PlasTEP

plasma for environment protection

Cost estimate of deNOx for a flue gas from MAN B&W marine engine

Prepared by PlasTEP partner #04, Risø Laboratory for Sustainable Energy, Technical University of Denmark

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1 Introduction

This document is about the cost estimate of deNOx process for a flue gas from a 2 stroke MAN B&W marine engine. The principle of the low temperature ozone deNOx process is briefly introduced. Based on chemical simulations, for an economical deNOx process, it is important for have deNOx process to be performed at low temperature (no more 100 ^{o}C). According to the simulation results, for a 100 ^{o}C flue gas, 2 kg O_3 is needed for 1 kg NO_x removal at a reduction rate of more than 80 percent. The overall cost estimate in the last part of this document is following the calculation methods and data with a reference report done by Lars Jørgensen from Danish Gas Technology Centre and the PlasTEP handbook.

2 The plasma deNOx process

Plasma generated ozone and the flue gas are mixed and then introduced to a reactor with a sufficient residence time (5 seconds in our case) for a deNOx process. In the reactor NOx is oxidized with ozone to form N2O5 that is easily removed from the flue gas in a wet scrubber system.

Reactor
RE1: NO + O3 = NO2 + O2; A=3.16E-10, EA=3.1, B=0
RE2: NO2 + O3 = NO3 + O2; A=1.20E-13, EA=4.87, B=0
RE3: NO2 + NO3 = N2O5; A=9.42, EA=0, B=-4.5

Scrubber
N2O5 (g) + H2O (l) = 2 HNO3 (l)
The nitric acid formed in the scrubber is neutralized with sodium hydroxide.

For an efficient deNOx process, a flue gas of a temperature not higher than 120 °C is required, mainly due to the decomposition of ozone and N2O5 at high temperatures.

RE4: O3 = O2 + O3P ; A=7.16E-10, EA=22.26, B=0
RE5: N2O5 = NO2 + NO3; A=4.57E5, EA=21.86, B=-3.5

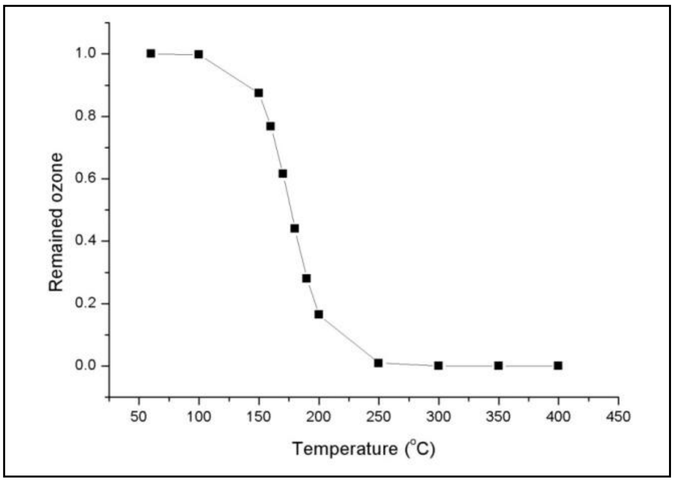

Figure 1: The decomposition of ozone at increasing gas temperature. (RE4)

3 Chemical mechanism of O3-NOx

Processes influencing on the NOx oxidation in the flue gas after the ozone injection were modeled by use the chemical kinetics simulation program CHEMSIMUL [1]. A reactor with a 5 seconds residence time for the flue gas is assumed for the simulation. A 14-species, 38-step chemical kinetics model is used to model O3-NOx reactions in the reactor.

Figure 2 shows the simulated NOx reduction rate at various temperatures for a flue gas from marine engine running at 25% load, various ozone input with molar ratio of O3/NOx from 3, 2, 1.5. One can see that this technique has limitation at high temperature, therefore the cooling of flue gas is necessary for this technique.

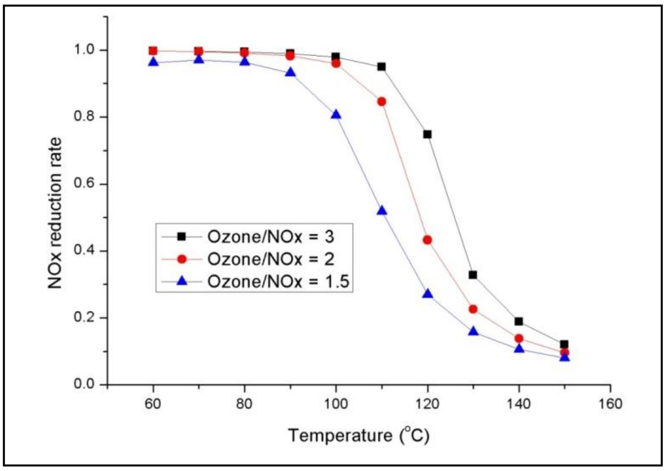

Figure 2: NOx reduction rate at various temperatures

By simulation result from CHEMSIMUL, the **theoretical** ozone consumption for 80% NOx reduction is:

100 °C: **1.5** kg O3 / kg NOx removed (O3/NOx = 1.5) *NOx is calculated as NO
120 °C: **3.2** kg O3 / kg NOx removed. (O3/NOx >= 3)

However, in real situation, based on our experience from previous measurements for deNOx projects, some ozone loss (e.g. unreacted ozone etc.) should be considered. Therefore, it could be assumed that:

100 °C: **2 kg** O3 / kg NOx removed (O3/NOx >= 2) *NOx is calculated as NO
120 °C: **4 kg** O3 / kg NOx removed. (O3/NOx >= 4)

At 25% load points for MAN marine engine, NOx flow rate is 27 kg/h.
→ So, at 100 °C, at least **54kg/h** ozone is needed.
→ And at 120 °C, **108 kg/h** ozone is needed.

Therefore, for an economical deNOx treatment, the flue gas has to be cooled at most with a temperature of 100 °C. In the cost estimate as followed, we assume the flue gas is cooled to be **100 °C**.

Engine model: 6S50ME-C8, output: 9960 kW		Load points			
Input Parameters	**Unit**	**25%**	**50%**	**75%**	**100%**
Flue gas flow rate	kg/h	27000	53000	73000	90000
Flue gas flow rate	Nm^3/h	21000	41000	56000	70000
NO$_x$	ppm	957	1124	1056	882
NOx	kg/h	27	62	79	83
O$_3$ demand	kg/h	54	124	158	166

Table 1: demand of O3 (kg/h) for a flue gas at 100 °C

4 Investment/capital costs

The below cost estimate is following the calculation methods and data with a reference report done by Lars Jørgensen from Danish Gas Technology Centre [2].
The total investment costs cover all parts of the deNOx plant:

1. Ozone generator
2. Equipment for oxygen supply
   LOX – Liquid Oxygen
   PSA – Pressure Swing Adsorption (concentrated oxygen)
   Air

3. Reactor

4. Scrubber/absorption system

Building costs have been omitted from the calculations.

For flue gas at 100 °C (83 kg NOx/h, ozone 166 kg/h), a Lesni A/S ozone generator with 200 kg/h is needed. It is priced at 13,06 Mio. DKK (approx. 1,75 Mio. EUR).

A Lesni A/S PSA plant with 200 kg/h is priced at 16,6 Mio. DKK (approx. 2,3 Mio. EUR).

No prices were received for air preparation systems. In the present report the capital costs for air preparation systems have been estimated to be half the price of a PSA plant.

Reactor
The flue gas flow rate moves within a range of (21000 to 70000 Nm³/h, depending on load points). Therefore, a reactor which is capable of treating a 100000 Nm³/h flow is required. It is priced at round 530,000 DKK (approx. 71,000 EUR).

Scrubber system
The scrubber system with a capacity of treating a 100000 Nm³/h is priced at 3,8 Mio. DKK (approx. 510,000 EUR).

5 Depreciation on equipment

The deNOx plant is depreciated through the operating costs. In this report a payback time of 15 years (assumed) has been used.

6 Operating costs

6.1 Ozone production

6.1.1 Power consumption

Power consumption unit	Oxygen		Air
	LOX	PSA	
Feed gas preparation	-	10	5
Ozone generator	10		15
Chiller/cooler	3		5
Total power demand	13	23	25

Table 2: Power consumption for ozone generation in kW / kg O3

Calculations in document are made at these price levels for electricity:

→ DKK 0,30/kWh
→ DKK 0,80/kWh
→ DKK 1,30/kWh

6.1.2 Liquid oxygen supply

Liquid oxygen from AGA costs around 1 DKK/m³ O_2 (approx. 0,134 EUR). These expenses cover the rental of an oxygen tank, services, automatic surveillance and oxygen consumption.

6.2 Scrubber and water treatment

Annual operating costs for a scrubber system (100,000 m^3/h): 320,000 DKK. (approx. 43,000 EUR)
Flue gas temperature: 100 °C (assumed)
NOx level: around 30-90 kg/h,
average is 60 kg/h (assumed)
NOx reduction level: 80 %
Price of electricity: 0.30 DKK/kWh (assumed)
Operating time: 3500 h/year (assumed)

Capital costs	**LOX**	**PSA**	**Air**
Ozone generator	4.15	4.15	6.22
LOX plant	1		
PSA		5.27	
Air preparation			2.63
Reactor	0.17	0.17	0.17
Scrubber system	1.5	1.5	1.5
Total depreciation	**6.82**	**11.09**	**10.52**
Operating costs			
Ozone generator, power cons.	7.8	7.8	11.7
Ozone generator, service & main.	1.8	1.8	3.62
LOX plant	23		
PSA, power cons.		6	
PSA, service & main.		1.8	
Air preparation			5.4
Scrubber system, service & main.	0.92	0.92	0.92
Scrubber system, finishing dis. water	0.25	0.25	0.25
Total operating costs	**33.77**	**18.57**	**21.89**
Total costs for NOx removal	**40.59**	**29.66**	**32.41**
Total costs in EUR	**5.50**	**3.98**	**4,35**

Table 3: Costs for NOx removal in DKK at 100 °C flue gas temperature and 0.30 DKK/kWh electricity

Result
With an electricity of 0.30 DKK/kW around 41 DKK/kg NOx have to be calculated for a LOX deNOx, corresponding to a 0.49 DKK/kW for a 9960 kW MAN marine engine.

	DKK		
	LOX	PSA	Air
0.3 DKK/kW electricity	41	30	33
DKK/kW	0.3	0.36	0.4
0.8 DKK/kW electricity	46	39	40
DKK/kW	0.55	0.47	0.48
1.3 DKK/kW electricity	67	76	72
DKK/kW	0.8	0.91	0.86

Table 4: DKK/kg NOx removal or DKK/kWh produced by MAN marine engine

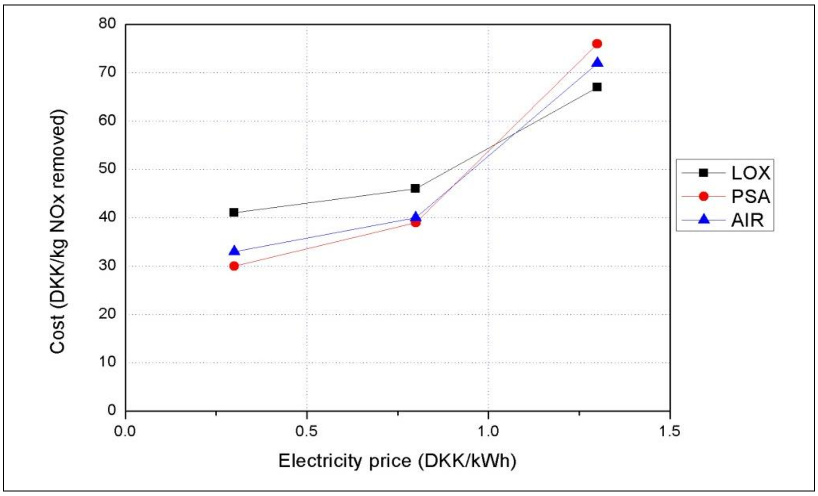

Figure 3: NOx removal costs versus electricity

6 Conclusion

The costs of related to the production of ozone are very sensitive to the electricity price. The main part of the specific price is related to the production of ozone. Furthermore, the annual time of operation has a major influence on the specific price, i.e. DKK/kg NOx.

7 References

[1] P. Kirkegaard, E. Bjergbakke, and J.V. Olsen, Risø-R-1085 (ed.2) (EN), 1 (2006).
[2] Lars Jørgensen (DGC), Costs related to ozone production and NOx removal by plasma deNOx process, Pilot test and optimisation of Plasma Based DeNOx.

Appendix

SCR design specifications for a 2 stroke MAN B&W marine engine

Engine model: 6S50ME-C8
Output: 9960 kW
Fuel: Heavy fuel oil with 3 wt% sulphur

		Load points			
Input Parameters	**Unit**	**25%**	**50%**	**75%**	**100%**
Flue gas flow rate	Kg/h	27000	53000	73000	90000
Flue gas flow rate (0°C,760mmHg)	Nm^3/h	21000	41000	56000	70000
Exhaust gas temperature before/after turbocharger (T/C) $T_{ambient}$=10°C (winther)	°C	299/245	308/217	337/207	395/221
Exhaust gas temperature before/after turbocharger (T/C) $T_{ambient}$=25°C (ISO)	°C	320/270	330/240	360/230	420/245
Exhaust gas temperature before/after turbocharger (T/C) $T_{ambient}$=45°C (tropical)	°C	350/305	360/273	392/262	455/278
Max temperature	°C	490	490	490	490
Max pressure before T/C (110% load)	Bara	4.2	4.2	4.2	4.2
Pressure before T/C	Bara	1.3	2.0	2.9	3.7
NO_x	ppmvd@15%O_2 dry	957	1124	1056	882
NO_2 of NO_x	%	5	5	5	5
SO_x	Kg/h	28	55	81	112
SO_3 of SO_2	%	5	5	5	5
O_2	ppm wet	15.8	15.2	15.1	14.3
H_2O (calculated)	%@15%O_2 dry	6.8	5.8	5.7	6.2
CO_2	ppm wet	3.8	4.2	4.4	4.9
Particles	mg/Nm^3	240	280	300	320
Output Parameters					
NO_x reduction	%	75	75	75	75

N.B. The pressure drop across the reactor is not allowed to exceed 150 mmH_2O