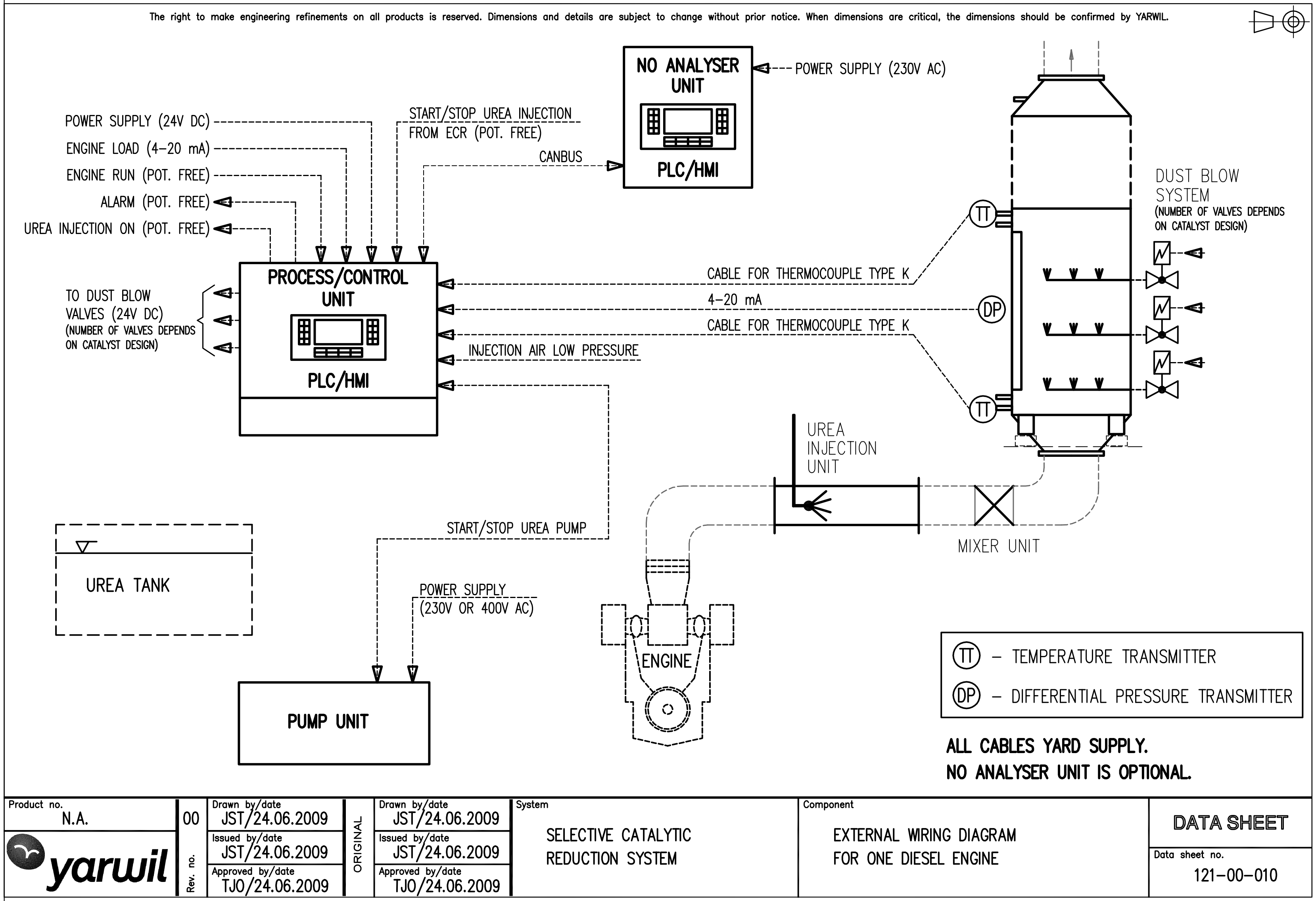
- * I've tried to make this survey as easy as possible for you to answer within a reasonable period of time.
- * In total, I've sent this to 6 shipping companies included yours, all with SCR experience.
- * The paper will be open to the public reader at NTNU's archives and can be sent to you on request.
- * Any information that you regard as sensitive, please let me know and I will add this to an appendix that will be marked as confidential and not open to the public.

Thank you for your great cooperation!

1	How many vessels in your fleet are equipped with SCR?	Ans:	*1*
2	What type of vessels are these? (AHTS, PSV, FSV, LNG/LPG, Tanker etc)	Ans:	AHTS PSV FSV LNG/LPG Oil Tanker LNG/LPG: x
3	What type of SCR system is installed? (Maker)	Ans:	*Write name of the maker here*
4	On what type of engine are the SCR installed?	Ans:	Maker: MAN Output: *5700 bhp*
5	On what fuel quality do you operate the engines?	Ans:	HFO MDO MGO Sulphur content HFO: x
6	Are ceramic stones in the catalyst washcoated or homogenously extruded?	Ans:	Washcoat Homogenously Exstruded Not sure. Please contact maker Haldor Topsøe
7	What is the pitch of the catalyst material?	Ans:	4mm 5mm 6mm Same as no 6.
8	What is the Urea quality supplied from your vendor?	Ans:	% Urea solution in water (e.g. 40%) *??*
9	What type of instruments do you have for exhaust gas measurements?	Ans:	*??*
10	What is the measured reduction of NOx from the SCR on your vessels?	Ans:	75-85%
11	What is the real reduction if you consider effect loss due to changes in the operational profile?	Ans:	??
12	Do you have equipment for measurement of methanol slip?	Ans:	*??*
13	Does your SCR system have a unit for dust/soot blowing installed?	Ans:	Yes
14	IF YES in 13: What is ususally the interval used to perform a dust/soot blowing?	Ans:	*Automatic ??*
15	If no fixed interval is used in 14, what parameters do you use to identify when a dust/soot blowin is needed, and what are their limits?	Ans:	
16	What is the expected life time on the catalyst material on your SCR units?	Ans:	*Maker anticipated 3 years. Experienced only 3 -6 months*
17	How often do you change the catalyst material, and what parameters and limits are set in order to do so?	Ans:	3-6 months. Exhaust gas back pressure.
18	Do you see a drop in the reduction efficiency after 1000 operational hours?	Ans:	yes
19	Does the dozing unit (urea dozing control) get signals from the engine alone, or is it linked to a continously NOx monitoring system?	Ans:	??
20	Do you change the setting on the dozing unit during the life time in order to increase the urea dozing and compensate for a drop in the reduction efficiency?	Ans:	??
21	What are the temperature limits on the exhast gas flow in order to activate the urea dozing?	Ans:	Temperature before catalyst Temperature after catalyst ??
22	What is the pressure drop over the catalyst in new condition?	Ans:	at 25% MCR 50% MCR 75% MCR 100% MCR Specify unit (e.g. Bar, Pa) ??
23	What is the current pressure drop over the catalyst?	Ans:	Current operatioal hours 25% MCR 50% MCR 75% MCR 100% MCR e.g. 16000 ??
24	What do you consider as the main challenges operating a SCR system, and what are your main concerns today?	Ans:	HFO and high sulphur content in fuel. Low load operation with too low exhaust gas temp.
25	How do a operation profile for one of your vessels look like, and could you please attach it to this document?	Ans:	SCR vessel. From load port to discharge port normal: 18-20hrs running on 85% load. Same on return trip.
26	Are there in any of your operational states that you have considered shutting down the SCR system?	Ans:	SCR was shut down Feb' 2006

Appendix D

General Arrangement of SCR


The right to make engineering refinements on all products is reserved. Dimensions and details are subject to change without prior notice. When dimensions are critical, the dimensions should be confirmed by YARWIL.
NO ANALYSER UNIT
PLC/HMI
POWER SUPPLY (230V AC)
POWER SUPPLY (24V DC)
ENGINE LOAD (4–20 mA)
ENGINE RUN (POT. FREE)
ALARM (POT. FREE)
UREA INJECTION ON (POT. FREE)
START/STOP UREA INJECTION FROM ECR (POT. FREE)
CANBUS
PROCESS/CONTROL UNIT
PLC/HMI
TO DUST BLOW VALVES (24V DC)
(NUMBER OF VALVES DEPENDS ON CATALYST DESIGN)
CABLE FOR THERMOCOUPLE TYPE K
4–20 mA
CABLE FOR THERMOCOUPLE TYPE K
INJECTION AIR LOW PRESSURE
TT
DP
TT
DUST BLOW SYSTEM
(NUMBER OF VALVES DEPENDS ON CATALYST DESIGN)
UREA INJECTION UNIT
MIXER UNIT
START/STOP UREA PUMP
UREA TANK
POWER SUPPLY (230V OR 400V AC)
PUMP UNIT
ENGINE
TT – TEMPERATURE TRANSMITTER
DP – DIFFERENTIAL PRESSURE TRANSMITTER
ALL CABLES YARD SUPPLY.
NO ANALYSER UNIT IS OPTIONAL.
Product no.
N.A.
yarwil
Rev. no.
00
Drawn by/date
JST/24.06.2009
Issued by/date
JST/24.06.2009
Approved by/date
TJO/24.06.2009
ORIGINAL
Drawn by/date
JST/24.06.2009
Issued by/date
JST/24.06.2009
Approved by/date
TJO/24.06.2009
System
SELECTIVE CATALYTIC REDUCTION SYSTEM
Component
EXTERNAL WIRING DIAGRAM FOR ONE DIESEL ENGINE
DATA SHEET
Data sheet no.
121–00–010