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Investigation of urea deposit formation in vehicles with Selective Catalytic Reduction system

Master's Thesis in Automotive Engineering

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ABSTRACT

In order to reduce NO_X emissions from a diesel engine a urea-water solution called AdBlue is injected into the exhaust system. Risk of deposit formation is high due to unwanted side reactions that may occur during the decomposition of AdBlue during transient engine operation.

The objective of the thesis is to increase the knowledge about the formation and decomposition of urea deposits and to develop an experimental method for studying these phenomena. The knowledge will form a base for a kinetic model for deposit formation and decomposition.

A literature review was performed to identify unwanted side-reactions that may occur when urea is injected and what parameters influence the formation of deposits. In order to test how these parameters influence the rate of deposit formation, a test set-up was designed for engine bench tests rig at Volvo Cars. The tests were carried out with consideration to critical parameters and limitations of the test rig.

Urea deposits were detected at all operation points, even at temperatures as high as 450˚C. All deposits formed during the tests could be decomposed when dosing was stopped and the temperature was increased above 450˚C. A correlation between theoretical calculations, i.e. a heat balance over the wetted area, and experimental results could be seen. The effect of energy transfer can be seen in the experiments as a temperature drop on the surface where the spray hits. The build-up and break-down have been captured on film and shows a non-linear rate.

It is to some extent possible to predict if there will be deposits in the system by a theoretical comparison of the available energy in the exhaust gases to the energy required to decompose the urea-water solution. One parameter that has a great influence on the energy calculations is the area that the liquid spray hits, i.e. the area were the main heat transfer occurs. If this surface can be increased the amount of urea-water solution that can be decomposed into ammonia will increase. A better surface distribution and spray dispersion will provide better control of the amount of liquid that will reach the surface and a better base for predicting deposit formation with energy calculations.

Key words: Urea deposits, urea injection, selective catalytic reduction, diesel exhaust aftertreatment, heat transfer model, AdBlue

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Preface

This master thesis has been performed at Volvo Car Corporation in Gothenburg completing a Master of Science degree in Automotive Engineering at Chalmers University of Technology. The project has been done at Exhaust After Treatment department 97621 at Volvo Car Corporation from January to June 2014.

Acknowledgments

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Table of abbreviations

CAD	Computer aided design
CFD	Computational fluid dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE	Design of experiments
DPF	Diesel particulate filter
ECU	Engine control unit
EGR	Exhaust gas recirculation
FPD1	Funktions provning dynamisk 1
FTIR	Fourier transformations infrared spectroscopy
GSA	Geometric surface area
H_2O	Water
HC	Hydrocarbons
HNCO	Isocyanic acid
ICE	Internal combustion engine
kg	kilogram
kPa	kilo Pascal
mg	milligram
min	Minute
NH_3	Ammonia
Nm	Newton meter
NO	Nitric oxide
NO2	Nitrogen dioxide
NOx	Nitrogen oxides
OEM	Original equipment manufacturer
rpm	Rounds per minute
s	Second
SCR	Selective catalytic reduction
SCRF	Selective catalytic reduction on filter
TP5	Tramissions provning 5
VED4 MP	Volvo environmental diesel 4 cylinder medium power
VCC	Volvo Car Corporation

Contents

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1 Introduction

In this chapter a background for the project is described along with the scope, purpose and limitations.

1.1 Background

Internal combustion engines (ICE) are the far most common power source for road vehicles in the world, in combination with good infrastructure of fuel supply and high
energy density makes it a very attractive propulsion technology. However, well known is the problem with the increasing number of vehicles in the world and therefore the need to decrease the emissions such as nitrogen oxides (NO_X), carbon dioxide (CO_2), hydrocarbons (HC), soot and carbon monoxide (CO) from the combustion of fossil fuels.

The amount of emissions that a vehicle is allowed to emit is regulated by international law and emission regulations are becoming more stringent. Vehicles produced later than 2017 must fulfill Euro 6c legal demands where the lowered limits for NOx emissions will, for most OEMs, require the use of an active reduction system.

Introduction of selective catalytic reduction (SCR) systems that actively reduce NOx is a solution for fulfilling Euro 6c standards. Ammonia (NH3) is added to the exhaust gases and reacts with NOx to form CO2 and water (H2O). Since ammonia in pure form
is toxic and caustic it has been decided to use a solution of water and Urea ($CO(NH2)_2$) called AdBlue. Urea decomposes into ammonia at high enough temperature and with the help of a catalytic surface.

The decomposition of urea-water solution is thermally activated; it starts with evaporating the water from the fluid, leaving the urea molecules. Urea molecules are decomposed in two stages and the reactions release one ammonia molecule in each stage.

If the decomposing of urea is not completed the intermediate phases in the decomposition can react with urea and form different unwanted by-products. These by-products are solid polymers (deposits) that might stick onto pipe walls, injectors and SCR surfaces and cause NO_X conversion efficiency to go down, making the system less effective and may lower the performance of the engine. These deposits can be decomposed if the temperature is high enough. However raising the exhaust gas temperature might have a negative impact on fuel consumption. Therefore it is of interest to get a good understanding on how deposits are formed and broken-down in order to reach an efficient dosing strategy avoiding deposit formation.

1.2 Purpose

The general purpose of this study is to increase the knowledge and understanding about formation and breakdown of urea deposits in exhaust after-treatment systems for light duty diesel vehicles. Specifically an experimental method for detection of urea deposits is developed. Experiments were performed on a closed-coupled catalyst system in order to gather data on deposit formation. The experimental data was used

to develop and validate a heat transfer model for deposit formation. The study is carried out in collaboration with Volvo Car Corporation (VCC).

1.3 Scope

In order to fulfill the purpose of the project a number of questions will have to be answered with theoretical and experimental studies

- Evaluate methods for detecting deposits
- Where in the system are deposits formed at different operating points?
- How much urea can be injected before deposits are formed
- What is the thermal limit, i.e. temperature and mass flow of exhaust gas, for injection of a given amount of Urea into the exhaust system?
- How does the distribution of liquid, i.e. the wetted area, influence the formation of deposits?
- What are the temperature and exhaust mass flow dependences of the formation and decomposition rates respectively?

1.4 Limitations

The project focuses on a theoretical and experimental investigation on formation and decomposition of urea deposits in a close coupled after treatment system and the following limits of the work apply:

- Experiments are performed on VCC exhaust aftertreatment design including layout, substrate type and washcoat formula.
- Experiments performed at VCC facilities with equipment supplied by VCC.
- The project does not cover any calculation/simulations on spray quality, droplet size or spray penetration.
- The physical testing will be carried out in an engine test rig with a four cylinder inline diesel engine.
- Experiments will be conducted with two types of injectors provided by VCC.
- The study will try to replicate the real conditions in the exhaust system.
- The study will not will not focus on dosing strategies for Urea-SCR systems.

2 Theory

In this chapter the theory supporting the outcome of this project is presented. Starting with describing why there is a need for an active SCR-system because of upcoming legal demands on emissions from combustion powered vehicles. The chapter continues with a description of the chemical reactions that occur. Finally heat transfer mechanisms are introduced and the theory behind design of experiments (DOE).

2.1 Diesel Combustion

Combustion in a diesel engine is initialized by compression of a lean fuel and air mixture until the charge has absorbed necessary amount of energy for combustion to start. The combination of excess air and high temperatures enables atmospheric nitrogen to react according to the extended Zeldovich mechanism seen in equation (2.1), (2.2) and (2.3) the reactions are as follows with the addition of Lavoie *et al* [1]

$$O + N_2 = NO + N \qquad (2.1)$$
$$N + O_2 = NO + O \qquad (2.2)$$
$$N + OH = NO + H \qquad (2.3)$$
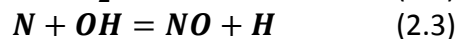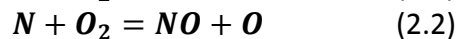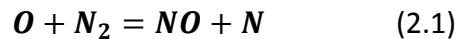
NOx formation depends on the characteristics of the combustion; typical flame temperatures suggest that the predominant source of NOx is nitric oxide. However in engine out emission measurements the concentration of NO2 could range from 5-30 percent of the total NOx emissions due to the possibility of NO oxidizing to NO2 when there is a surplus of oxygen.

Since high temperature is causing high levels of NO_X formations it is desired to lower the combustion temperature to a level with lower NO_X formation. One common and efficient way of lowering the in-cylinder temperature is to dilute the fresh intake air with gases that have lower oxygen content, often cooled exhaust gases. This is called exhaust gas recirculation (EGR) when part of the exhaust mass flow is taken from the main gas flow after the exhaust port and transported through a cooler and then fed back into the intake system [1]. A controlled valve changes the amount of exhaust that is fed back to the intake.

2.2 Environmental impact

NO and NO2 are toxic for humans and have a negative impact on the environment. NO2 is considered more toxic for humans and animals than NO and can cause breathing problems and severe lung diseases. A high concentration of NO2 decreases the immune system's ability to fight of bacterial and viral infections and if exposed to concentrations above 200 ppm it might be fatal [2].

The toxicity of NOX is not the most significant concern why it should be decreased the environmental impact from this emissions are even worse. NOX can produce acid rain, photochemical smog and ground level ozone when it reacts with different components in the atmosphere. Acid rain is produced when NOX reacts with oxygen

and water to produce nitric acid. Acid rain can cause acidification of water and death of forests [3].

Photochemical smog is a combination of several pollutants like CO, sulfur oxides, fine particles and volatile organic compounds. Smog normally appears in city areas where the concentration of these emissions is higher since there are more vehicles operating in the same premises. Smog can be seen as gray haze, which forms a thick lid on many cities around the world. From photochemical smog ground level ozone can be formed. This happens when NO_X and HC reacts and form ozone. Ozone can cause damage to lungs, the respiratory system and also to damage crops and other vegetated areas [3]. Since the number of internal combustion engines are increasing rapidly it is of big interest to decrease the emitted levels of NO_X.

2.3 Emission regulation

The negative health and environmental effects have led to the introduction of emission legislation that state he allowed emission levels. European emission standards have been in use since the beginning of 1990's. The current standard for new registered passenger and light duty vehicles is called Euro 5b (a summary of the Euro5b level can be seen in Table 2.1) which stretches up until September 2014 when Euro 6 is introduced. From the current Euro 5 standard to Euro 6 the permitted nitrogen oxides emissions will be lowered by 55 % [4] which is a technical challenge for light duty vehicle manufacturers.

Table 2.1 European emission legislation development over time

	Date	CO [g/km]	NO_X [g/km]	Particulate matters [g/km]	HC+NOx [g/km]	Particulate number [#/km]
Euro 3	2000.01	0.64	0.50	0.05	0.56	-
Euro 4	2005.01	0.50	0.25	0.025	0.30	-
Euro 5b	2011.09	0.50	0.18	0.005	0.23	6.0×10^{11}
Euro 6	2014.09	0.50	0.08	0.005	0.17	6.0×10^{11}

In 2017 a new test method for determining a vehicle emission levels in daily driving will be introduced. This new test method is called real driving emission (RDE). RDE will replace the current European test method, New European Driving Cycle (NEDC) that is in use today. The idea of RDE is that the vehicle will be tested on a much bigger part of the performance map. Instead of having a pre-defined driving cycle, as in the case for NEDC, RDE will be performed in real traffic with a random driving route.

2.4 Catalyst substrates and washcoat

A catalyst is made of a substrate that works as a support for the washcoat. The two most common types of substrates are a metal type and a ceramic type. The metal type consists of thin steel sheets that are corrugated in a specific way to form a cell structure that can be seen in Figure 2.1 and then rolled into a cylindrical shape. The walls in the ceramic substrate are built up by a matrix extruded into a specific shape, see Figure 2.1. The washcoat works as the carrier of the catalytic substance and is often made of metal oxides such as Al_2O_3, TiO_2, SiO_2 and zeolites. The catalytic substance is normally a precious metal and is blended into the washcoat. The washcoat is used to create as big surface area as possible, where the reactants can come into contact with the catalytic substance, and therefore increase the performance of the catalyst [5].

Figure 2.1 Metal and ceramic substrate[1]

A substrate for a diesel particular filter (DPF) is often of ceramic type with porous walls. The main difference for a filter substrate as compared to a flow-trough substrate is that each channel is blocked in one end to force the gas flow through the walls. The pores in the walls are big enough to let the gas through without causing a significant pressure drop, but small enough to capture the soot as illustrated in Figure 2.2 [5].

Figure 2.2 Wall flow in a diesel particulate filter[2]

[1] https://www.dieselnet.com/tech/cat_substrat.php
[2] https://www.diselnet.com/tech/dpf_wall-flow.phh

2.5 SCR-System layout

Exhaust gases evacuated from the combustion is flowing through the headers down to the first stage of the exhaust aftertreatment system. AdBlue is injected into the exhaust system before the SCR so that the AdBlue and exhaust gases can mix. The urea is then decomposed into ammonia that will travel down to the SCR coated DPF(SCRF) where NO_x is reduced with ammonia. After the SCRF an SCR is placed to increase the NO_x conversion efficiency and take care of ammonia slip from the SCRF seen in Figure 2.3. The amount of AdBlue is controlled by the engine control unit (ECU) and the injector is often cooled with water from the engine cooling system. A tank houses a pump that pressurizes the AdBlue for the injector, see Figure 2.3.

Figure 2.3 Typical SCR-system layout[3]

2.6 Selective catalytic reduction (SCR) chemistry

Selective catalyst reduction of NOx has been frequently used in stationary applications
for around 30 years. The most common type of SCR uses ammonia as a reductant to reduce NO and NO2 to harmless components [6]. The ammonia that is used in the system is either pure ammonia gas or generated from a nitrogen and hydrogen rich substance. The most common way in automotive applications is to use an aqueous urea solution that goes under the brand name AdBlue. There are several reasons that make AdBlue the preferred reductant instead of ammonia gas. One reason being that pure ammonia in gas form is difficult to manage and if released is highly toxic and caustic [7].

These are the normal SCR reactions that can occur when using ammonia as a reductant in an automotive application [8]:

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[3] www.hybridcars.com/technolgies-greener-gasoline-disel-and-hybrid-delphi-53674/
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$$2\ NH_3 + NO +\ NO_2\ \rightarrow\ 2\ N_2 +\ 3\ H_2O \qquad (\ 2.4\ )$$

$$4\ NH_3 + 4\ NO + O_2 \rightarrow 4\ N_2 + 6\ H_2O \qquad (\ 2.5\ )$$

$$8\ NH_3 + 6\ NO_2\ \rightarrow 7\ N_2 + 12\ H_2O \qquad (\ 2.6\ )$$

$$4\ NH_3 + 6\ NO\ \rightarrow 5\ N_2 + 6\ H_2O \qquad (\ 2.7\ )$$

Considering the low temperature range reaction (2.4) is the fastest reaction and therefore it is favorable to have a ratio of 50 % $\frac{NO_2}{NO_x}$, this means that there is equal amount of moles of NO_2 and NO, for good low temperature performance. Reaction (2.5) is the standard SCR reaction, mainly since diesel exhausts has a high content of NO. This reaction is slower than reaction (2.4), reaction (2.7) is even slower than reaction (2.5) and therefore less ammonia is consumed by these chemical reactions in automotive applications. If the $\frac{NO_2}{NO_X}$ is biased towards excess NO_2 reaction (2.6) can occur but it is also considered as a slow reaction. If the temperature is high the following undesirable reactions can occur [8].

$$4\ NH_3 + 4\ NO + 3\ O_2\ \rightarrow 4\ N_2O + 6\ H_2O \qquad (\ 2.8\ )$$

$$4\ NH_3 + 5\ O_2\ \rightarrow 4\ NO + 6\ H_2O \qquad (\ 2.9\ )$$
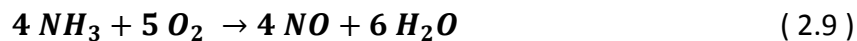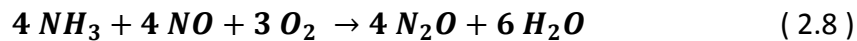
Reaction (2.8) produces nitrous oxide (N_2O) that has a severe impact on the greenhouse effect [9]. Reaction (2.9) shows that ammonia can oxidize to NO and therefore it is undesirable since it will increase the NO concentration.

2.7 Urea decomposition

AdBlue is an aqueous urea solution with 32.5 % urea and 67.5 % water by weight. The chemical formula for urea is $CO(NH2)_2$ and it is chosen for its ability decompose into ammonia. The aqueous urea solution is injected into the exhaust gases where the water is evaporated and the remaining urea melts at 133˚C and starts to decompose. The decomposition of urea is a two-stage reaction that starts with thermolysis of urea to ammonia (NH_3) and isocyanic acid (HNCO) seen in reaction (2.10).

$$CO(NH_2)_2 + heat\ \rightarrow NH_3 + HNCO \qquad (\ 2.10\ )$$
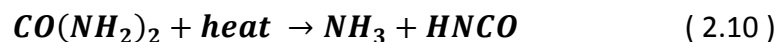
After the thermolysis the isocyanic acid undergoes hydrolysis to ammonia and carbon dioxide with following reaction [8].

$$HNCO + H_2O\ \rightarrow NH_3 + CO_2 \qquad (\ 2.11\ )$$

Reaction (2.10) and (2.11) shows that for each mole urea that decompose results in two moles ammonia. The thermolysis is an endothermic reaction and the hydrolysis is an exothermic reaction but the total reaction from one urea molecule to two ammonia molecules is endothermic. The second stage of the decomposition has shown to be stable in gas phase, which means that reaction (2.11) will not occur in gas phase. To make the hydrolysis reaction occur a catalyst is needed, this catalyst is normally of the same type as for the SCR catalyst [10].

2.8 Urea deposits

The reactions explained above in Section 2.7 Urea decomposition, are the desired reaction paths for urea but the decomposition of urea is complex and can take several different undesired pathways. Since the hydrolysis reaction is slow and needs a catalyst to happen, it gives opportunity for isocyanic acid to react with undecomposed urea. The products that are formed when isocyanic acid reacts with urea are complex polymer chains such as biuret, triuret, melamine, ammeline, ammelide and cyanuric acid [11]. Below the typical reactions can be seen [13].

$$CO(NH_2)_2 + HNCO \rightarrow NH(CONH_2)_2 \qquad (2.12)$$

$$NH(CONH_2)_2 + HNCO \rightarrow Triuret \qquad (2.13)$$

$$3HNCO \rightarrow C_3N_3(OH)_3 \qquad (2.14)$$

$$NH(CONH_2)_2 + C_3N_3(OH)_3 \rightarrow Ammeline + 2H_2O \quad (2.15)$$

$$NH(CONH_2)_2 + C_3N_3(OH)_3 \rightarrow Ammelide + H_2O \quad (2.16)$$
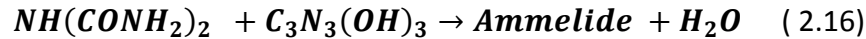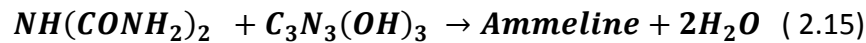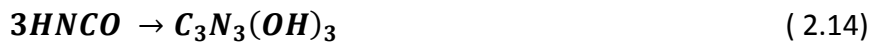
2.8.1 Temperature dependence of formation and decomposition

Studies on urea decomposition have mainly been done in laboratory environment where a solid urea sample has been placed in a gas chamber and gradually heated. The weight of the remaining urea has been under close monitoring to see how much urea that has decomposed into gas phase (thermogravimetric). The gas that is formed during the decomposition is then analyzed with different methods to evaluate what different gas components that are formed during different temperatures [12]. In studies it has been seen that the different polymers are formed and decomposed at slightly different temperatures. The first polymer that is formed is Biuret from the reaction between isocyanic acid and undecomposed urea. The formation of Biuret takes place between 150-190 ˚C and starts to melt and decompose at around 193-250˚C [13].

Cyanuric acid is formed from either a reaction of Biuret and isocyanic acid or from just polymerization of isocyanic acid [13] [15]. These reactions start from around 175˚C and continue up to around 250˚C. The decomposition of Cyanuric acid takes place of a wide temperature range from 250˚C all the way up to 400 ˚C [13].

Ammeline and Ammelide are observed as reactions happening parallel with both Biuret and Cyanuric acid formation. These polymers are formed from Biuret and Isocyanic acid in different combinations [13].

2.8.2 Cooling effects when impingement hot surface

Since the first part of the urea decomposition, equation (2.10), is endothermic it will cause the temperature to drop in the system. This temperature drop will be significant if a droplet of AdBlue hits a hot surface in the exhaust system. If another droplet hits the same spot on the surface before the surface has been given the time heat up to equilibrium temperature the new droplet will cool down the surface further [14]. [14]. Since the temperature plays a big role when the urea deposits are formed this cooling effect of a surface can increase the risk of deposit formation on surfaces where the liquid impinges. In the study performed by Xo et al [14] it could be seen that the temperature of the surface where the droplet hits was cooled down with 5-30 ˚C but the temperature recovered within 5 seconds. These tests were performed with a long time elapsed between the droplets reaching the surface. In real operating conditions a continuous spray hitting the surface will sustain the cooling effects rather than letting the surface heat up in between. The resulting temperature drop on a surface when impinged by the spray can be seen in the study from Strots et al [15]. The temperature on the wall dropped about 20 ˚C when dosing started and stayed at a fairly constant level as long as the dosing was active.

2.8.3 Geometry dependence of formation and decomposition

The geometry of the exhaust system around the place where the injector is positioned has to be optimized to decrease the risk of deposit formations. It is advised to place the injector in a way that avoids spray impingement on the walls. As far as possible it is suggested that the spray should be sprayed into the gas stream so that the droplets can follow the gas flow easily. This can be done by mounting the injector in an S-shaped pipe where the spray is injected into a straight pipe. [16].

An important aspect when designing the piping around the injector is how much the exhaust gases will recirculate back into the mounting boss of the injector. An area with high recirculation is a low pressure zone where the temperature quickly drops which increases the risk of formation of urea deposits in that area. Computational fluid dynamics can be used as a help to avoid recirculation where the behavior of the gas flow can be calculated and visualized.

The distribution of ammonia on a cross-section of the SCR catalyst should be as even as possible to utilize as much of the catalysts capacity as possible. Therefore it might be of interest to use a mixer to help mixing urea with exhaust gases. A mixer is a device that is mounted in the exhaust system to make the flow turbulent so that the vortices in the turbulent flow mix the gas and urea better. The mixer can in some cases be used to break up the urea spray into smaller droplets by letting the AdBlue spray hit the mixer [16]. Instead of using a mixer the spray could be directed towards a substrate, which is then acting as a mixer. The surface temperature of the mixer will experience the same cooling effects explained in Section 2.8.2. when there is

impingement on a hot surface, introducing a mixer can increase the risk of deposit formation in the system.

2.9 Heat transfer

By transferring thermal energy from the exhaust gasses to the injected AdBlue, evaporation of the water and decomposition of urea is made possible. Increasing the liquid dispersion over the substrate enhances the ability to transfer sufficient amount of heat to the liquid from the gas. The energy needed to decompose a certain amount of fluid is determining the amount that can be injected in the system.

2.9.1 Conduction

Conductive heat transfer describes energy transfer through motion and interaction between molecules in a substance. The energy is transferred from more energetic particles to less energetic neighboring ones, these atomic particles which transfer energy could be atoms, molecules, electrons etc. Conduction of heat can occur in solids, gas and liquids with differences in how the energy is transferred within the state of the material. Thermal conductivity is material specific, depending on the properties of the material.

Heat transfer per unit area through conduction is proportional to the temperature gradient. The proportionality constant depending on material properties is the material thermal conductivity denoted k in equation (2.17) is used to define the equation for different materials, as seen in equation (2.17) [17].

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \qquad\qquad (\ 2.17\ )$$

2.9.2 Convection

Convection of heat is a combination of conduction and fluid motion. Motion of one fluid past another fluid or surface with a thermal gradient will initialize an energy transfer.

Convection is a complicated phenomenon to describe due to the combined effects of conduction and fluid motion. When a fluid is flowing past a surface or another fluid of different temperature the heat is conducted through the boundary layer by random motion of gas molecules near the surface of the medium being flowed past due to the thermal boundary layer build up near the surface. The heat is then transported towards or against the boundary layer [17].

When a fluid is forced to flow over a surface by an external device it is called forced convection. When a phase change occurs the heat transfer taking place is also considered convection such as vapor bubbles rising or condensation droplets falling.

The rate of convection heat transfer is proportional to the temperature difference and could be expressed with Newton's law of cooling as in equation (2.18). Where h is the system dependent heat transfer coefficient [17].

$$\dot{Q}_{conv} = hA_s(T_s - T) \qquad (\,2.18\,)$$

2.9.3 Radiation

Whenever there is a temperature above the absolute zero, matter will transfer heat by emitting energy in forms of electromagnetic waves or photons. Heat from radiation can be emitted without any media transferring the energy and may therefore be transferred in vacuum as well.

Heat transfer by radiation is proportional to the fourth power of the Stefan Boltzman constant and the equation of heat flux is then computed as in equation (2.19), σ is the Stefan Boltzman constant, ε is a non-dimensional coefficient of thermal emissivity ranging from $0 < \varepsilon < 1$, T_s is the temperature of the surface and T_∞ is the temperature of the surroundings [17].

$$\dot{Q}_{rad} = \varepsilon\sigma(T_s^4 - T_\infty^4) \qquad (2.19\,)$$

3 Method

In this chapter the experimental methodology is described including setup and measurement equipment. Theoretical calculations for heat transfer and urea decomposition is also presented.

3.1 System set-up

The system used in the experiments utilized back-ward dosing, meaning that AdBlue is injected towards the exhaust flow and onto a substrate surface. The injector is positioned so that the injected liquid is spread over as big area of the substrate as possible. After the wetted substrate a second substrate is positioned. This substrate was used to create the correct backpressure in the system. After the two substrates a production muffler was placed also with the intention to create a correct backpressure.

3.1.1 AdBlue injectors and delivering system

During the tests two different injectors were used with the same injection pressure. The difference between the two injectors was the spray pattern, both regarding number of holes and the spray angle. The first one that was used had 3-hole and a spray angle of 16˚. The spray angle is defined as the angle between the outermost visible edges of the spray if seen from the side, shown in Figure 3.1. The second injector that was used had 6-hole and had a spray angle of 53˚. To be able to compare the real value of the area on the substrate where the spray hit to the area seen in the CAD model the number of wetted cells by the spray were calculated by visual inspection.
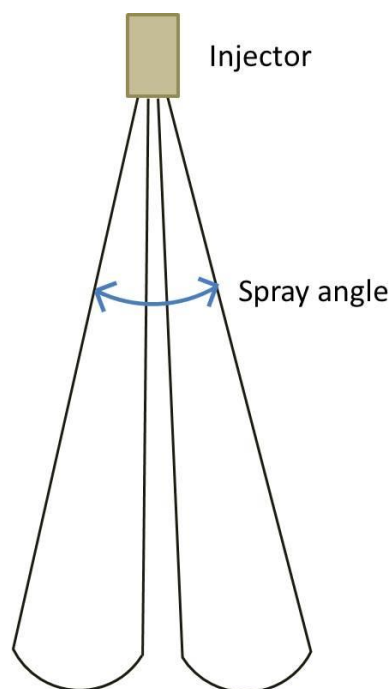

Figure 3.1 Schematic view of spray angle from the injector

Both injectors used a fixed injection frequency and to control the injected amount, the opening time of each pulse could be altered by the control algorithm. Since the

minimum opening time of the injectors gave too high dosing amount when requesting low dosing. This was compensated by keeping the injector closed for a longer period of time in between the pulses. This strategy makes the integral of injected AdBlue over time correct but the instantaneous amount will be greater.

The supply pump pressurizes AdBlue liquid from the storage tank through plastic lines to the injectors. The supply pump and the dosing control unit that was used were the same for both injectors. The dosing control unit used the same software interface, INCA PC, as the engine control unit.

3.1.2 Catalyst substrates

The substrate, which was sprayed upon, was coated with SCR type washcoat that may catalyze the hydrolyze reactions of urea break down and thereby reduce the risk of deposit formation.

The following downstream substrate was coated with inert washcoat to obtain a representative backpressure, but did not contain any active components so no SCR reaction could take place. The intention was to increase the measurement accuracy by measuring the concentration of ammonia and isocyanic acid after this substrate since the concentration is more uniform than before. For a more in-depth description of the measurement of ammonia and isocyanic acid see Section 3.3 Measurement equipment.

3.2 Engine test rig

All experiments were performed in an engine test rig at VCC and the same engine, a Medium Power (MP) - VED4, were used for all tests. Two different engine test cells were used, the first rig was Funktions Proving Dynamisk 1 (FPD1) where the engine was run without the gearbox and the dynamometer was connected directly to the crankshaft of the engine. The second rig was Transmissions Provning 5 (TP5) where the engine was connected to a manual gearbox and one dynamometer where connected to each output driveshaft from the differential. With the dynamometers it was possible to control the engine speed and load to get the desired operating point in the engine performance map. In TP5 the dynamometers measure the torque and speed on the wheels. The torque and speed on the crankshaft were calculated with the gear ratio and the known driveline losses. Before the tests were started on each engine a complete part load mapping was performed to make sure that the engines where functioning well and running according to specification.

The engine was controlled through engine control unit via an interface in the computer software INCA where all engine parameters could be viewed and changed in real time. INCA was also used to communicate with auxiliary measurement equipment such as modules for thermocouples, pressure sensors and gas analysis equipment. INCA worked as data logger so all the parameters that were monitored during a test were also logged and saved for data analysis later.

3.3 Measurement equipment

In order to collect data during experimental testing a number of sensors was installed to the system. The measuring devices are described in the following chapters alongside with the function of them and how they were implemented into the setup.

3.3.1 Temperature Sensors

Temperature sensors were installed on several places in the system but the most important ones where positioned on the surface of the substrate. By approximating where the spray would hit and calculating the possible hit area from spray simulations and injector positions it was possible to place thermocouples in the wetted area. Temperature sensors which measured exhaust gas temperature in several places on the system were installed in order to measure the temperature at the different load points at different locations. A temperature sensor was also installed on the camera used for filming in order to avoid overheating of the camera tip.

3.3.2 Gas measurement

Exhaust components were measured with an FTIR (Fourier transformation infrared spectroscopy). The measurement probe was placed downstream the second substrate in order to have sufficient mixing off the emission that was desired to measure in the experiment. The FTIR was used to measure concentrations of NOx, NH3 and HNCO in the exhaust gas. It is possible to calculate and compare the amount of produced NH3 and HNCO from the injected urea compare it with the measured amount in order to see if there are any losses in the system. The mass balance set-up for the system was used to calculate if NH3 and HNCO concentrations were less than theoretically injected.

In addition to the FTIR, a sensor to measure engine out NOx emissions was placed before the substrate by doing so the needed amount of AdBlue for 1:1 conversion of NOx could be calculated. This was done to compare the dosing used in the experiments with the dosing that was likely to be used in the production dosing strategy.

3.3.3 Optical measurement

In order to sample data about growth and gradients of deposit, an optical way of measuring the formation was needed. In order to look into the exhaust system when dosing an inspection glass was installed onto the back of the substrate-surface. The glass was installed by constructing a stainless steel collet which was welded onto the canning. For glass a fused quartz-glass was chosen which can withstand temperatures up to 1720oC.

Fused quartz has a near zero thermal expansion coefficient of 0.55*10-6/ oC which makes it very suitable for applications such as an engine where a lot of fast temperature changes is made when going up and down in load and speed, the low thermal expansion makes the fused silica resistant against cracking due to thermal shock. The glass is not thermally expanding in the same way as the metal collet in which it was fitted into does. The glass was fitted into the collet with at clamping

mechanisms which enabled the collet to thermally expand without putting tension on the glass.

The collet in which the glass was fitted into was made to fit flush with the original canning inside of the substrate so that minimal effect was made on the original performance of the system. With the glass installed, filming was made possible during injection of AdBlue onto the substrate surface.

The substrate with the glass installed can be seen in Figure 3.2 is circular and has a diameter of55 mm

Figure 3.2 Inspection glass on the substrate side

The camera used for filming the injection of AdBlue into the system was a fiber optic camera from which some fibers was used for illumination and others for filming. The camera tip had to be cooled when running at high load and rpm because of the accumulation of heat. The camera was cooled with compressed air which was blown onto the camera tip in order to cool it during longer runs at medium and high point. By installing a temperature sensor adjacent to the camera, the temperature was monitored from the control room and made sure not to rise above the specifications for the camera.

The need for good illumination was crucial when filming longer events. Due to delays in the manufacturing process and limitations in testing time a second method to provide light on the filmed surface was not possible to manufacture and assemble to the system.

3.3.4 Pressure sensors

Pressure sensors were installed before the inlet to the substrate and after it in order to measure the pressure difference over the catalyst, the sensors used were CAN-BUS-

compatible sensors. The pressure difference between the sensors was then sampled during all the experiments in order to find out if the build-up of deposits eventuallywould increase the pressure drop over the catalyst and therefore give a correlation between the pressure and deposit formation.

3.4 Energy calculations

The ability to transfer energy from the exhaust gas to the injected fluid is crucial in order to have a functional NOx reduction system. Knowing how large the area is which the spray is covering, temperature of the flow and the mass flow of exhaust gas determines how much AdBlue that is possible to inject for different engine loads. A script for calculating the possible amount of injected AdBlue was developed using Matlab.

3.4.1 Thermal conductivity calculations

Thermal conductivity was calculated using Prandtl number correlation experimentally derived, also using dynamic viscosity calculated with Sutherland formula. The Prandtl number is a dimensionless number which, describes the ratio between kinematic viscosity and thermal diffusivity. Prandtl number was calculated with an experimentally derived equation.

Dynamic viscosity with Sutherland's formula is calculated as in equation (3.1) with T_s as the Sutherland-constant, η_0 is the dynamic viscosity at a reference temperature of $25^{\circ}C$ and $T_{exh}$is the exhaust gas temperature

$$\boldsymbol{\eta = \eta_0 \left(\frac{T_0 + T_s}{T_{exh} + T_s} * \left(\frac{T_{exh}}{273} \right)^{\frac{2}{3}} \right)} \qquad (3.1)$$

Specific heat is calculated with an experimentally derived polynom which together with dynamic viscosity and Prandtl number is used to calculate thermal conductivity as seen in equation (3.3).

$$\boldsymbol{k = \frac{\eta * C_p}{Pr}} \qquad (3.2)$$

Channel size of the substrate is known as well as the mass flow over the catalyst this enables us to first calculate the density of the exhaust gases at different temperatures using the ideal gas law. Using this channel speed is calculated using equation (3.5) where $\dot{m}_{exh}$ denotes the mass flow of exhaust gasses, ρ is the density of the gasses, nr_{cells} is the number of cells in the substrate and A_{ofa} is the open frontal area of the channels. This meaning the area available for exhaust mass flow is A_{ofa}.

$$v_c = \frac{\frac{\dot{m}_{exh}}{nr_{cells}}}{(\rho * A_{ofa})} \qquad (3.3)$$

Reynolds number is calculated for laminar channel flow as seen in equation (3.6) where d_h is the hydraulic diameter of the channels.

$$Re = \frac{\rho * v_c * d_h}{\eta} \qquad (3.4)$$

An experimentally derived Graetz number is used for determining the Nusselt number correlation for the specific substrate used. Graetz number is a dimensionless number, which characterizes laminar flow in a duct and provides a measurement on the flow thermal development.

$$Gz = \frac{d_H}{L} * Re * Pr \qquad (3.5)$$

Using the experimentally derived Nusselt number the heat transfer coefficient can be calculated with equation (3.7), where d is the depth of spray penetration.

$$h = \frac{k}{d} * Nu \qquad (3.6)$$

Using these equations, the energy need for heating up the AdBlue to a specified temperature when dispersed over an area can be calculated as in equation (3.8). Geometric surface area GSA is a measurement which describes the surface per liter of catalyst combined with the penetration depth of the injected AdBlue.

$$\dot{Q}_{exh} = h * A_{hit\ area} * d * GSA * (T_{exh} - T_{AdBlue}) \qquad (3.7)$$

Total amount of dosing is then calculated with equation (3.9), where h_{water} and h_{urea} is the evaporation enthalpy of water and thermolysis temperature of urea, f_{water} and f_{urea} is the fraction of the species.

$$\dot{m}_{AdBlue} = \frac{\dot{Q}_{exh}}{(h_{water} * f_{water} + h_{urea} * f_{urea})} \qquad (\ 3.8\ )$$

The results from the heat transfer equations are possible mass flow of AdBlue which could be injected into the system. Provided that the area which the spray hits is large enough, and that the energy provided from the exhaust gasses is high enough to decompose the injected AdBlue. A crucial input to the calculations is the area estimation of where the spray hits, for a more detailed description of this see Results section and Discussion

3.5 Testing

A test plan was developed at the early stages in the project order to have a baseline for experiments throughout the project period. At first the experiments was planned out to three different sessions with the intention of trying out three different injectors and compare the performance of them. This section will describe how the operating points where chosen, how design of experiment was used in some sense to conduct non biased evaluation and how it was executed.

3.5.1 Operating points

The studied engine operation points were selected with consideration to customer usage, i.e. representing frequent load/speed lifetime duration to typical operating conditions, and simultaneously a broad span in exhaust mass-flow and temperature. Studies being made on breakdown and formation of deposit where used as a start when choosing from the frequent operating points of the engine. The reason for doing this was that the data from the testing would be representative for actual operation of the engine and the data sampled could be used for further investigations within the subject.

The operating points can be seen in Table 3.1, the points will from now on be referred to as low, medium and high point.

Table 3.1: Operating points for testing

	Low	Medium	High
Exhaust temp [°C]	228	340	455
Mass flow [kg/h]	53	162	306
Load [Nm]	57	150	300
Speed [rpm]	1376	2000	2300

An alternative testing point was developed when filming deposit formation running on the low and medium point due to that in the original engine calibration there is a significant amount of soot emissions at lower load and speeds. The reason for this was

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that EGR is used to lower the combustion temperatures and the amount of fresh air charge therefore lowering the engine out emissions of NOx.

The higher amount of soot in the emissions made the visibility through the glass worse and disabled the possibility to film through the glass during an extended time period. The solution to this was to alter the operating point by turning of the EGR and tune the engine so that the same flow and temperature was achieved as in the Low point.

3.5.2 Design of experiments

Deciding which parameters might have most significant influence on the formation of deposits and which ones to vary in the experiments was evaluated using design of experiments as a starting point where the parameters which was believed to influence the formation was evaluated by studying previous research done within the area [5].

First draft of a DOE for testing was made with a six factor trial where the factors were exhaust temp, exhaust flow, injected AdBlue, time, ambient temperature and AdBlue temperature with three levels; low, medium and high.

The first setup of the DOE was however revised after initial testing and further investigations of which factors would be possible to change within the desired levels of the DOE setup. From calculations and testing of the actual system, some of the factors were ruled out due to them not changing the response when being altered or because the possibility to change the factor enough for making a difference both in the actual system and in testing response was not significant.

From this a new DOE was designed with a three factor trial instead of the original six factors. The new factors evaluated were; exhaust gas energy, AdBlue injected and time with three levels, low, medium and high. Exhaust temperature and exhaust mass flow proved to be difficult to alter significantly when conducting the experiments. At first this was done with altering fuel injection timing and percentage of EGR. By changing injection timing the amount of residual fuel burnt outside the cylinder or late in the cycle did not produce the wanted temperature change. Altering the EGR percentage managed to change the mass flow since exhaust gas was not recirculated to the cylinders and therefore increased the mass flow over the substrate.

The DOE was used for setting up the initial test plan with a fractional factorial test plan where the dependency of temperature and mass flow was to be evaluated. After initial testing and development of calculations a de-coupling of mass flow and temperature was not possible when conducting the experiments

3.5.3 Test procedure

All tests were performed in the same way in order to have comparable results between the tests. The test started with running the engine without any dosing active to get it up to working temperature. When working temperature of 90°C in the cooling water was reached and the exhaust temperature had stabilized the dosing was started. Around 40 seconds before the dosing started the data recorder was set to sample in order to capture the initial changes for the dosing.

After the experiments were finished, dosing was switched off and the recorder was kept on to capture the end of the run. In the first test session the engine was motored

with no combustion to cool down the system faster. That was not done in the second test session since the energy in the flow during motoring could cause deposits to decompose before the system was inspected. In the second session the engine was stopped just after the dosing was stopped and then the system was cooled down by itself.

3.5.4 First session

Testing was started up in Volvo Car Corporations engine testing facilities in a rig named FPD1. The beginning of testing was spent on learning the system and setting up the equipment needed for data acquisition during testing. The testing in FPD1 was done using the 3-hole injector previously mentioned. During testing in FPD1 there was no glass installed due to delays in manufacturing. In the initial testing phase there was no FTIR installed and time was spent developing the experimental plan. The plan was not completely done prior to beginning experiments since some of the factors and responses were not sure to influence the results.

3.5.5 Second Session

Due to the need for Volvo Car Corporation to do other testing in FPD1, the second session was moved to another testing facility called TP5. The second session of testing was done using a 6-hole injector with the rest of the system mounted onto another engine of the same type.

Installation of the inspection glass was done approximately after half of the available time in TP5. With the glass installed, filming was made possible during injection of AdBlue. In the end of the second session longer experiments were done in order to see if there was deposits build up over a longer period of time and if this could be monitored. The dosing was set to the limit on what the system was supposed to be able to handle. After a trial run it was decided to decrease the amount to 85 % of what was possible to decompose. This was done due to uncertainties in the area approximations and calculations.

3.5.6 Decomposition

After running test where deposits had been detected, a method for making sure the system was clean before conducting the next test was developed. From literature [13] studies about deposit formation and decomposition it was concluded that above 400 oC all of the possible deposits formed should be decomposed with enough time, this was confirmed with test results.

The method used was to increase load and rpm and conduct a diesel particle filter (DPF) regeneration for 5 minutes. DPF regeneration adjusts engine calibration parameters so that temperature is increased in the exhaust system and over the catalyst stones.

The decomposition method was used so that repetitive trials were conducted every time, meaning that the engine was started and heated to working temperature in the same way before starting the regeneration.

4 Results

In this section the result of testing and calculations will be presented.

4.1 Tests with Injector 1: 3-hole type

First session of experiments was conducted with the 3 hole injector in engine test cells at VCC. The footprint of the injector can be seen in Figure 4.1 where the total wetted area on the substrate was measured to be 1.1 cm^2.
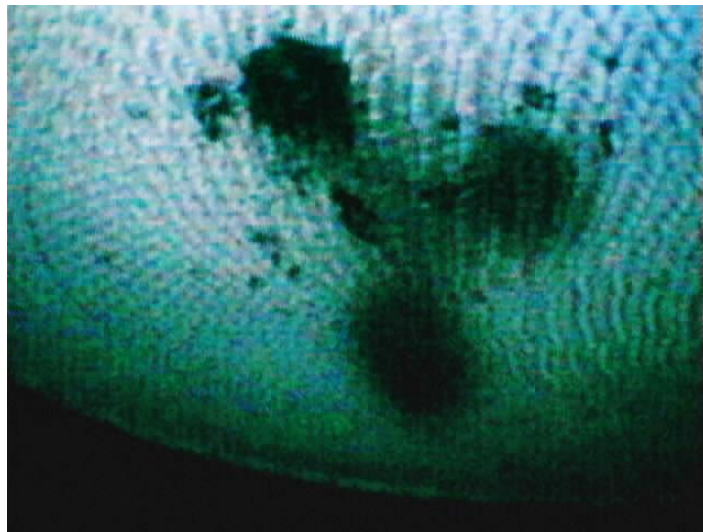

Figure 4.1 Footprint of spray on substrate surface

The amount of AdBlue that is possible to decompose depends on several parameters. Combined they determine how much AdBlue that can be injected with the energy content in the exhausts without initiating deposit formation. For the measured hit-area of the 3-hole type injector the maximum decomposable amount of AdBlue was calculated for each experiment with corresponding temperature and mass flow, see equation (3.9).

4.1.1 Low energy point

The operating point defined to have the lowest available energy in the experiments was conducted with an engine speed of 1376 rpm and produced torque of 57 Nm. This resulted in an exhaust mass flow of 54 kg/h and exhaust temperature of 225°C. Calculated amount of AdBlue that could be decomposed with the energy in the system was 1.97 mg/s, as seen in Table 4.1.

Table 4.1 Operating parameters for low point

Parameter	Value
Engine speed [rpm]	1376 rpm
Engine torque [Nm]	57 Nm
Exhaust mass flow [kg/h]	54 kg/h
Exhaust temperature [˚C]	225˚C
Maximum decomposable amount of AdBlue [mg/s]	1.97 mg/s

Initial testing started with a dosing quantity of 1.1 mg/s which corresponds to a $\frac{NH_3}{NO_x}$ ratio of 0.5. No deposits could be seen after a run-time of 30 min. Dosing was then increased in increments, first to a total of 5mg/s and later 15mg/s. Both of the experiments with increased dosing did not result in any deposits after 30 min run-time. Since no deposits were seen, the amount was again increased, at this time to 30 mg/s. After 30 min a small amount of deposits could be seen on the substrate surface. The inspection was carried out after the engine had cooled down and not in real time. As previously mentioned in Section 3.5.4, no glass was installed during these experiments.

Complete decomposition of 30 mg/s injected AdBlue would have resulted in a measured concentration of 655 ppm NH3 and HNCO. The combined concentration of NH3 and HNCO was measured using FTIR during the experiments and the results can be seen in Figure 4.2.

The total concentration of NH3 and HNCO stays fairly constant at 375 ppm when dosing, when dosing stopped a peak of 550 ppm in concentrations could be seen. This increase indicates that decomposition is taking place when the engine is motored to cool it down. Compared to the calculated value there was a loss of 45 % in concentration over the 30 min test.
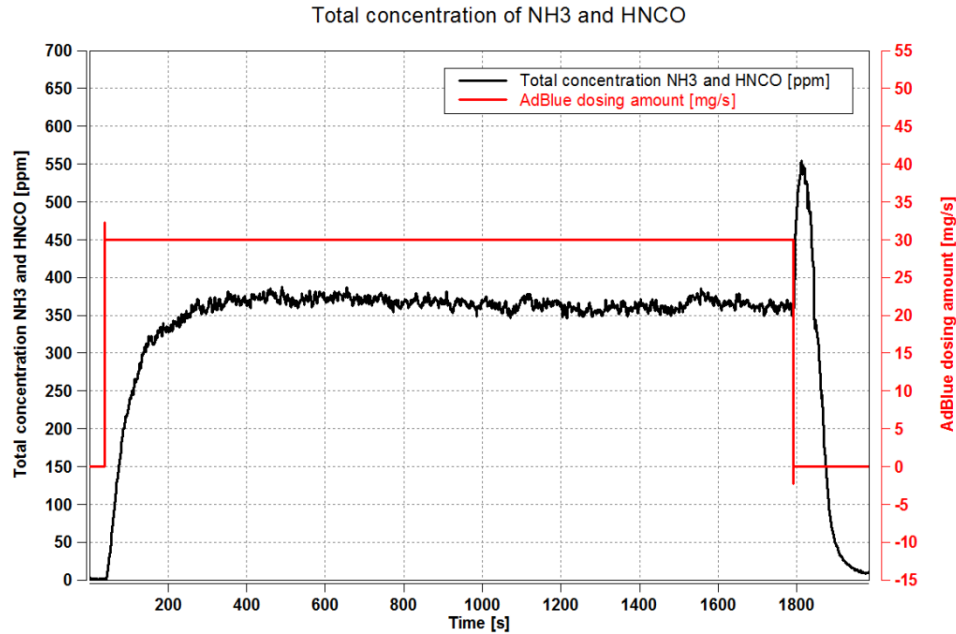
Figure 4.2 Total concentration of NH3 and HNCO at low point with 3-hole injector

When AdBlue is injected onto the system a drop in temperature is measured at the substrate surface. Thermocouples were placed so that measurements where the spray hit could be sampled, comparing it to where the spray did not hit. What could be seen was a significant drop in temperature upon the surface where the spray hit as shown in Figure 4.3. The blue line in the plot is representing the moving average of compared to the raw data. When dosing is started the temperature drops from 225°C to approximately 80°C and fluctuates with the injection of AdBlue. The temperature that the surface experience when dosing is lower than the melting temperature of urea, which can increase the risk of deposits. When the dosing is stopped the temperature starts increasing until it reaches the temperature before dosing was initialized. The sudden change of the temperature after 1000 seconds cannot be explained at the time of writing.
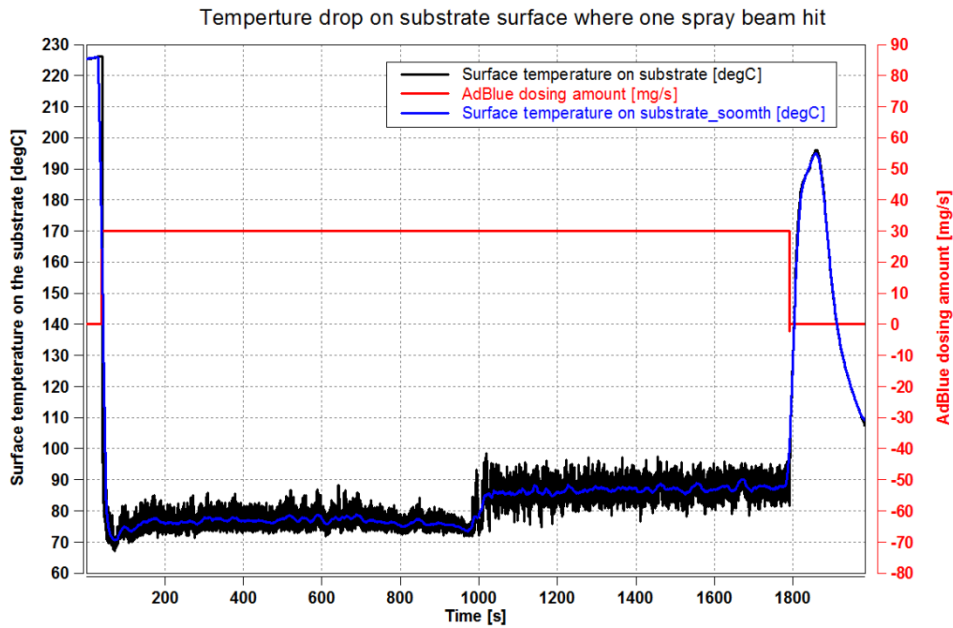
Figure 4.3 Temperature drop on substrate surface at low point with 3-hole injector

The differential pressure over the substrate was measured in order to see any change in pressure when deposits were formed. In Figure 4.4 the recorded differential pressure can be seen and it is obvious that the measurement is not correct. The data shows that the pressure after the substrate is higher than before and that is not the reality. From looking at the raw data it has been concluded that the pressure sensor mounted after the substrate was wrongly calibrated.

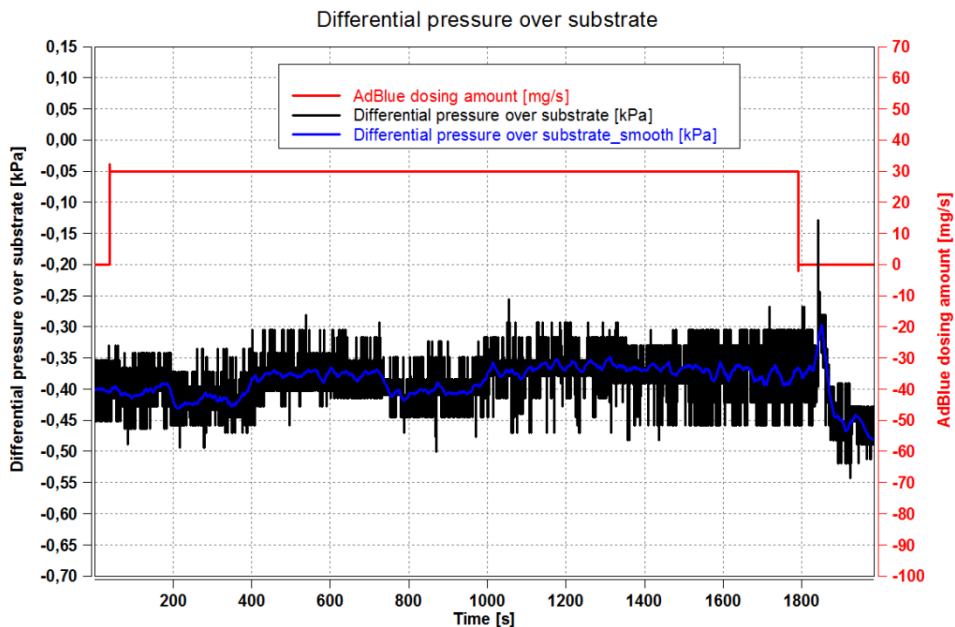**Figure 4.4 Differential pressure of the substrate at low point with 3-hole injector**

After the test the injector was dismounted and an endoscope camera was used to take pictures of the of the substrate surface. The picture, seen in Figure 4.5 in spite of the poor quality displays small amount of deposits that has been formed at the substrate

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surface. The amount is not significant and during this experiment there was not possible to see any larger formations of deposits where the spray had hit.

Figure 4.5 Deposits covering the cells on the substrate at low point with 3-hole injector

4.1.2 Medium energy point

The second point of interest was defined as the medium energy point. At this point engine speed and load was set to be, 2000 rpm and 150 Nm. This resulted in an exhaust mass flow of 162 kg/h and exhaust temperature of 332˚C.

With the calculated area that the spray actively hit at these conditions the amount of AdBlue that is possible to decompose is 8.92 mg/s. The operation parameters can be seen in Table 4.2

Table 4.2 Operation parameters for medium energy point

Parameter	Value
Engine speed [rpm]	2000 rpm
Engine torque [Nm]	150 Nm
Exhaust mass flow [kg/h]	162 kg/h
Exhaust temperature [˚C]	332˚C
Maximum decomposable amount of AdBlue [mg/s]	8.92 mg/s

Deposits could be noticed after 30 minutes into the experiment while dosing 15 mg/s. The injected amount exceeded the theoretical maximum and deposits were formed as expected. At these conditions with dosing active, a theoretical concentration of NH_3 and HNCO should be measured to 108 ppm. The actual concentration measured using

FTIR fluctuated during but had an consistent average around 90 ppm, as can be seen in Figure 4.6. The fluctuations have a periodic appearance and it shows no tendency to decay over time. The loss of mass over the test compared to the theoretical concentration is 13.5%.
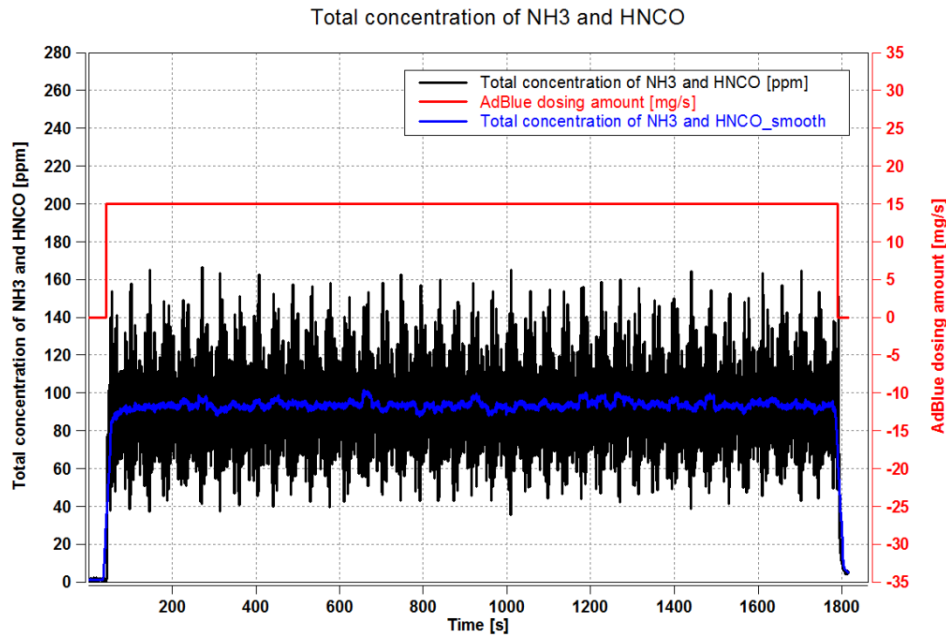
Figure 4.6 NH3 and HNCO concentration at medium point with 3-hole injector

The measured temperature on the substrate during dosing is decreasing and fluctuates around 10-15˚C corresponding with the injection pulsation when dosing. The temperature graph can be seen in Figure 4.7 there is a drop in mean value temperature 550 seconds into the experiment. This drop might be explained by deposits formed during the experiment covers the tip of the thermocouple on the substrate making it isolated from surrounding exhaust gas. Since no glass was installed it is not possible to say for sure how the formation took place during that time.

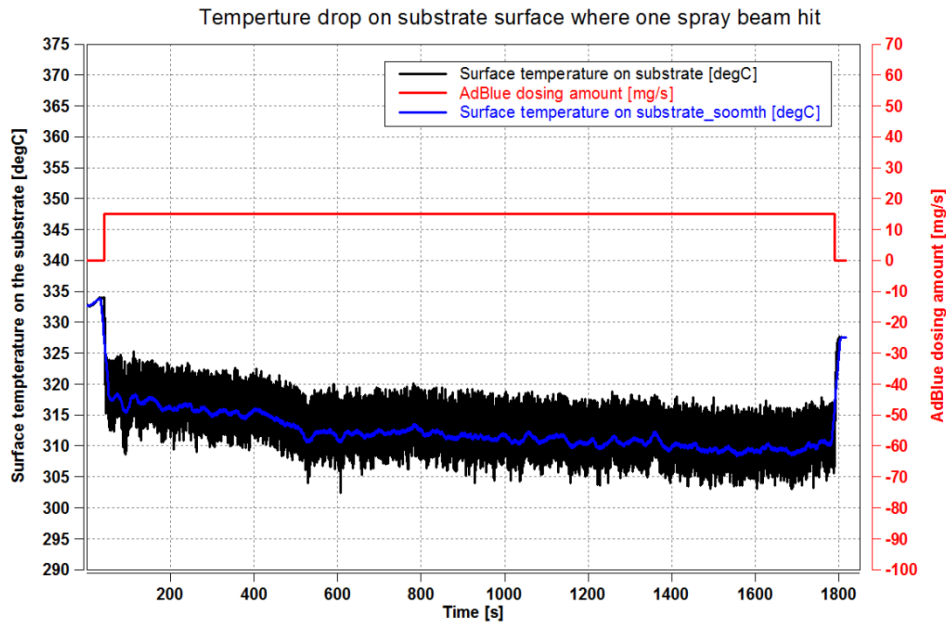**Figure 4.7 Surface temperature on substrate at medium point with 3-hole injector**

The differential pressure measurement at this operating point did display a pressure drop over the substrate. There is an increasing difference in pressure during the test but since the amount of deposits was not substantial the increase in pressure was deemed to other causes. The data can be seen in Figure 4.8 where the black line is the raw data; the blue line is a moving average over time and the red line shows when AdBlue dosing was active.

The average differential pressure increases over time with 0.07 kPa. Since the deposit is not substantial which can be seen in Figure 4.9, it is not likely that the deposit causes the increase in differential pressure over the test. Due to the characteristics of the exhaust flow from the engine a pulsating pressure is read out due to the exhaust valve opening and closing in the cylinder head.
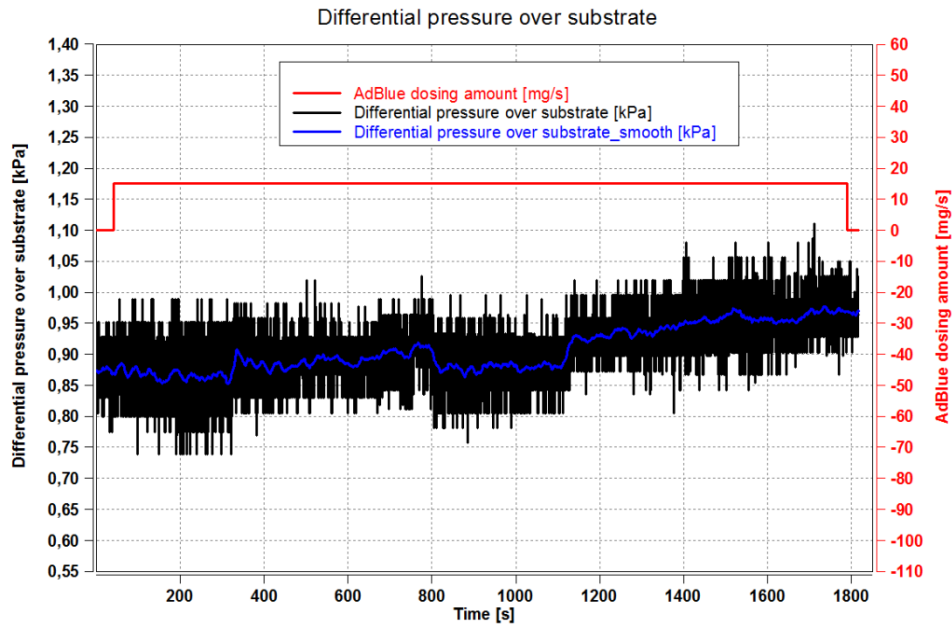
Figure 4.8 Differential pressure over substrate at medium point with 3-hole injector

The deposits are formed where one of the spray beams hit the substrate. It covers the cells as can be seen in Figure 4.9. The deposit continues to grow out from the substrate putting layer to layer onto the initial sample which enables growth in the flow direction to a thickness of approximately 1 mm. This amount of deposit is not considered severe but it can grow to become a problem if the dosing continues over a longer time period. Since there is not enough energy to decompose the injected amount of urea, the deposits will create a isolating layer between the liquid and the substrate which might increase deposit formation.

Figure 4.9 Deposit on the substrate surface at medium point with 3-hole injector

4.1.3 High energy point

This operating point an engine speed of 2300 rpm and a torque of 300 Nm was chosen, giving a mass flow of 306 kg/h and a temperature of 465˚C. With the available energy calculated, the system could decompose 23.78 mg/s of AdBlue. The experiment was conducted for 30 minutes while injecting 15 mg/s. After the test there was no deposit present. Operation parameters can be seen in Table 4.3.

Table 4.3 Operation parameters for high energy point

Parameter	Value
Engine speed [rpm]	2300 rpm
Engine torque [Nm]	300 Nm
Exhaust mass flow [kg/h]	306 kg/h
Exhaust temperature [˚C]	465˚C
Maximum decomposable amount of AdBlue [mg/s]	23.78mg/s

4.2 Tests with Injector 2: 6-hole type

The second test session was conducted using injector number 2, which is a 6-hole type injector. The injector featured a spray angle of 53˚, compared to 16˚ of the 3-hole injector; see Section 3.1.1 for more data on the injectors.

Due to the injector spray angle and position of the injector beams, the footprint on the substrate looked very different from the 3-hole injector. Four of the beams were hitting the top of the substrate but only two of them were hitting the substrate fully as can be seen highlighted in Figure 4.10.

Figure 4.10 Spray foot-print for 6 holes injector

The red rings indicate the footprint from the 6-hole injector, the three spots in the middle at the right hand side marks where the previous 3-hole injector beams hit. The two beams on the top were only hitting the substrate partially. The left one of the two top beams did not hit the substrate. The last two beams were hitting the mounting boss for the injector and did not reach the substrate surface. This lead to a calculated area of 3.27 cm2 for the six hole injector with 2.5 of the six beams hitting the substrate surface.

4.2.1 Low energy point

For this test session another engine was used, still a VED4 MP, which made for some differences in load and speed mapping in order to get the same testing conditions. The same engine speed and torque was used for the experiments, which

for the low point meant a speed of 1376 rpm and a load of 57 Nm. The mass flow and temperature differed slightly from the first engine. This engine provided slightly different values, with a mass flow of 50 kg/s and temperature of240°C. With the hit area of 3.27 cm^2 (as compared to a hit area of 1.1 cm3 for the 3-hole injector) the available energy made for a maximum AdBlue dosing of 6.91 mg/s. Operating parameters can be seen in Table 4.4.

Table 4.4 Operating parameters

Parameter	Value
Engine speed [rpm]	1376 rpm
Engine torque [Nm]	57 Nm
Exhaust mass flow [kg/h]	50 kg/h
Exhaust temperature [°C]	240°C
Maximum decomposable amount of AdBlue [mg/s]	6.91 mg/s

Experiments started with dosing 30 mg/s for 30 min with no deposits seen on the substrate, the run time was increased to 60 min, which resulted in deposits on substrate. Dosing was decreased to 15 mg/s while running for 60 min, which resulted in deposits. During the 15 mg/s test the filming worked so it was possible to follow the formation live.

The data presented in this section of the report will be from the 60 min test with 30 mg/s dosing since that test showed the most deposits. With 30 mg/s dosing the theoretical concentration of NH_3 and HNCO in the exhaust gases are 722 ppm. Figure 4.11 shows the recorded concentration measurement where the black line is the raw data, blue line is the moving average over time and the red when dosing was active.
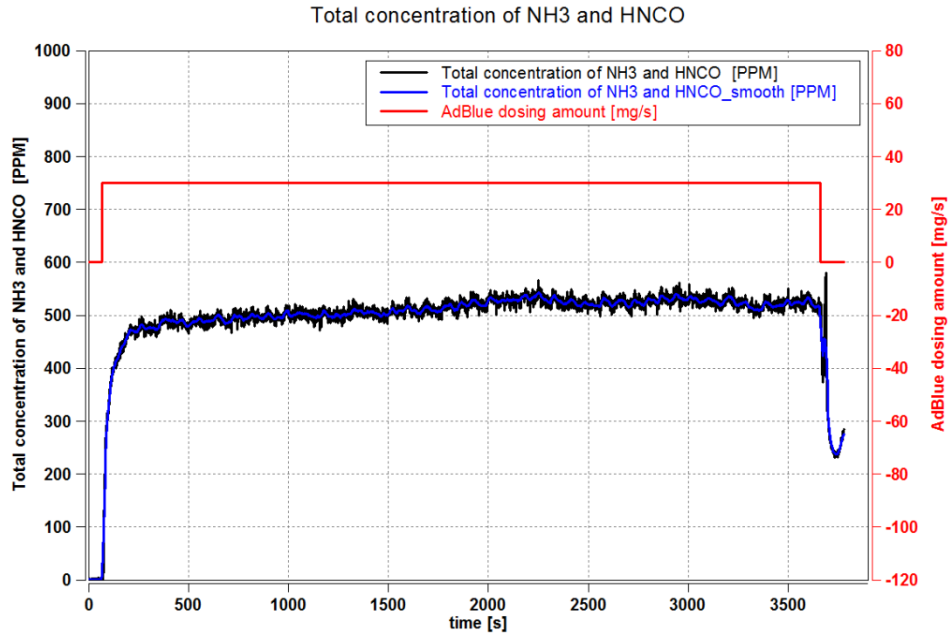
Figure 4.11 Total concentration of NH3 and HNCO at low point with 6-hole injector

A seen the average concentration stays around 500 ppm but is increasing slightly during the test. The difference to the theoretical concentration was 29.5%. It is not possible to see any trends of decreasing concentration as the theory suggests when deposits are formed. During these tests the engine was stopped directly after dosing was shut off to make sure that there was no hot air flow that could decompose the deposits before they were inspected.

The surface temperature where one of the spray beams hit decreases constantly during the experiment and the average temperature drop with 10°C from start to stop of dosing; see Figure 4.12. This indicates that the deposit gradually isolates the thermocouple during the test as the deposit builds up in size and thickness. The initial drop in temperature when the dosing is started is around 50° C and the temperature is above the melting and decomposing temperature for urea. At the end of the test the temperature did not recover to the starting temperature due to that the engine was switched of just after the dosing was stopped.
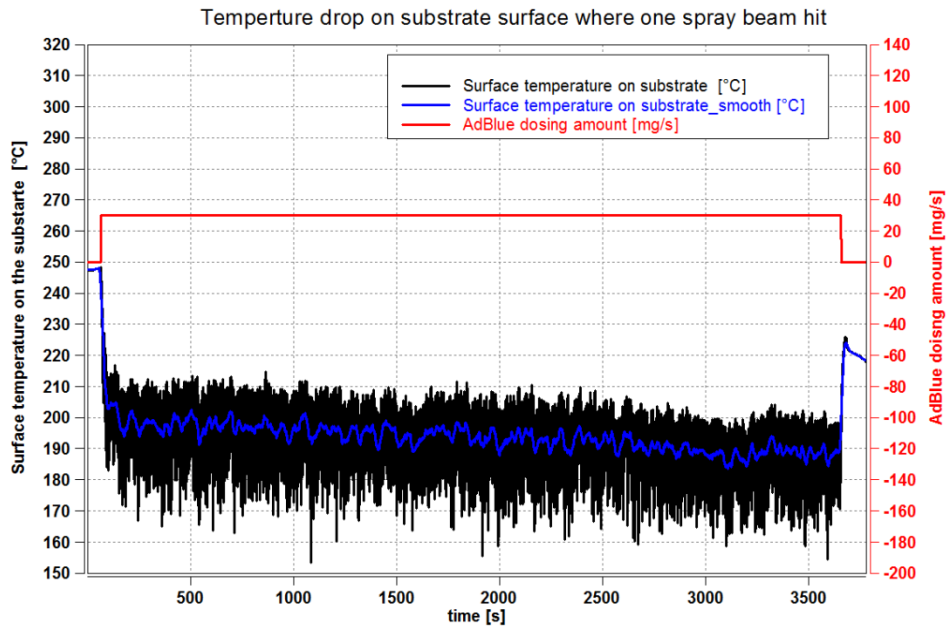
Figure 4.12 Temperature drop on substrate surface at low point with 6-hole injector

Examining the differential pressure data, in Figure 4.13, it can be seen that the moving average is close to constant over the whole test with just a small increase, of less than 0.1 kPa. The increase has a linear appearance and no sudden change can be seen. It was not possible to say if this increase was due to the deposit formation.
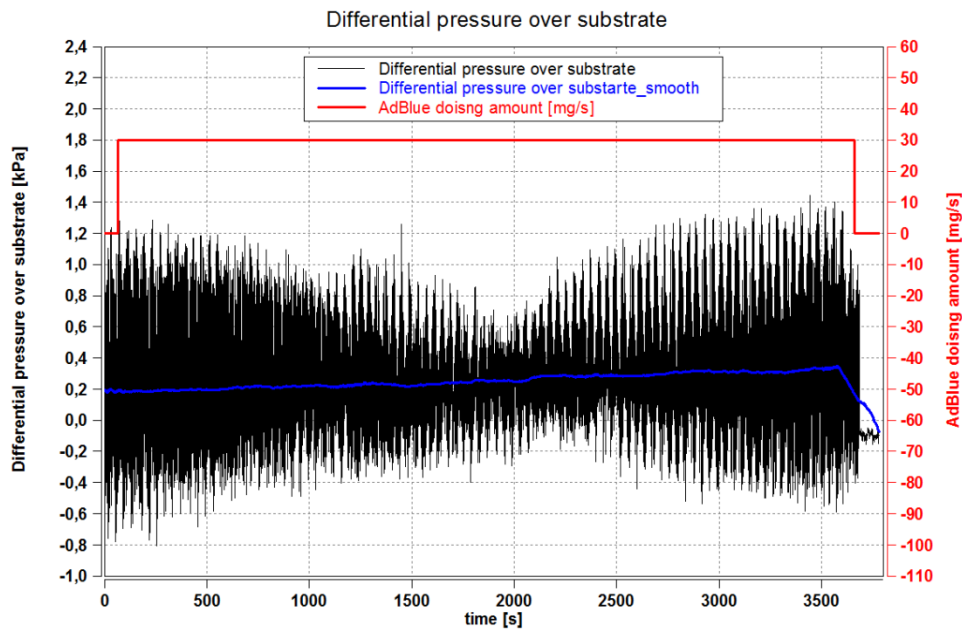

Figure 4.13 Differential pressure of the substrate at low point with 6-hole injector

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When inspecting the substrate after the test it could be seen that both the spots on the substrate were covered with deposits as can be seen in Figure 4.14. Deposits were also formed on the spot where the beam partially hit the substrate, both on the substrate surface and the sheet metal cylinder around it. The thickness of the deposits was approximately 1 mm.

Figure 4.14 Deposits on substrate on low point with 6-hole injector

4.2.2 Medium energy point

The running condition for the medium point was set to 2000 rpm and 150 Nm which rendered a mass flow of 162 kg/h and temperature of 342˚C. With the energy content available in the exhaust, possible dosing was calculated to 28.18 mg/s.

A dosing of 15 mg/s and a run time of 30 min was first tested, this resulted in no deposits. The dosing was then increased to 30 mg/s with the same run time, which gave deposits on substrate. The run time was then increased further to 60 min to see how the deposits growth was developed. Operations parameters can be seen in Table 4.5.

Table 4.5 Operation parameters

Parameter	Value
Engine speed [rpm]	2000 rpm
Engine torque [Nm]	150 Nm
Exhaust mass flow [kg/h]	162 kg/h
Exhaust temperature [˚C]	342˚C
Maximum decomposable amount of AdBlue [mg/s]	28.18 mg/s

The theoretical concentration of ammonia and isocyanic acid under these conditions is 216 ppm. Figure 4.15 displays the recorded concentration during the experiment. There is no visible decreasing trend of the concentration and it is stable at around 185 ppm. Compared to the theoretical concentration there is a difference of 13.1% over the experiment.
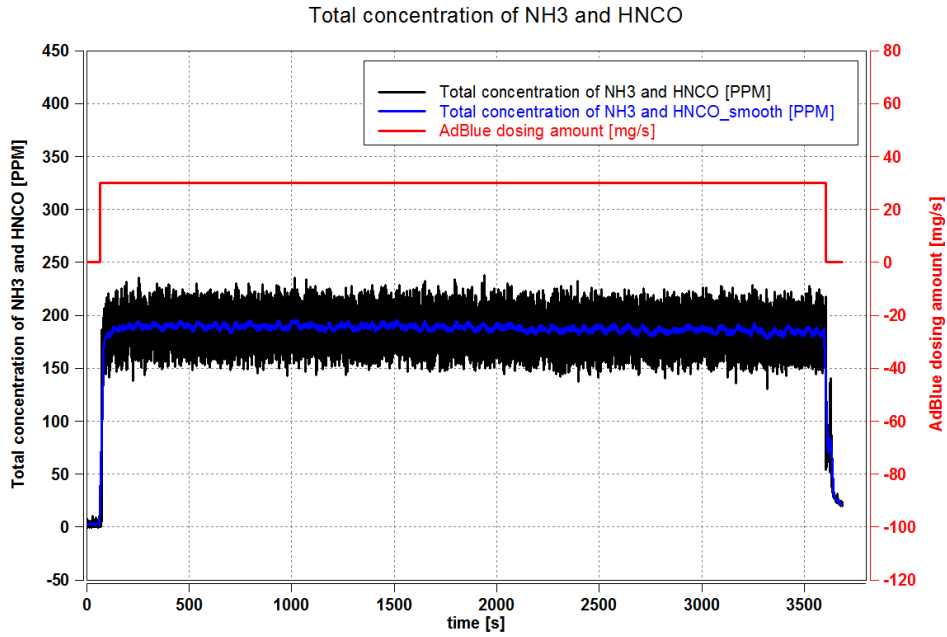
Figure 4.15 Total concentration of NH3 and HNCO at medium point with 6-hole injector

In Figure 4.16 there is a drop in temperature shown after 1500 seconds, at 2100 the rate at which the temperature drops increases even further. Comparing this to pictures taken at these time events it is clearly seen that deposit growth has begun to cover the thermocouples which in the end triggers the significant drop of 50°C.
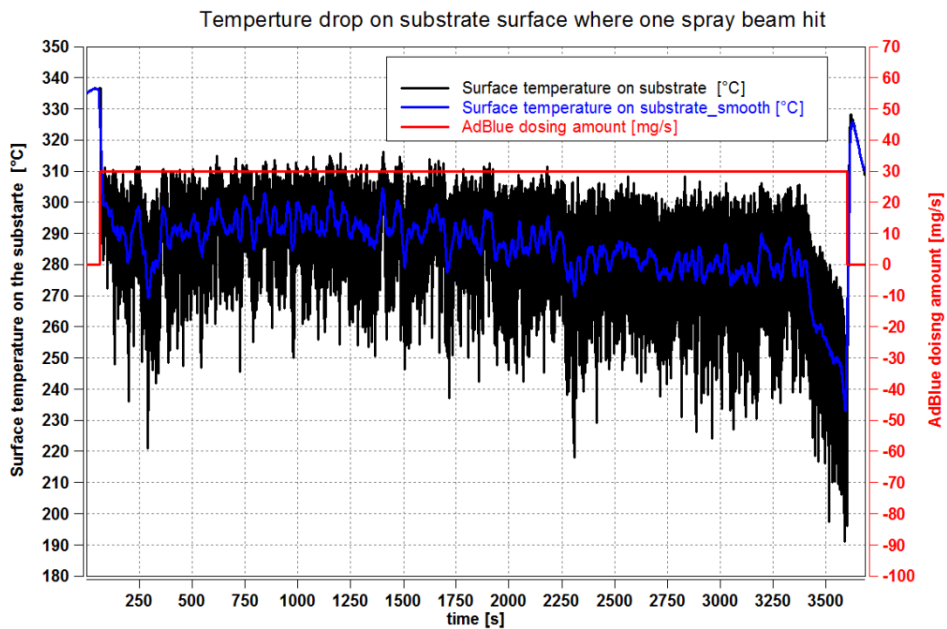

Figure 4.16 Temperature drop on substrate surface at medium point with 6-hole injector

During the experiment the average differential pressure increases slightly but it is similar to the increase that has been noticed previously. The data for this experiment can be seen in Figure 4.17.
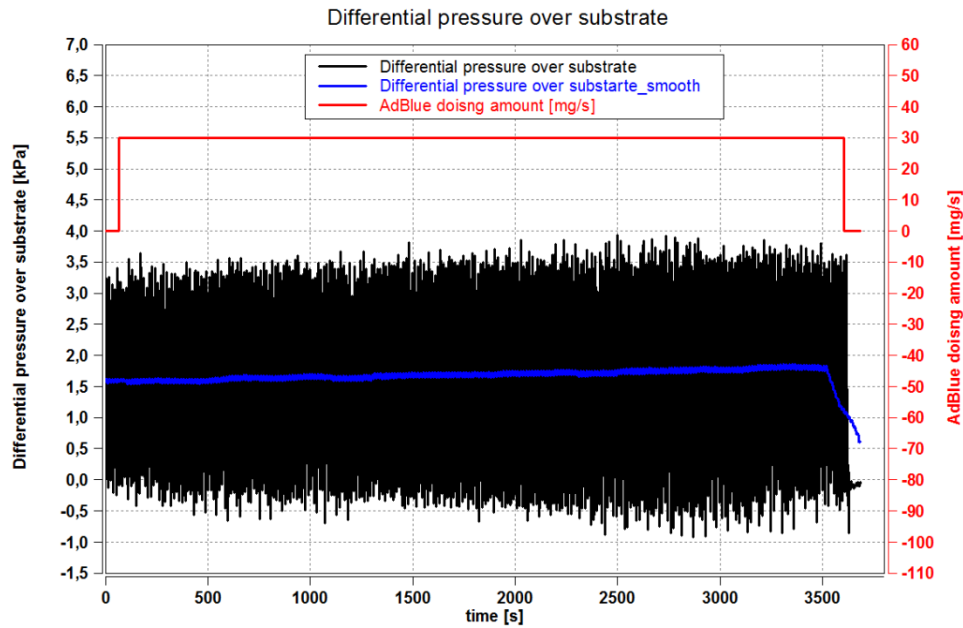
CHALMERS, *Applied Mechanics*, Master's Thesis 2014:30

Figure 4.17 Differential pressure of the substrate at medium point with 6-hole injector

To verify that the increase in differential pressure is not caused by deposits a 30 min test was done without any dosing. The results from that comparison can be seen in Figure 4.18. . The graph shows the moving average of both differential pressures, the blue line is representing differential pressure when dosing is active, the black line displays differential pressure when not dosing which acts as a reference experiment. The red line is amount of AdBlue dosed into the system during the experiment. The graph shows a small offset between the experiments with no dosing and the run with

30 mg/s dosing, but the offset is constant which leads to believe that there is difficult to make any conclusions about deposit formation dependent on differential pressure measurement.
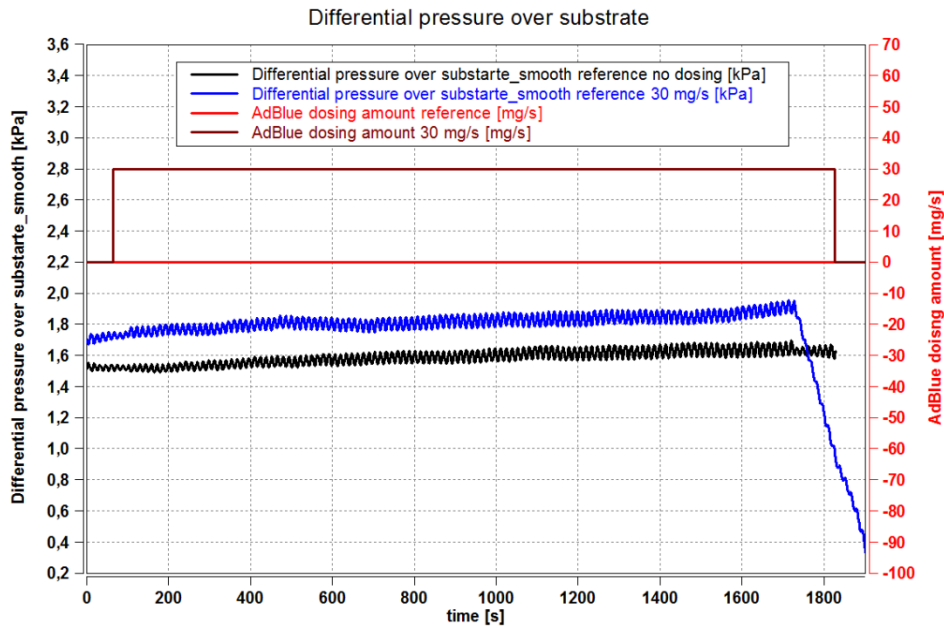
Figure 4.18 Differential pressure comparison at medium point with 6-hole injector

Figure 4.19 is showing that the deposits do not cover an extensive amount of cells and have a thickness of 1mm.

Figure 4.19 Deposits on substrate

4.2.3 High energy point

Experiments at high point were conducted with an engine speed of 2300 rpm and torque of 300 Nm resulting in an exhaust mass flow of 334 kg/h and a temperature of 453˚C. The amount of AdBlue that can be decomposed with the available energy was calculated to be 70.98 mg/s. The dosing was initially set to 73.5 mg/s with a run time of 30 min however this did not render deposits, dosing was then increased to 80 mg/s with the same run time. Deposits were not present when inspecting therefore, an experiment running with dosing amount corresponding to $\frac{NH_3}{NO_x}$ ratio of 1 in this operation point was conducted. Since this point is outside the area where EGR is used the NOX output from the engine is high so the needed AdBlue amount was 255 mg/s. The dosing was injected during 30 min, experiment was captured on film. Operation parameters can be seen in in Table 4.6.

Table 4.6 Operation parameters

Parameter	Value
Engine speed [rpm]	2300 rpm
Engine torque [Nm]	300 Nm
Exhaust mass flow [kg/h]	334 kg/h
Exhaust temperature [˚C]	453˚C
Maximum decomposable amount of AdBlue [mg/s]	70.98 mg/s

Theoretical concentration of NH_3 and HNCO when dosing 255 mg/s at the high point is 893 ppm and the recorded concentration can be seen in Figure 4.20 For the first 1000 seconds the concentration stays constant at 850 ppm, after that a decrease of 50 ppm in concentration can be seen which renders a drop in total concentration of 7.4% over the experiment. Deposits are seen on footage before the drop in concentration could be detected with the FTIR.
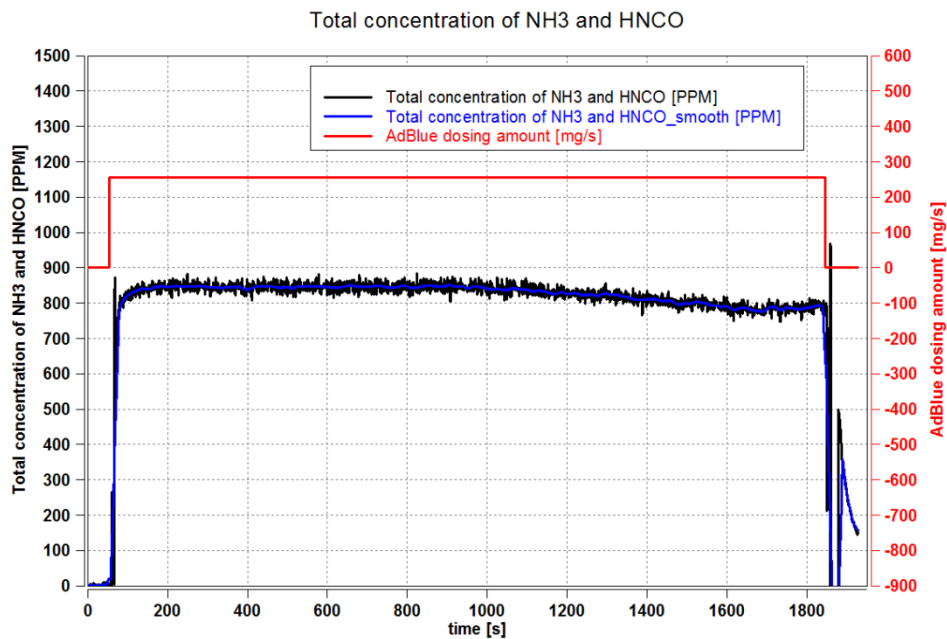

Figure 4.20 Total concentration of NH3 and HNCO at high point with 6-hole injector

The temperature drop of 350˚C is the largest drop recorded during all tests, see Figure 4.21. As seen the fluctuating behavior decreases at around 800 seconds and stabilizes at a temperature around 100 degrees which is not sufficient for urea thermolysis.
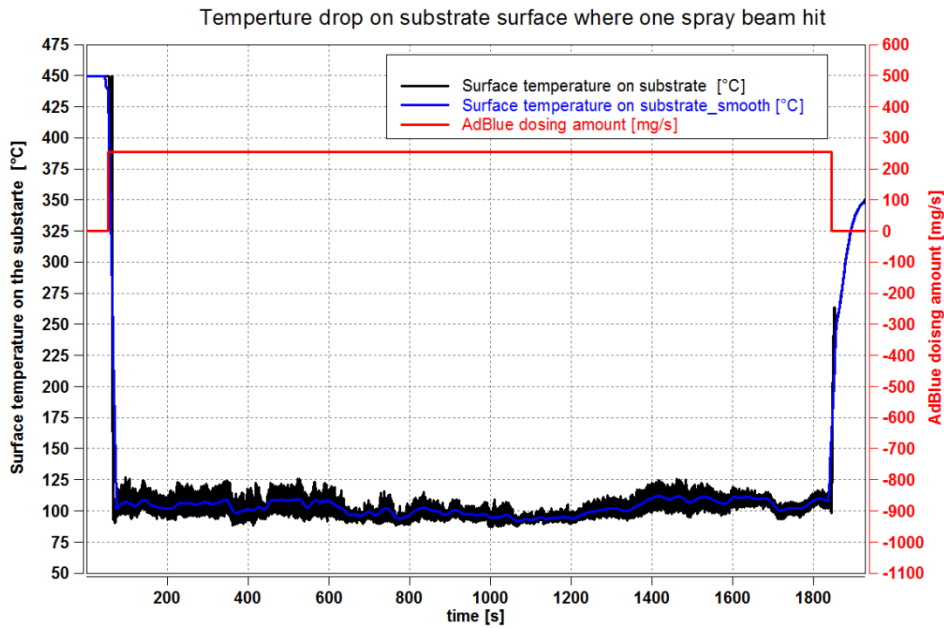
Figure 4.21 Temperature drop on substrate surface at high point with 6-hole injector

The differential pressure can be seen in Figure 4.22 with no significant change of pressure as the deposit build up on the substrate surface. The drop in floating average at the end of the sampling period is due to the engine being shut of making the calculation showing a larger value.

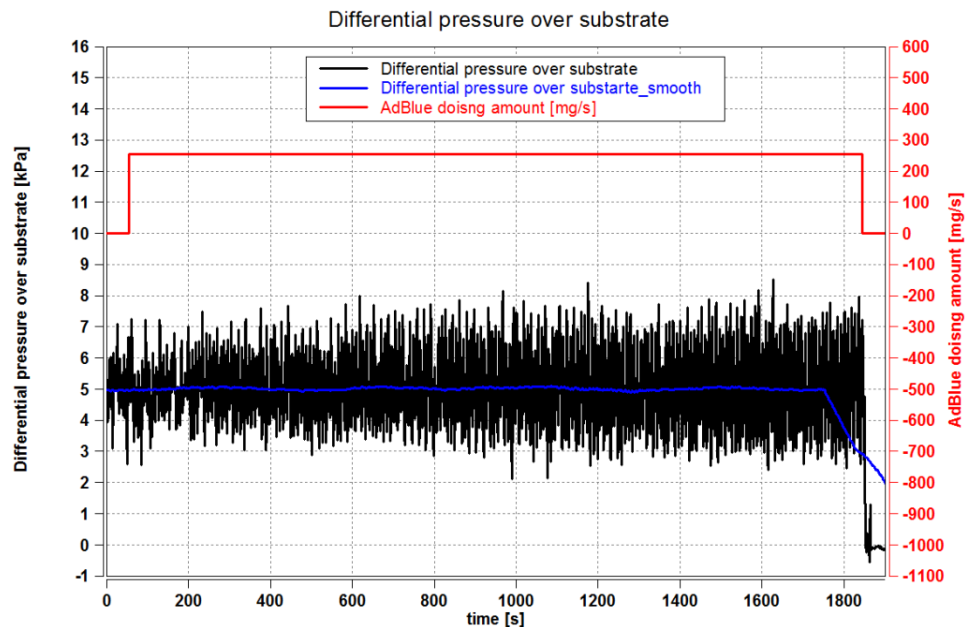**Figure 4.22 Differential pressure of the substrate at high point with 6-hole injector**

The deposits formed during this test had a thickness of 7-8 mm and was shaped as ring with a somewhat hollowed out center as seen in Figure 4.23 from filming of the build-up it can be seen that the formation of the deposits is not a linear sequence but rather exponential. Initial build-up takes longer time but continuous dosing after

initiation shows that speed of growth increases over time, making deposits formation at a higher rate.

Figure 4.23 Deposits on substrate on high point with 6-hole injector

4.3 Pulsating dosing strategy

Since the injector has a fixed opening frequency and a minimum opening time which limits the amount of AdBlue that can be dosed,. When the amount of AdBlue dosing requested is low the control algorithm for the injector will inject one bigger dose and then keep the injector closed longer. This behavior can be seen on the temperature where the spray hits, the temperature drops when the liquid hit the surface and starts to recover until the next pulse is cooling it again. In Figure 4.24 the temperature is shown for different amount of dosing, each line corresponds to one dosing quantity.
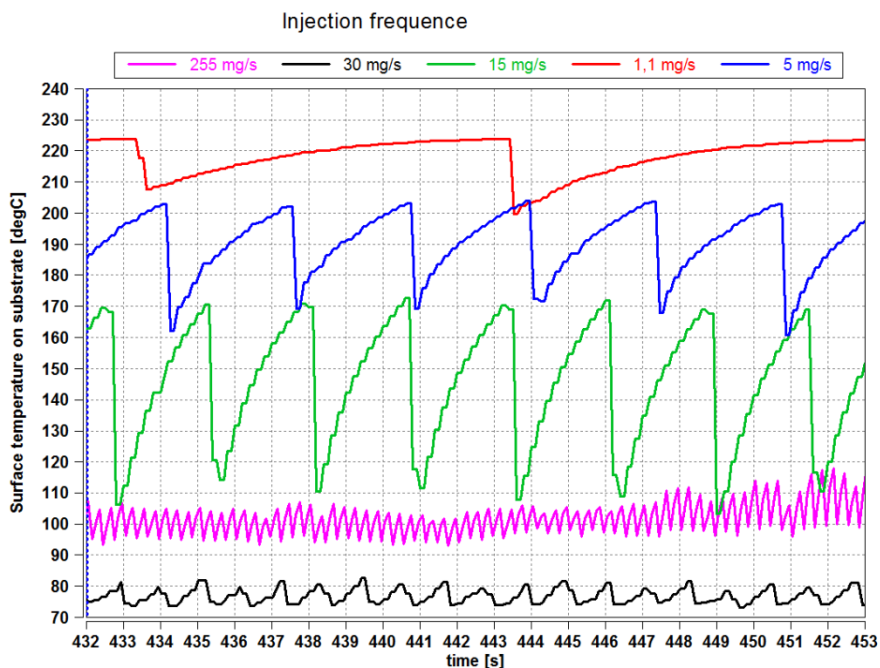

Figure 4.24 Pulsating dosing

It can be seen that the red line representing the temperature corresponding to 1.1 mg/s has a 10 seconds interval between each injection while the blue 5 mg/s and green 15 mg/s have roughly 3 seconds between each injection. As expected the largest dosing of 255 mg/s utilized the highest frequency as it has 0.3 seconds between the

injections. When there is no liquid hitting the surface there is enough time to decompose both the liquid and deposits if they are formed, when dosing is close to what the system can handle. This might increase the possibility for the system to decompose slightly more than calculated and or at least prolong the time before lasting deposits can be seen.

4.4 Initial temperature drop

The initial temperature drop on the surface when the liquid reaches the surface varies depending on the temperature of the surface. When same amount of liquid was injected into the system at different temperatures the drop onto the substrate was lower at higher temperatures. This was confirmed by the data from experiments; in in Figure 4.25 the average surface temperature for the first 150 seconds of one experiment on each operation point is shown. The dosing in all three experiments was 15 mg/s. At the low point the temperature drops with almost 90˚C but on the high point the drop is only 6˚C and in between the drop at the middle point is 15˚C.
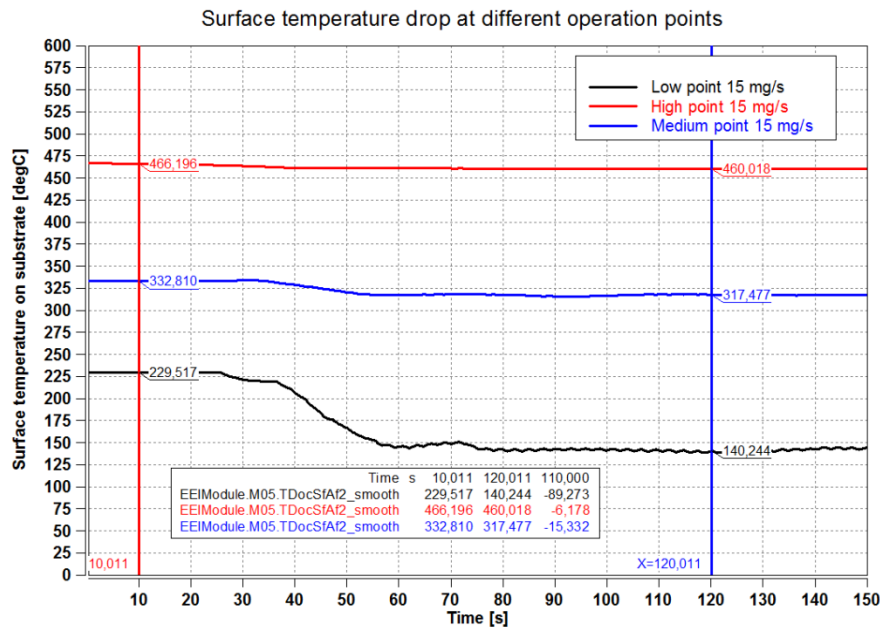
Figure 4.25 Surface temperature drop when dosing 15 mg/s at different operation points

If the starting temperature is kept constant and the amount of liquid reaching the surface is altered the temperature drop will change, larger amount injected corresponds to a bigger drop in temperature. This result can be seen in Figure 4.26 where the temperature during the first 500 seconds of test at the low point is shown. The start of injection for 5 mg/s started 130 s later that the rest of the tests. The dosing amount is varied from 1.1 mg/s to 30 mg/s and the difference in temperature drop is a couple of degrees for the 1.1 mg/s and 140˚C for 30 mg/s.

Figure 4.26 Surface temperature drop with different dosing on low point

4.5 Mass balance errors

NH3 and HNCO concentrations were sampled in order to calculate mass-balance differences between measured and theoretical value. The results from testing showed different behavior between the operating points.
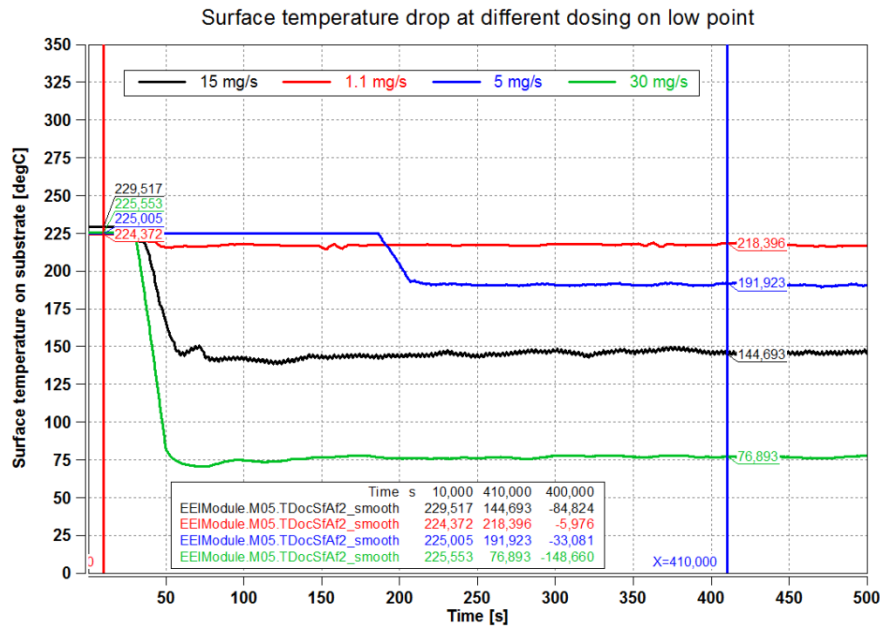
In all of the measurements done with the FTIR there was a difference between the theoretical value and sampled one. The data is presented for low, medium and high point for cases both with and without deposits.

4.5.1 Low Point

The result from testing was divided into two categories; one where there were deposits detected and one where there were not. The mean deviation from theoretical value for those two categories along with the standard deviation of this value can be seen Table 4.7.

Table 4.7 Concentration deviation on low point

	Deposits	No deposits
Mean value [%]	44.933	30.665
Standard deviation [%]	12.574	0.8305

4.5.2 Medium Point

Deviation from theoretical concentration values at medium point can be seen at in Table 4.8.

Table 4.8 Concentration deviation on medium point

	Deposits	No deposits
Mean value [%]	11.888	21.745
Standard deviation [%]	1.555	2.8991

4.5.3 High Point

Deviation from theoretical concentration at high point can be seen in Table 4.9, there is no standard deviation for the high point when seeing deposits due to insufficient testing at this operating point, only one test was performed.

Table 4.9 Concentration deviation on high point

	Deposits	No deposits
Mean value [%]	7.4	26.1
Standard deviation [%]	0	2.7955

4.6 Deposit decomposition

Deposit decomposition was studied after testing when deposits had been formed during the experiments. The decomposition was done using the method described in Section 3.5 Testing. The decomposition of deposits was studied for two cases after running on the low point with two different dosing amounts and running times. The two cases can be seen in Table 4.10

Table 4.10 Operation parameter for deposit decomposition

	Running Time	Dosing
Low Point	180 min	7 mg/s
Low Point	60 min	15 mg/s

The amount of deposits collected can be seen in Figure 4.27 for 60 and 180 min respectively, the amount was during visual inspection deemed to be approximately the same for both cases. The sequence of decomposition was filmed with the fiber-optic camera and is available for VCC.
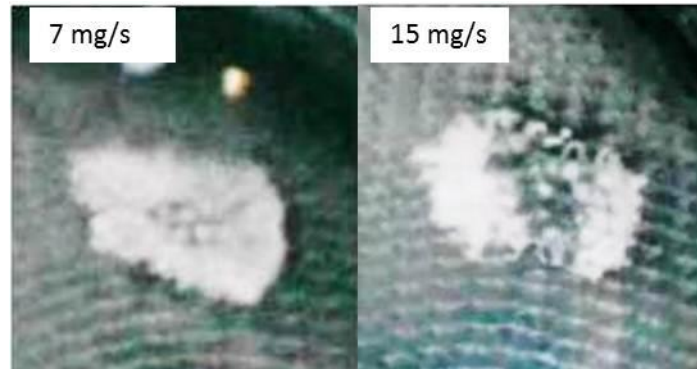

Figure 4.27 Deposit amount before decomposition

4.6.1 60 min 7 mg/s

Decomposition sequence was initialized by starting the warm-up of the engine at 2300 rpm and 300 Nm. In Figure 4.28 28 the sequence of decomposition is shown with a spacing of one minute, going from start to completely disposed. The exception being the last picture in the sequence where there is spacing with 2.5 minutes in between since decomposition of the very last traces is slower.

This is showing start of engine warm-up sequence where particle filter regeneration started after approximately 4 minutes. Following the time sequence in Figure 4.28 it can be seen that almost all of the deposits are decomposed after 4 minutes. After 7.5 minutes all is gone after just having to run 2.5 minutes of regeneration. The test was performed with no dosing active, going a step further would have been with dosing still active. The focus however was on finding a method for decomposition of deposits and to find the required time for doing so.

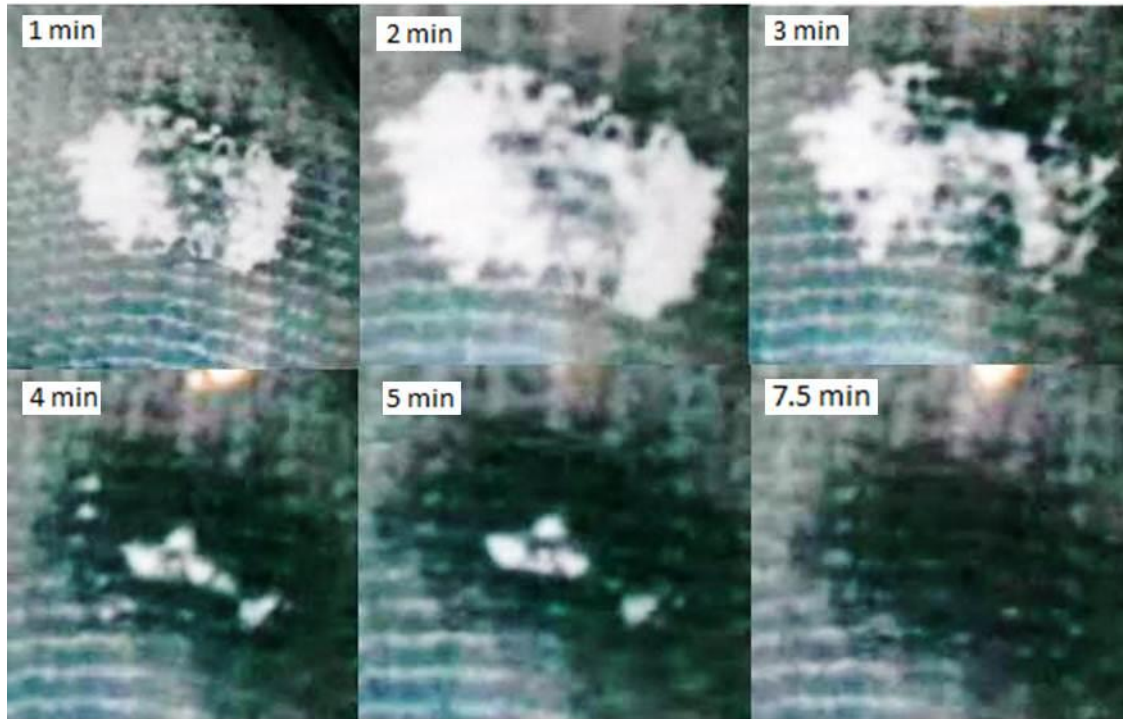**Figure 4.28 Deposit decomposition**

4.6.2 180 min 15 mg/s

The method utilized for the decomposition was the same as for previous case and the evolution is displayed with one minute intervals except for the last picture in the sequence which has a two minute gap. Most of the decomposition is done when the regeneration starts at the four minute mark. The sequence of decomposition can be seen in Figure 4.29
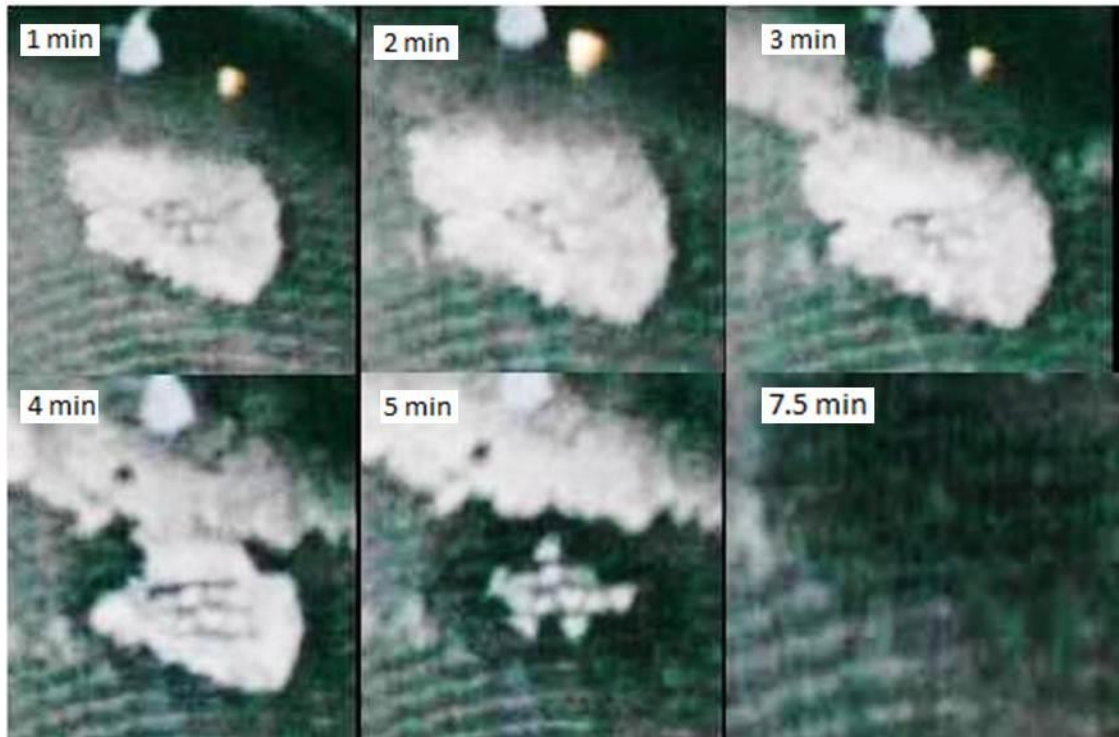
Figure 4.29 Deposit decomposition

4.7 Mass flow, temperature and area influences

experiments was limited, a model for calculating the separate influences was developed. Heat balance and energy calculations on how much energy would be needed to decompose the injected AdBlue was done. The influence of the different parameters that affect the decomposition was studied by keeping them constant one at the time. The three parameters studied was: mass flow, temperature and area. This was then used for making an analysis on how sensitive the system is for a change of respective parameters.

In Figure 4.30 and Figure 4.31 surface plot is shown for how change in temperature and mass flow will affect the amount of AdBlue that is possible to inject with the constant area of the two different injectors.

The different parameters which influence the amount which can be injected into the system is displayed in Figure 4.33, Figure 4.34 and Figure 4.35 where it can be seen how big of a response is given for a change of parameter value.
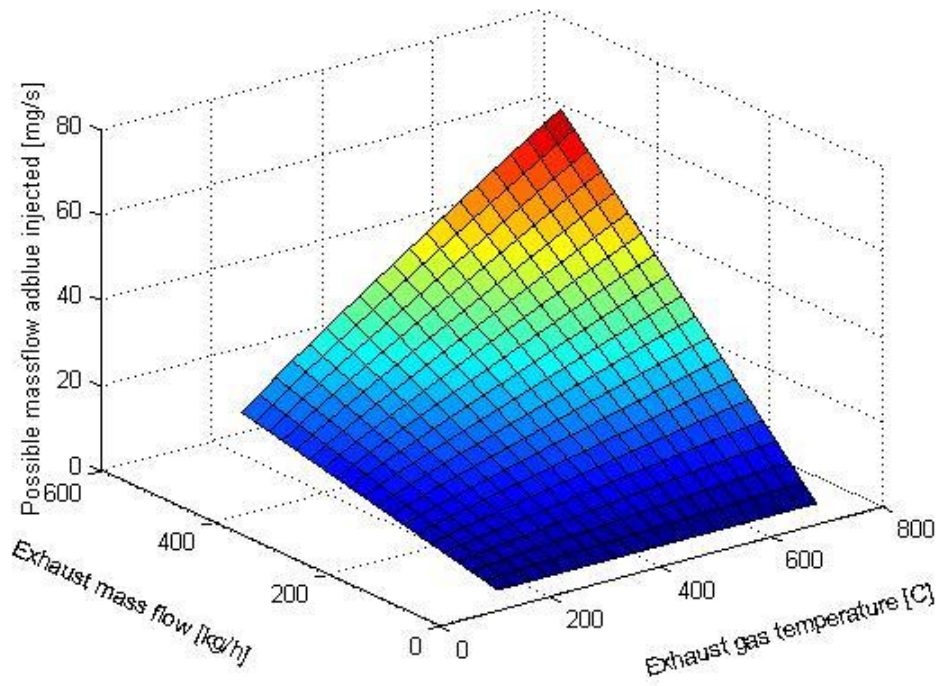
Figure 4.30 Possible amount to decompose with the available energy for three hole injector
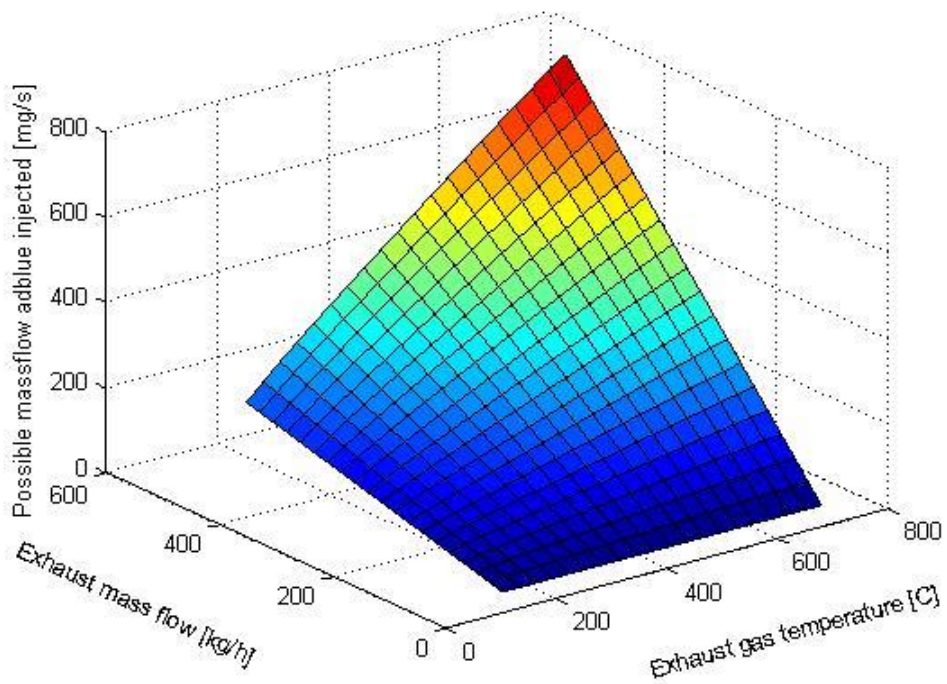
Figure 4.31 Possible amount to decompose with the available energy for six hole injector

4.7.1 Mass flow influence

In a plot for how change in exhaust mass flow affect the possible amount to inject when temperature and hit area is kept constant. A temperature of 340 ℃ was kept constant with a hit-area of 1.1 cm2. In Figure 4.32 the mass flow of the operating points previously mention in the study are displayed as vertical lines.
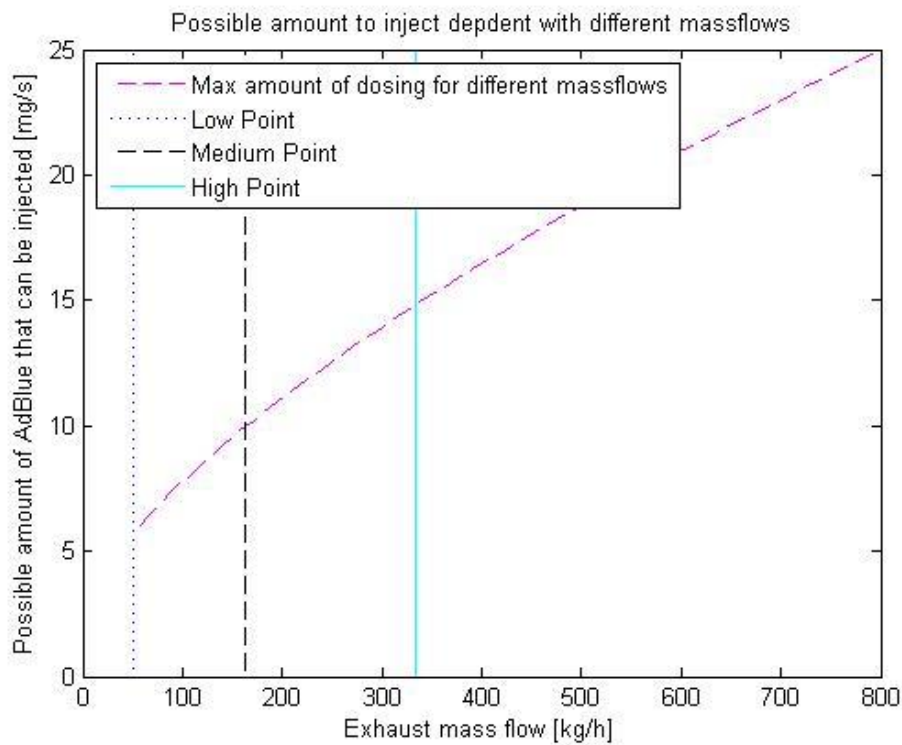
Figure 4.32 Mass flow dependency with injected amount

4.7.2 Temperature influence

In Figure 4.33 temperature influence on dosing is displayed when mass flow and hit area is kept constant. Mass flow was kept constant at 155 kg/h and the area was kept constant at 1.1 cm². In Figure 4.33 the temperature of the operating points is displayed as vertical lines.
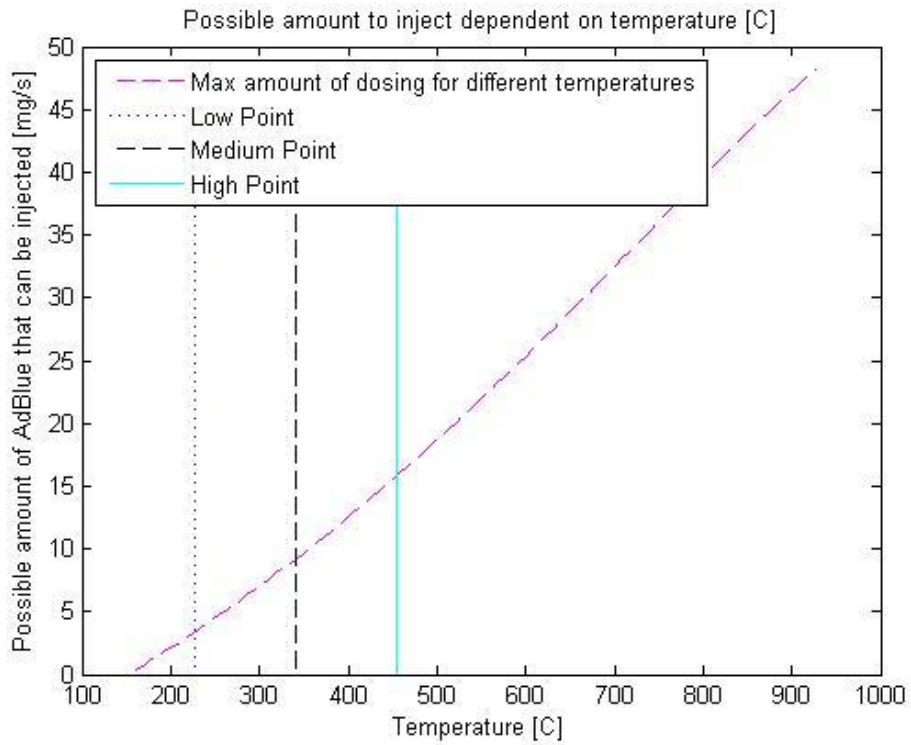
Figure 4.33 Temperature influence on injected amount

4.7.3 Area influence

Figure 4.34 displays how change in area affects the dosing amount for constant temperature and mass flow. Temperature and mass flow was kept constant at 340 ℃ and 155 kg/h respectively. Figure 4.34 the lines is representing the different hit-areas for the 3-hole and 6-hole injector.
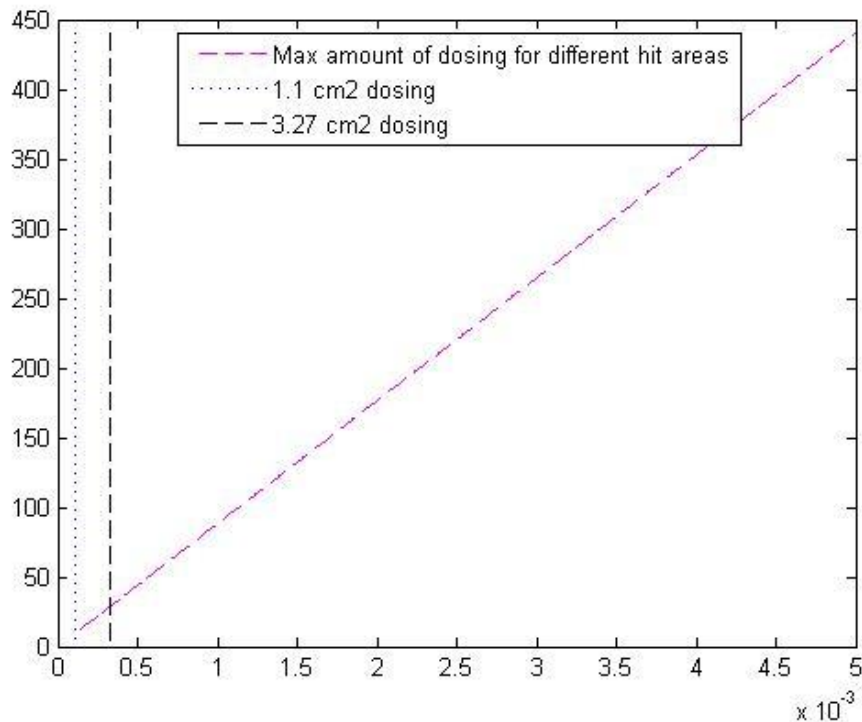
Figure 4.34 Area influence on injected amount

4.8 Filming

Filming onto the substrate with a fiber optic camera worked well for some of the operating points and for shorter test runs. The reason for this being that the injector mounting design was not optimized for the injector utilized in the second testing session. This was when the inspection glass had been installed.

For filming at low points the EGR valve had to be shut off completely and an operating point with the same exhaust flow and temperature as when having the valve open was calibrated. By doing this the view from the glass became less obstructed by soot during the longer experiments.

When running for longer time with the 6-hole injector a problem with the vision became evident, two of the spray jets were hitting the injector boss closest to the wall of the catalyst canning. This meant that AdBlue eventually started to run down the inside of the canning reaching the glass where it got stuck onto the glass, obstructing the view Figure 4.35 displays the view from early in the test and later after some time when the accumulated AdBlue had disrupted the view, disabling the possibility to get clear footage of injection sequence.

Figure 4.35 View from camera in the beginning of sampling and after some time

5 Discussion

5.1 Mass Balance and concentrations

The initial plan with measuring concentrations of primary NH3 and HNCO was that a mass balance could be calculated over the catalyst giving a measurement of how much of the injected AdBlue was lost in the system. If there was a drop in concentration it could mean that deposits were formed and that the difference in concentrations between theoretical and the measured value was seen because of this.

In all experiments an offset between the theoretical value and the measured one was seen even when there were no deposits detected during the test or when inspecting afterwards. The expected drop in concentration over time was not seen when deposits was formed and the response. One trend was that the difference between the theoretical and the measured value was lower when deposits were formed but kept a constant offset. This was seen for all points except the low point where the difference from theoretical concentration was higher when deposits were formed.

A reason for this could be that the NH3 that is formed when decomposing the urea is oxidizing on the substrate surface which would mean that the offset seen is due to NH3 and HNCO being decomposed into other species and not forming deposits. Another explanation could be that the NH3 is reacting with NOX and is reduced that way but the measured concentrations of NOX in and out showed that there was little reduction of NOX from engine out, to tailpipe measurement. For the low point, if NH3 is not oxidizing due to the low temperature. The drop in concentration could be explained by more of the urea tied up in deposits.

The exception from the constant offset in concentration was when dosing alpha value of one at high point when a drop in concentration could be seen after 1000 seconds, see Figure 4.20. The drop in concentration that is seen does not correspond to when deposits are formed. On the footage from this experiment deposits is seen before the drop occurs which indicates that the FTIR could not detect changes that indicated start of deposit formation.

Difference in theoretical concentration and the measured one was less when detecting deposits at medium and high point. An explanation for this might be that when deposits are built-up there is less risk of NH3 oxidation due to the lower surface temperature on the deposit surface itself. The loss seen might then better correspond to the loss in concentration from the theoretical value. At the low point however the temperature relationship is as expected, the concentration drop is higher when deposits are present. The temperature in the system is maybe low enough avoid an eventual oxidization of NH3.

5.2 Energy and heat balance calculations

Equations for heat balance were validated with experiments. Possible amount to inject with the specific hit area, temperature and mass flow was evaluated by seeing if the equations matched tested values.

three hours and with 85% of maximal possible dosing showed that there still was deposits on the low point and the medium point. The system is very sensitive for a change in area and this could be a possible explanation for having deposits when conducting these experiments. The hit area might be smaller and therefore the ability

of decomposing urea is less. The dosing amount of 85% was chosen since the calculations and measurements for hit-area were difficult to measure accurately. The injector boss was not positioned in the exact way as designed after manufacturing of the system, which made the calculations of spray hit area inaccurate. Instead visual inspection of the wetted spray area was utilized to approximate the hit-area. In the calculations a uniform concentration was assumed where the spray hit. This might be a source for error since hit area and concentration probably changes with mass flow due to higher gas momentum compared to spray droplet momentum.

The experiments when running three hours and dosing the possible decomposable amount according to calculations still initialized deposit build-up at the low point. The reason for this might be that there are some parameters which provide an inaccurate input to the calculations, the area is typically one of those. Since a small change in hit area has a large response on possible injection amount, a small error will drastically change what is possible to inject.

Accurate input on hit-area for calculations is needed in order to make a better prediction on deposit formation. In order to provide this an accurate way of measuring the area by either spray simulations or testing could be done. A possible way of testing hit-area could be that an injector is positioned according to the same parameters as on the real system. Then sprayed upon a surface which absorbs the liquid and afterwards measure the wetted area. To capture the influence of different mass flows, the experiment could be set-up in a tube with an added flow for simulating the exhaust flow of the engine.

A good estimation of wetted area this would provide a better input for the calculations and prediction of deposit formation. Other parameters that are material specific were not evaluated but might improve the accuracy of the predictions.

5.3 Deposits formation and decomposition

During the first test session the engine was motored by the dynamometer after the experiments was completed in order to cool the system down quicker. By doing this the engine was pumping air through the system without any combustion. Even if the temperature of the gasses were lowered, it will probably have been enough energy in the gasses to decompose some of the deposits that might have been built up during the experiment. When the glass was not installed it was not possible to see if there were any deposits formed during the run that decomposed when motoring. This can be one explanation to why it was possible to inject 30 mg/s at the low point with the 3 holes injector without seeing any deposits.

The laboratory studies that were performed on decomposition of urea showed that the decomposition of deposits was finished at around 400˚C. At the high point the temperature was 453˚C when injecting urea, still it was quite a sustainable amount of deposits formed the operating point. This indicates that even if the temperature of the gas is high, the cooling effect from the liquid hitting the surface can be enough to start deposit formation. As an example, in Figure 4.21, the recorded temperature drop during test on the high point with 255 mg/s dosing was around 350˚C, lowering the surface temperature to 100˚C which leads to an increased risk of deposit formation.

5.4 Temperature drop

Results recoded from experiments shows a significant drop in surface temperature when AdBlue is injected onto the surface. The total energy consumption for performing hydrolysis and thermolysis of urea and water results in a temperature drop of the surroundings due to the need of energy to perform these operations. This could be seen in the experiments where a drop in temperature was measured when injecting into the system. When deposits began to cover the tip of the thermocouple an isolating effect could be studied where the lowered temperature suggested that once deposits had started to grow the formation accelerated. The samples from the thermocouples can be used as measurement of deposit growth, but it is restricted to measure the propagation over a certain area. From that data a map could be created where it is possible to track when the temperature drops, to see how the deposit is propagating over the area. This method has limitations since it needs several thermocouples and they have to be placed quite close to each other to give good enough resolution.

Since the drop in temperature seen in some tests can be as high as 350°C, a consequence could be that the surface is cooled down to such an extent that it is lower than evaporation temperature of water and urea thermolysis temperature. When the next droplet hit the cold surface it might not be able to decompose and instead initialize a starting point for deposits growth. If the same amount of spray is distributed over a bigger area the temperature drop will be smaller and the risk of deposit build-up will decrease.

The large effect a change in area had on possible amount to decompose was shown with energy and heat balance calculations but not fully confirmed with the experiments conducted. Since there was possible sources for error in area estimation, which has been discussed previously there is not for sure possible to say if a larger spray distribution over the surface would decrease the risk of forming deposits however better knowledge of how the spray actually hit the surface would better confirm the findings in this study.

5.5 Differential pressure

From experiments it was not possible to see any correlation between the deposit formation and change in differential pressure over the substrate. Even if the number of plugged cells increased the differential pressure experienced the same behavior. One explanation for this might be that the amount of deposits was not enough to cover as many cells needed for the differential pressure to change. The fluctuating pressure from the engine made it hard to distinguish changes in the pressure. It can be easier to detect a change in differential pressure if the mass flow was even higher than the one in the experiments. Before it can be ruled out as a response measurement for deposit formation, reference test should be performed to see how the differential pressure varies without any AdBlue injection. The reference tests should be performed for all operating points taking into consideration the pressure raise caused by the particulate filter when it is filled up with soot. Since normal driving mostly consists of transient operations it will be difficult to measure a change in differential pressure in real driving conditions.

5.6 Filming into the exhaust system

Using a glass to make it possible to record the formation and decomposition live proved to be a very useful tool to detect deposits.This makes it possible to see what is happening while running and there is no risk of not seeing eventual deposits being decomposed after the experiment was finished. The glass is sensitive to contamination that may ruin the visibility. At low and medium operating point where there is a high percentage of EGR used, soot particles stuck onto the glass surface obstructing the view. Two of the injectors beams did partially hit the injector boss making AdBlue run down onto to the glass making visibility worse as the experiment was conducted. By switching off the EGR this was solved, and to get the correct temperature and mass flow, new engine operating parameters was calibrated. This solution works well when just looking at deposit formation and decomposition but is not suitable if emissions are measured since without EGR the engine produces significantly more NOX. By not having the beams hitting the injector mounting boss the glass will be much clearer since there will not be any liquid on the glass attracting particles.

When particles are stuck onto the glass reflections from the external light source could be seen. It is very likely that the camera will capture the reflection from the glass instead of what is happening on the other side. It was seen that the more light used to illuminate the substrate improved visibility on the recordings. It is therefore preferable to have several lights sources in the system. It is not possible to package another glass where a second light source can be housed but it is possible to mount a glass rod through the canning. This glass rod will then work as a fiber optic light which can feed light into the system without reflections on the glass used for filming. The end of the glass rod can be grinded to an angle that suits the mounting position so that the light is fed to the area of interest.

The camera used for filming had to be cooled during running since the radiation heat from the exhaust system heated it above its operating range. It was cooled by using compressed air blowing over the tip of the camera and therefore also on the glass. It would have been better to use a water cooled coil around the camera tip so that cooling down the glass could have been avoided.

6 Conclusions

A kinetic model for deposit formation has been started where prediction of deposit formation have been evaluated and confirmed for parts of the operating points tested.

A method for continuing testing of the kinetics for deposit formation and decomposition have been developed which can be applied for testing system performance in different aspects; this can be applied for future testing.

Influence of parameters such as temperature, exhaust mass flow and distribution of liquid has been evaluated by constructing a script where calculations on possible dosing amount are compiled. With the right inputs provided this can be used to evaluate how much AdBlue could be injected into the system.

From this several conclusions can be made:

- Deposit formation can be predicted by heat balance equations when the right input is provided.
- By distributing the spray over a larger area the risk of deposit formation will decrease for temperatures over 180 degrees
- Manufacturing tolerances for injector position is extremely important in order to get the desired spray pattern.
- Deposit formation is not linear.
- Alfa values of 1 will most probably be achievable if right spray properties and system design is applied.
- An Alfa value of 1 should be theoretically achievable if the spray is distributed over the substrate surface.

7 Future work

To improve and make the studying of deposit formation and decomposition more efficient in the future the following areas have been identified

7.1 Testing improvement

- Install a second light source that illuminates the substrate surface, preferable a fiber optic glass rod for small packaging. This will increase the quality of the films that capture the formation and decomposition.

- Mount the camera on the engine or the gearbox to minimize disturbances in the image quality.

- Since the glass was installed in the system quite late into the experiments, not too many good quality films were made. Continuation of this work is important since the films are a good tool for studying kinetics of deposit formation.

- Improve manufacturing tolerances for injector position.'

7.2 Theory improvement

- In order to see if it is possible to use differential pressure as measurement of when deposits are formed, reference data must be collected where the engine is operated without any dosing active. It should also be included how the pressure is affected by the particulate filter filling up.

- Improve the energy balance calculation by getting better data of the hit area, the actual concentration of AdBlue reaching the substrate and take into account the pulsating injection.

- Take into account gas momentum of AdBlue droplets vs the exhaust flow.

8 References

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