Plasma Technology and emission reduction.

Maritime University of Applied Sciences

Principal: Mr. Snoeijer
Managers: Mrs. van der Drift, Mr. van Kluijven

Projectmembers group 3
Roxanna Mulders 0849435 e-mail: 0849435@hr.nl
Terry Jansen 0853311 e-mail: 0853311@hr.nl
Nick Zonneveld 0846614 e-mail: 0846614@hr.nl
Derk Kremer 0850156 e-mail: 0850156@hr.nl

Rotterdam, 11-6-2012
# Table of content

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF CONTENT</td>
<td>2</td>
</tr>
<tr>
<td>1. BACKGROUND</td>
<td>3</td>
</tr>
<tr>
<td>2. PROJECT ASSIGNMENT</td>
<td>4</td>
</tr>
<tr>
<td>3. PRODUCTS</td>
<td>6</td>
</tr>
<tr>
<td>4. NEW LEGISLATIONS</td>
<td>7</td>
</tr>
<tr>
<td>5. FORMATION OF NOX &amp; SOX?</td>
<td>8</td>
</tr>
<tr>
<td>6. WHAT IS PLASMA?</td>
<td>9</td>
</tr>
<tr>
<td>7. REQUIRED PARTS &amp; IMPLEMENTATION</td>
<td>10</td>
</tr>
<tr>
<td>8. EFFICIENCY</td>
<td>11</td>
</tr>
<tr>
<td>9. ADVANTAGES &amp; DISADVANTAGES?</td>
<td>15</td>
</tr>
<tr>
<td>10. CONCLUSION</td>
<td>16</td>
</tr>
<tr>
<td>11. RECOMMENDATION</td>
<td>16</td>
</tr>
<tr>
<td>12. REFERENCE</td>
<td>17</td>
</tr>
</tbody>
</table>
1. Background

“Emission reduction” is a project created by the Maritime University of Applied Sciences. This project has been issued to the students of the Maritime University to help them getting acquainted with working on projects. The Maritime University of Applied Sciences is located at the Lloydkade in Rotterdam. This project is an initiative of Mr. Van Kluijven to stimulate students on finding solutions that reduce current national and international problems related to excessive emissions.

The STC-Group is an education facility with multiple locations around the world. These locations facilitate in College, High School and University education. The project has been assigned to this project group by the Maritime University of Applied sciences.

The project members are Terry Jansen, Nick Zonneveld, Roxanna Mulders & Derk Kremer. This is a very motivated team that is studying at the Maritime University of Applied Sciences. They have followed and successfully completed the Maritime officer education and are in the possession of an associate degree.

Stakeholders in the project are: in the first place the project group members themselves, and secondly the University of Applied sciences and lastly the entire Maritime sector.

Eventually Mr. Van Kluijven and Mrs. Van der Drift will be our managers/supervisors and make sure that the group stays on the right path. They will approve the Plan of Approach and all other related business. Our principal Mr. Snoeijer will guide us in this project. He can provide us with contacts and answer subject related questions. Mr. Snoeijer will eventually be the one that approves our report for its content.
2. Project assignment

Problem

For the maritime sector the problem is that MARPOL Annex VI sets limits on NOx and SOx emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances. These limits are set due to the high amounts of emission, which cause acid rain (NOx) and a high amount of sulfur oxide concentrations in the ambient air. This is bad for the environment and the human health.

Problem definition & Objective

Problem definition;

The rules concerning emissions are getting stricter by the year. The shipping industry needs to reduce their emission of Nox & Sox to comply with the IMO regulations. By 2020 these emissions may not exceed 0.1% for Nox and 0.5% for Sox. So we came up with the following problem definition is:

*The amounts of NOx/Sox in shipping air emissions are too high.*

Objective;

The aim of the project is to investigate how to reduce the high amounts of NOx/Sox air emissions in shipping with plasma technology. Our project group chose for this subject because they saw great potential in this system. It does not need any excess materials and is low in maintenance.

In order to achieve the objective, a main question is formulated with a number of sub questions.

Boundary’s;

Apart from CO2 and H2O the exhaust gases also contain nitrogen oxides, unburned hydrocarbons and soot in diesel engines. These latter substances are undesirable because they are (partly) responsible for air pollution. As project group, we will examine how to reduce these emissions using plasma technology onboard ships.

Of course there are activities that we as the project group will not research. The group will not investigate what the costs are to produce this product. Nor will the group investigate what the regulations are regarding implementing this technology onboard ships.

Several agreements have been made in order to run this project as scheduled. These agreements are related to communication as well as to the delivery of several documents, as pointed out in the planning in the chapter 8.

The group is responsible for the project of the plasma technology. Furthermore, the project group is not responsible for the actual implementation onboard the ships.
Main question:
How can plasma technology be used onboard ships to reduce the Sox & Nox?

Subquestions:
1. What is plasma technology?
2. What is the required legislation to implement plasma technology onboard ships?
3. How can plasma technology be implemented onboard ships?
4. What is the efficiency of plasma technology?
5. What are the advantages and shortcomings of plasma technology?

Research methods

During the desk research period, a literature research method was used. Via a quantitative research method, allot of information was gathered via the internet, brochures & other media. This information was filtered and used in the report. This information was also used to form questions for the interview that was held with Mr. Schilt of TNO Eindhoven.

During the field research period, an interview was held with Mr. Schilt. The information gathered here is of kwalitative value. Since we asked direct questions with extensive answers. The information that was gathered during this interview has been processed and implemented into the final report.
3. Products

In this project we will search for an answer of the our topic “emission reduction”. To make the final report for this topic we have to make the next products:

- Plan of approach
- Interviews
- Agendas
- Minutes
- Schedules
- Reports
- Multimedia
- Project presentation
- Hour recording
- Research Main report
4. New legislations

The International Maritime Organization (IMO) is an agency of the United Nations which was formed to promote maritime safety. IMO ship pollution rules are contained in the “International Convention on the Prevention of Pollution from Ships”, also known as MARPOL 73/78. The Annex VI from the Marpol is titled “Regulations for the Prevention of Air Pollution from Ships”.

MARPOL Annex VI sets a limit on NOx and SOx emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances such as FREON. The annex VI regulations include a global cap of 4.5% m/m on the sulphur dioxides in the exhaust gasses. Annex VI contains provisions allowing for special SOx Emission Control Areas (SECAS) to be established with more stringent controls on sulphur emissions. In these areas, the sulphur content of fuel oil used on board ships must not exceed 1.5% m/m. To achieve this, ships may fit an exhaust gas cleaning system or use any other technological method to limit SOx emissions. This is what we are aiming for with plasma technology.

The first global limit on sulphur in marine fuels was set at 4.5 %. Under the revised Annex this limit was lowered to 3.50 % in 2012, and it will be further strengthened to 0.50 % in 2020 (subject to a review in 2018). As an alternative to use low-sulphur fuels, ships are allowed to use exhaust gas cleaning systems (e.g. Plasma) or use other methods to limit their sulphur emissions (e.g. use alternative fuels such as gas).

The regulations for the maximum sulfur content of fuel is thus considerably reduced in time.

Worldwide:

<table>
<thead>
<tr>
<th>Year</th>
<th>S0x Max: 4.5%</th>
<th>S0x Max: 3.5%</th>
<th>S0x Max: 0.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

the current sulfur emission control areas (Secas) are from 2011 Emission Control AREA’s called. for the Emission Control Area applies.

<table>
<thead>
<tr>
<th>Year</th>
<th>NOx Max: 1.5%</th>
<th>NOx Max: 1.0%</th>
<th>NOx Max: 0.10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the IMO, it is allowed to reduce the emissions from ships by any mean necessary. As long as it doesn’t pollute in any other way.

Sources:
http://www.dieselnet.com/standards/inter/imo.php
5. Formation of NOx & SOx?

**Thermal Nox**
Thermal NOx is formed when nitrogen (N2) and oxygen (O2) in the air merge with one another by combustion. This creates Nitrogen oxides (NOx).
NOx is created with any sort of flame of any temperature.
The combining of these 2 substances becomes easier at a higher temperature which will cause a higher amount of NOx released into the air.

**Fuel Nox**
Fuel NOx is formed by the reaction of nitrogen bound in the fuel with oxygen in the combustion air. This is a problem for oil powered engines. Since these oils contain Nitrogen, gas powered engines on the other hand rarely have fuel NOx since the gases do not contain sulphur.

**Sulpher Dioxides**
Sulpher dioxide is formed by combining S (sulpher) which is found in the combustible fuels and Oxygen (O2) which is found in the combustion air. These 2 combined create the unwanted byproduct Sox.

\[
\begin{align*}
N &= O^2 \\
S &= O^2 \\
N &= NO^2 \\
S &= SO^2
\end{align*}
\]

Sources:
http://www.cleanboiler.org/Workshop/HowNOx.htm
6. What is plasma?

3.1 Definition

Plasma is known as a forth matter. Most common matters are: liquids, solids and gases. Plasma is a direct extension from the gases.

A normal gas phase atom consists of an equal number of positive and negative charged particles. The core consists of positive protons and the shell consists of negative electrons. This combination makes them neutral.

The plasma phase is created by increasing the temperature or by adding any sort of energy. When this happens, one or more electrons will break free from the atom and move freely in space. The left over atom will consist of the same amount of protons but fewer electrons. This process is called ionization.

When sufficient atoms are ionized and enough electrons are moving freely, the electrical characteristics of the gas will change. In this phase the plasma is created and can be visible.

Plasma can be seen as a blue electrical arc. The plasma cannot be felt.

3.2 How is plasma created?

To create plasma a very high electrical current is needed. However, this energy is only needed for a very short period of time, mainly a few nanoseconds ($10^{-9}$ s). Via a power converter a fairly low current can be converted into a very high current. This process is continually repeated over a thousand times per second.

Via a high current cable the generated power pulse is supplied to a reactor that is fitted with metal and cables or deckled edges. (The gas that needs to be treated will flow through this reactor)

The current will jump between these metal plates and cables or deckled edges in the shape of electrical sparks. These electrical sparks will ionize the atoms thus creating plasma and create the chemical characteristic that will break the NOx and other unwanted particles.

This process is entirely chemical and does not rely on thermal heating of the gas, making it use less energy than conventional chemistry.

To improve the chemical reaction with the dirty gas, water mist nozzles are fitted in the reactor. The water mist droplets will merge with the dirt gasses, thus improve the splitting of molecules. The water droplets will simultaneously act as a conveyor belt for extracting dirty particles.

3.3 Plasma reaction

Exhaust gasses from the main engine pass through the plasma reactor. The gasses make contact with the plasma inside the reactor, changing its characteristics.

Nitrogen oxides (NO), carbon oxides (C$_x$H$_y$) and oxygen dioxides(O$_2$) enter the plasma reactor combining the C$_x$H$_y$ + O$_2$ creating C$_x$H$_y$O$_z$. The NO products stay unchanged.

The altered gas substances then pass through the catalyst. The NO2 + C$_x$H$_y$O$_z$ combine and split into Nitrogen, hydrogen oxide and carbon oxides. These substances are already in the natural air, thus not being harmull.

The big sticky particles coming from the engine are no problem for the catalyst, since the plasma reactor breaks the particles into small pieces. which can be handled by catalyst.

Sources:
http://www.hmvt.nl/hmvtwiki/corona
http://education.jlab.org/qa/plasma_01.html
7. Required parts & Implementation

**Plasma reactor**
Plasma is created in a reactor, this is where the chemical reaction takes place. This reactor can be manufactured in any size necessary to meet demand.

**Generator**
To create the plasma that will react with the NOx & Sox, a very high voltage is. The power needed to create the plasma will be generated by the ship generators. These generators will need to supply a voltage of more or less 440 Volt.

**Transformer**
To create the 6,000 to 10,000 volts needed, a transformer is needed. This is the heaviest part of the entire installation. The transformer transforms the 440 V to 6000/10000 Volts.

The best place to install the transformer will be nearby the plasma reactor. By placing it nearby, a compact system can be created.

**Control panel**
To start and stop the system, a control panel is needed. This can be located in any part of the engine room. Probably the best place for this instrument is the control room, since an engineer does not climb the funnel every time he has watch.

**Catalyst**
The catalyst converts the engine emissions into less harmful substances that can be admitted into the air.

**Implementation**
This system can be made in such a way that it can fit in any existing and new build vessels. The best place where the reactor can be placed in existing vessels is in the funnel. It is easier to put it in new build because you can take it into account of the space in the engine room and put it on the best recommended place for this plasma reactor. This place will be somewhere close to the funnel.
8. Efficiency

Worldwide, there is research on corona plasma and related techniques for removal of contaminants from air streams. There is a huge collection of publications on removal of a range of substances. Examples include the removal of toluene, ethylene, ammonia, hydrogen sulfide, NOx, SO2, dioxins, fragrance, and more. However, plasma techniques based on electron beams and corona discharges become significant due to advantages such as lower cost, higher removal efficiency, smaller space volume, etc.

For the tests with removal of NO2 from dry air into a dry reactor, corona, which is done by TNO, is based on a fixed flow rate of 320 m3/hour. With the diesel in stationary preparation and dilution of flue gases from the diesel with fresh air to 320 m3/hr is an input concentration of approximately 30 ppm NOx (approximately 56 mg NOx/m3) is achieved. By the frequency of the corona discharge to vary a variable energy intensity is reached at which the effects of the corona treatment may be measured in the after air after the corona installation. By taxing the diesel increases the emission of NOx to 59 ppm at constant flow rate of 320 m3/hr. It also changes the relationship between NO and NO2 in the exhaust. By precisely the influx of diesel exhaust that can squeeze the concentration of NOx can be reduced to 15 ppm. In this manner, the effect of concentration and residence time are determined.

4.1 Removal Returns

The removal efficiencies measured in the test are expressed as a percentage reduction, compared with the unit of input energy per liter of gas: Joules per liter of air (J / l). For the different initial concentrations in ppm NOx in the ingoing air lines can then be generated by the reduction percentage at certain energy density at the selected initial concentration display. In the scheme above is gently can be deduced that a lower concentration has a positive effect on the removal of a particular energy density in J / l.
4.2 Energy density and energy efficiency

The blue points are relevant to the decomposition of NO. At low energy densities breaks down faster than NO NO2 (square blocks). Once NO is completely converted to NO2, the NO2 concentration will drop again. In the first instance is created, therefore, an increase of the NO2 concentration by the conversion of NO to NO2, the decomposition of NOx (sum of NO and NO2), in all cases showed a decreasing trend with increasing energy density. The black lines show the linear regression over the interpolated energy efficiency again, expressed in ppm NOx plotted as a function of the number of Y / l (ppm NO x / (J / l)).The linear regression line of NO2 gives only a partial aspect of the overall energy efficiency for NOx decomposition again.

4.3 Effect of slip, in the reactor

Complete removal of NOx in the tests have been impossible because there is a constant slippage of air plasma generated by the place of an estimated 10-15%. This slip is caused by the top and bottom of the electrode racks present in open space in the reactor. This space is estimated to be 10-15% of the reactor volume. The non-slip could be confined by the turbulence present in the air so that particles still present in contact with the cold plasma.

Figure 1.2 is the NO2 concentration with increasing energy density to an asymptote at about 1 ppm. This probably indicates the slip the running through the reactor. There is thus at increasing energy density there is a situation in which up to 100% NO2 can be removed. At a subsequent reactor design for a prototype to this aspect will be further attention should be given and the air flow will probably be in the longitudinal direction of the electrodes to flow rather than in the current direction at right angles.

4.4 Discussion of the energy efficiency results

The energy efficiency results of the tests with the dry reactor will be discussed with reference to Figure 1.2 t / m 1.5.

• In the tests 30 ppm NOx and 320 m3/hour (Figure 1-3) showed the highest removal efficiency can be reached from about 90% to 21 J / l energy density (decrease from 29 to 3 ppm NOx). The energy efficiency is on 1.3 ppm NO x / (J / l).

• The energy efficiency is reflected in a dry reactor with increasing concentration to be run from 1 ppm / (J / l) at 15 ppm to 1.9 ppm / (J / l) at 59 ppm concentration of output (compare Figure 1.2, 1, 3 and 1.4). To what extent this also at a wet reactor (spray water) is the case, it is not analyzed further.

• With increased flow also shows the energy efficiency of light to increase (Figure 1.5 vs. Figure 1.3).

• It is unclear whether these trends to further increase the flow or reducing the levels will continue. This requires extensive further research is needed under extreme conditions of both flow and concentration.
Figure 1.2 Concentration Gradient from 15 ppm NOx at 320 m³/h with increasing energy.

Figure 1.3 Concentration Gradient from 30 ppm NOx at 320 m³/h with increasing energy.
Figure 1.4 Concentration Gradient from 59 ppm NOx at 320 m$^3$/h with increasing energy.

Figure 1.5 Concentration Gradient from 31 ppm NOx for increased flow of 790 m$^3$/h with increasing energy.
9. Advantages & Disadvantages?

Advantages

Interaction between catalyst and soot is not a problem (even with sticky substances) because plasma breaks down the sticky substances in soot. Due to this break down the soot is the same as soot that comes from a car.

The plasma technology reactor is low maintenance because it consist of all metal, copper and ceramics. Metal is an element that is a good conductor for electricity and heat. Copper is a ductile metal with very high thermal and electrical conductivity mainly used as building material. A ceramic is an inorganic, nonmetallic solid prepared by the action of heat and subsequent cooling. Due to the composition of these materials and there characteristics there is hardly any maintenance needed.

No extensive knowledge about plasma or reactors is needed because it is all prefabricated and installed by experts. The knowledge needed for this installation is High voltage and basic preventive maintenance which is taught at Maritime college.

The installation is it “touch safe”, All the high voltage is covered by the ceramics. It is inside the reactor so unreachable from the outside unless opened up by experts to do their maintenance.

It is suitable for existing engines because the system is prefabricated and does not need any special features on the engine. Its build in the funnel by experts, doesn't need a lot of space. The power supply and control unit are 1m by 1m

The purpose of this installation is filtering the exhaust gases which prevents harmful emissions in the air, which is good for the environment. In 2016 there is a new tier, this is tier 3 with stricter rules on the amounts of NOx and SOx in the air. With this system you apply to these new rules.

Reduction of NOx with more than 90% (similar to SCR) and less particles emissions
TNO tests prove that with 30 ppm NOx and 320 m3/hour the maximum efficiency is 90% at a 21 J/l energy density

Disadvantages

The installation uses a high volt, to achieve this high voltage you need a transformer. This gets this transformer to work u need more power which means more fuel. Due to this this installation has a High fuel penalty, too much use of fuel for efficient NOx removing
10. Conclusion

Our assignment was to find a solution to reduce the NOx and SOx amounts in exhaust gasses.

To find a solution we brainstormed about possible installations and found Plasma Technology. Because of our insufficient knowledge about plasma technology we started a desk research.

Our goal during this research was:

How to reduce NOx and SOx with the help of plasma Technology? Also how does plasma technology work?

To reach this goal we had a Main Question and Sub-questions. The sub-questions are needed to answer the main question

Main question:
How can plasma technology be used onboard ships to reduce the Sox & Nox?

Sub-questions:
1. What is plasma technology?
2. What are the required legislations to implement plasma technology onboard ships?
3. How can plasma technology be implemented onboard ships?
4. What is the efficiency of plasma technology?
5. What are the advantages and shortcomings of plasma technology?

To find an answer to these sub-questions we did desk and field research.
Desk research consisting of books and the internet. Field research was done by an interview with Mr. Schildt (professor at TU Eindhoven)
By answering the sub-questions we found our answer to the main question.

With this research we concluded the following findings.

Plasma is created in a reactor, also the chemical process takes place in this reactor. This reactor can be manufactured in any size necessary to meet demand. To create the plasma that will react with the NOx & Sox, a very high voltage is. The power needed to create the plasma will be generated by the ship generators.
To create the 6.000 to 10.000 volts needed, a transformer is needed. This is the heaviest part of the entire installation.

This system can be made in such a way that it can fit in any existing and new build vessels. The best place where the reactor can be placed in existing vessels is in the funnel. It is easier to put it in new build because you can take it into account of the space in the engine room and put it on the best recommended place for this plasma reactor. This place will be somewhere close to the funnel.

11. Recommendation

Our conclusion is that we do not recommend this system because it does not remove SOx and there is a high fuel penalty.
We researched with plasma and a catalyst. A better option is ESP (electrostatic precipitator)
12. Reference

Websites
http://www.dieselnet.com/standards/inter/imo.php
http://www.cleanboiler.org/Workshop/HowNOx.htm
http://www.hmvt.nl/hmvtwiki/corona
http://education.jlab.org/qa/plasma_01.html

Reports
TNO report Reduction of particulate emissions from ships using plasma technology.
Plasma technologie voor fijn stof verwijdering bij scheepsemissies
Plasma gasreiniging
Plasma-katalytische emissiereductie

Interview with mr. Schilt
Cd interview plasma onderzoek