Institutionen för systemteknik
Department of Electrical Engineering

Master Thesis

Modeling of the Melting Process in an AdBlue Tank

Master Thesis performed in Electrical Engineering
at The Institute of Technology at Linköping University
by

Emil Klinga

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Modellering av smältförloppet i en AdBlue tank
Modeling of the Melting Process in an AdBlue Tank

Författare
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Sammanfattning
Abstract

This master thesis is covering the modeling of the melting process in a tank filled with AdBlue. Due to AdBlue freezing at temperatures below -11 °C there is a need to add heat to be able to secure dosing in all situations. A rig for simulating freezing conditions is created with the possibility to store AdBlue in temperatures down to -40 °C. Temperatures are measured in and around the tank containing AdBlue and in the equipment used for adding heat. Two models are created from physical relations to estimate the mass of AdBlue melted, a static temperature model and a dynamic temperature model. The static model shows good results when calibrated at this specific setup and is very easy to use. The dynamic temperature model is more advanced but describes the real physical system better without external calibration.

Nyckelord
Keywords

AdBlue, Melting, moving boundary

Abstract

This master thesis is covering the modeling of the melting process in a tank filled with AdBlue. Due to AdBlue freezing at temperatures below -11 °C there is a need to add heat to be able to secure dosing in all situations. A rig for simulating freezing conditions is created with the possibility to store AdBlue in temperatures down to -40 °C. Temperatures are measured in and around the tank containing AdBlue and in the equipment used for adding heat. Two models are created from physical relations to estimate the mass of AdBlue melted, a static temperature model and a dynamic temperature model. The static model shows good results when calibrated at this specific setup and is very easy to use. The dynamic temperature model is more advanced but describes the real physical system better without external calibration.

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Södertälje, September 2015
Emil Klinga

Contents

1

Introduction

This master thesis supervised by Vehicular Systems at Linköping University covers the modeling of the freezing and thawing behavior of the AdBlue solution. AdBlue is used in the after treatment system of heavy duty trucks manufactured by Scania CV AB.

1.1 Scania CV AB [6]

A Swedish manufacture of heavy trucks, buses, industrial engines and marine engines. Main part of the businesses is located in Södertälje where the research and development and head office is located.

1.2 Vehicular Systems [5] - Linköping University

A part of the department of Electrical Engineering at Linköping university. The department has research in control, vehicular systems, diagnose and modeling.

1.3 Euro 6

A standard legal framework for regulating toxic emission in the exhaust system where Euro 6 is the latest and toughest in Europe. Euro 6 has a much stricter limit concerning NOx gases in the exhaust system than previous emission levels. Euro 5 NOx emission limit allow 2.0 g/kWh compared to 0.40 g/kWh for the Euro 6 emissions [4], therefore it is essential to have a working SCR system to keep the NOx gases under control.

1.3.1 NOx

NOx is a collection name of a combination between nitrogen and oxygen created in combustion processes in particular engines and power plants. NOx is harmful for the environment and can cause harm on living beings. NOx can create respiratory effects including inflammation in the airways in healthy people, and increases the symptoms in people with asthma [3].

1.4 After treatment System

To eliminate emissions from the exhaust gases as much as possible and handle the Euro 6 legislation, Scania uses an exhaust after treatment system consisting of a Diesel Oxidation Catalyst, Diesel Particulate Filter, AdBlue Dosing System, Selective Catalytic Converter and an Ammonia Slip Catalyst. The system is controlled by Scanias 3rd Generation Emission Control System. The aftertreatment system is presented in figure 1.1. The AdBlue tank (not shown in figure 1.1) can be seen in figure 1.2.

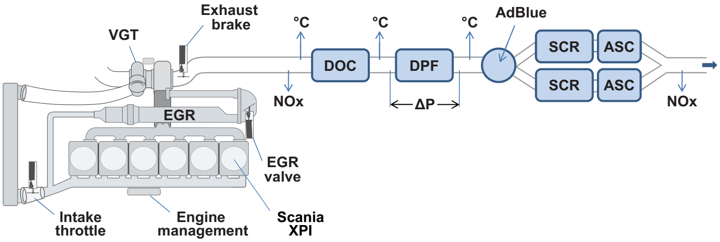


Figure 1.1: Schematic view over the engine and after treatment system

1.4.1 Diesel Oxidation Catalyst (DOC)

A catalyst that promotes chemical oxidation of exhaust gas components by oxygen, such as carbon monoxide, hydrocarbons and sulphate particles.

1.4.2 Diesel Particualte Filter (DPF)

A particular filter is as its name states a device made for removing particles and soot from the diesel exhaust system. There are a number of different kinds of filters in the range from single-use to reusable.

1.4.3 AdBlue Dosing

AdBlue is a mix between urea and water with a 32.5 % weight of urea. The concentration is chosen based on the eutectic mix to have as low freezing point as possible. The mission of AdBlue is to be a carrier of ammonia. The injection of AdBlue into the exhaust stream creates a chemical reaction with NOx creating nitrogen and water.

Figure 1.2: *Euro 5 AdBlue tank and combined heat spiral and urea delivery unit*

Figure 1.2 shows the AdBlue delivery system. The left figure is the tank mounted in today's trucks. The right picture shows the heat spiral combined with the AdBlue pick-up unit which transports AdBlue to the dosing unit.

1.4.4 Selective Catalytic Reduction (SCR)

A catalyst reducing NOx through chemical reactions. The SCR uses AdBlue as a reducing agent to reduce the amount of NOx emissions in the exhaust outlet. AdBlue is injected before the catalyst and is vaporized by the heat forming ammonia, water and CO_2. The ammonia and NOx gases mainly reacts as follows [16]:

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \tag{1.1}$$

$$4NO + O_2 + 4NH_3 \rightarrow 4N_2 + 6H_2O \tag{1.2}$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \tag{1.3}$$

1.4.5 Ammonia Slip Catalyst

A catalyst mounted after the SCR to ensure that any ammonia slip due to incomplete reaction or other causes is oxidized to NOx or nitrogen.

1.4.6 3rd Generation Exhaust Emission Control system (EEC3)

The EEC3 is an engine control unit used for controlling the after treatment systems and was introduced together with the Euro 6 Scania engines. The software for the EEC3 is developed by Scania.

1.5 Purpose

The purpose of this master thesis is to develop a model of the melting process in an AdBlue tank (see figure 1.2). The reason is to accurately estimate the amount of molten AdBlue in the tank during cold weather to be able to start dosing as early as possible.

1.5.1 Goals

- Create a Matlab/Simulink model of the melting process in an AdBlue tank based on the physical properties of the tank, heating coil, coolant fluid and AdBlue.
- Verify the accuracy of the model by comparison with data recorded during testing in climate chambers.
- Use the model to determine when AdBlue dosing can safely be started

1.6 Problem Formulation

This sections describes the problem formulation and the background from which the thesis proposal is generated.

1.6.1 Background

With current legislations according to the Euro 6 standard, Scania implements SCR with the goal to reduce NOx emissions. The system utilizes Adblue which freezes at -11°C [16] thus making it necessary to add heat to the tank during the cold season to be able to melt the solution if temperature goes below the freezing point. The heat is added via the engine coolant by leading it through a spiral located in the tank. To achieve a high efficiency thawing process it is important to have enough AdBlue in the system so the spiral is submerged and not in contact with air, therefore not dosing more AdBlue than the system is able to thaw.

1.6.2 Problem

The task is to improve the implemented model to estimate the amount of AdBlue thawed after a certain amount of time. The legislation demands that the system must be able to dose AdBlue in maximum 70 minutes after engine start [14]. Scania themselves demand that dosing should not start before enough AdBlue has been thawed to insure that the heat spiral is not isolated by a layer of air if the molten AdBlue is consumed faster than new AdBlue is thawed. Isolation will lead to the thawing of AdBlue stopping almost completely and dosing will be aborted. A problem with today´s software is that the pump starts to early and the amount of thawed AdBlue is used to fill up empty parts of the system and therefore only dries the tank and in an very early stage stops the thawing completely.

1.6.3 Model Design

The design will as long as possible be derived from physical equations describing the behavior of the phase transition during freezing and thawing.

2

Theory

This section describes the theory used in this master thesis to provide the needed information to create a model of the melting behavior of AdBlue

2.1 Heat Transfer

Heat transfer describes the energy transfer between materials with different heat or pressure. Heat transfer has three fundamental modes which are conduction, convection and radiation. These modes can occur by themselves or in combination with each other [15].

2.1.1 Conduction

Conduction is a mechanism that transfers energy while objects are in contact with each other. The basic is that a warmer medium has atoms in a higher energy state and therefore moves, or vibrates, faster than those in a cold medium. The atoms then transfers some of their energy to their neighbors in the colder medium and so on. The energy is therefore transfered between the molecules through each other. Conduction can take place in solids, liquids and gases. In a solid material conduction happens because of vibration of the molecules and in liquids and gases conduction is due to collisions between moving molecules. Conduction depends on the geometrical properties of a material such as shape and thickness.

Fourier's law gives the heat equation for heat flow through a wall as:

$$\dot{Q}_{cond} = \frac{A_{wall} \cdot k \cdot \Delta T}{b} \tag{2.1}$$

where A_{wall} is the effective area of the wall and k is the walls thermal conductivity [9].

2.1.2 Convection

Convection is a movement in a liquid or a gas created when a warmer medium give rise to a flowing motion due to changes in density between the warm and cold medium. A classic example is a normal room. The windows cools down the air which gets a higher density and falls to the ground. A heater is added under the window so the air instead gets hot, rises to the roof and cold air fills the void creating circulation of air in the room. Convection is only possible in gas or liquids due to the dependency on a flowing medium to exist.

Convection is divided into two types, natural convection and forced convection. The previous examples are of natural convection when the flow of heat happens by itself. Forced convection is for example when a fan is added to the equation creating a flow of a medium for example air, creating convection. Convection is a complex phenomena but has been observed to be proportional to the temperature differences. Newton's law of cooling describes convection as:

$$\dot{Q}_{conv} = h \cdot A \cdot \Delta T \tag{2.2}$$

where h is the convection heat transfer coefficient with unit $W/(m^2 \cdot {}^\circ C)$, A is the surface area and ΔT the temperature differences between a surface and a medium [9].

2.1.3 Radiation

Radiation is a direct transfer of energy from one medium to another. It consists of electromagnetic radiation transmitted between two bodies without the demand of a medium to conduct the heat. An example is the sun transmitting heat to the earth through radiation without any medium in between. For a real surface the radiation is [9]:

$$\dot{Q}_{rad} = \sigma \cdot \epsilon \cdot A \cdot T^4 \tag{2.3}$$

where σ is Stefan-Boltzmann's constant and ϵ is the emissivity of a body, normally a function of temperature and wavelength of the radiation. The radiation is dependent on the forth power of the temperature, which in turns means that the effect of radiation for colder bodies is negligible in comparison to conduction and convection in this particular system [11].

2.2 Overall Heat Transfer Coefficient

When working with heat transfer a lot of heat transfer processes involves both convection and conduction. Therefore it is very convenient to combine the different heat transfer coefficients to an overall heat transfer coefficient. The purpose is to estimate the heat flow from the heating spiral by a combination between the heat transfer between the liquid in the spiral to the wall, the heat transfer in the wall and the heat transfer to the surrounding medium. This is done by combining them as such [15]:

$$U = \frac{1}{\frac{1}{h_1} + \frac{x_t}{\lambda_t} + \frac{1}{h_2}} \tag{2.4}$$

where h_1 is the heat transfer coefficient between the liquid and the wall, the wall thickness x_t and the thermal conductivity λ_t describes the heat transfer in the wall and h_2 is the heat transfer coefficient between the wall and the surrounding medium.

2.3 Phase Transition

Due to the nature of this master thesis the phase transition is of interests when studying the modeling aspect. A medium consist of different phases depending on the ambient pressure and temperature. A phase transition is when the energy in the medium changes in such a way that the material changes phase. For example water has a freezing temperature of 0°C so if enough energy is added to a block of ice at the temperature of 0°C the ice will begin to melt and change state from solid to liquid. A problem with a phase shift is the so called moving boundary. When a medium is melting or freezing, the properties of the medium changes. For example, when ice turns into water the density gets higher. This creates a boundary within the material that consist of both solid and liquid phase, each with different properties. To be able to model this phenomenon a number of simplifications are needed. A number of articles are discussing this problem for example [7] and [12], and this phenomena must be simplified to achieve good performance. The goal is to have a light model that can be implemented in the engine ECU.

2.4 Reducing Agent

A reducing agent means that it is added to a compound to create a wanted reaction in this case reducing the amount of NOx gases in the exhaust flow. AdBlue vaporizes when injected into the exhaust stream leaving the water as steam and free ammonia to react with NOx gases. For AdBlue material data see table 2.1.

Table 2.1: *AdBlue material data [7]*

Melting temperature T_m	$-11°C$
Specific latent heat h_{ls}	$152.86kJ/kg$
Specific heat, solid, c_s	$1.6kJ/(kg\,K)$
Specific heat, liquid, c_l	$3.4kJ/(kg\,K)$
Density, solid, ρ_s	$1010kg/m^3$
Density, liquid, ρ_l	$1090kg/m^3$
Thermal conductivity, solid, λ_s	$0.75W/(m\,K)$
Thermal conductivity, liquid, λ_l	$0.57W/(m\,K)$
Dynamic viscosity (liquid phase), μ	$1.4\,mPa\,s$
Exponent (viscosity relation), n	1.5
Critical solid fraction (viscosity correlation), $\theta_c r$	0.4
Thermal expansion coefficient, β	$4.5 \cdot 10^{-4} 1/K$

Figure 2.1: *A sample of frozen AdBlue*

Figure 2.1 shows a sample of frozen Adblue. Liquid AdBlue has the same texture as water and when frozen turns into a crystal structure which shows a clear differences between the two states in a tank during freezing temperatures.

2.5 Resistor Analogy

This section will describe how the different mechanisms in heat transfer can be rewritten as an electrical circuit to get a good overview of the system and its behavior.

2.5.1 Heat flow

When looking at a heat transfer problem the resistor analogy can give a good overview of the problem and a more basic visualization of the mechanics driving the heat flow. In resistor analogy the temperature difference is seen as the voltage, and in the same way as in an electrical circuit, the voltage different drives the current. The current is therefore the heat flow between the mediums. Heat transfer coefficient and other similar constants are then seen as a resistor and in the same way as for the electrical circuit the voltage and current is dependent on the size of the resistors. The temperatures can be seen as stationary or dynamic in a heat system. In a dynamic system the temperature nodes are seen as capacitors with the ability to store heat and therefore detect temperature change in the heat system. The translation of the resistors are based on the same equations as for regular electrical circuits [8]:

$$I = \frac{U}{R} \tag{2.5}$$

where I is the current, U is the voltage and R is the resistance. For example, when calulating a heat flow through a wall:

$$\dot{Q}_w = h \cdot A \cdot (T_w - T_{amb}) \tag{2.6}$$

Translating the expression to electrical circuits using equation 2.5 will be:

$$U = T_w - T_{amb} \tag{2.7}$$

$$R = \frac{1}{h \cdot A} \tag{2.8}$$

$$I = \dot{Q}_w \tag{2.9}$$

The dynamic temperature model can be written as [13]:

$$\frac{dT}{dt} \cdot m \cdot c = \dot{Q}_{in} - \dot{Q}_{out} \tag{2.10}$$

where $\frac{dT}{dt}$ is the derivate of the temperature depending on time, m is the mass of the medium, c is the specific heat capacity for the medium and $\dot{Q}_{in} - \dot{Q}_{out}$ is the differers between the heat flow into the medium and the heat flow out of the medium.

3

Method

This section describes the method used to create models in the system and the experiments created to measure system properties and determine parameters for the simulations.

3.1 Heat Transfer

This section describes the heat equations derived for each different system needed to simulate the heat transfer.

3.1.1 Heat Spiral

The heat spiral uses the coolant flow to transfer heat to the tank. The coolant is controlled by an on/off valve which is opened when heating is needed. The heat flow between the coolant and the tank can be described as in figure 3.1.

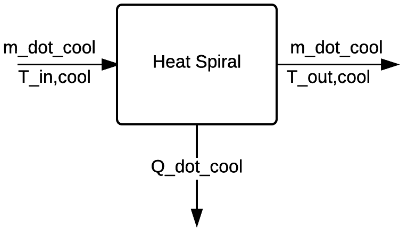


Figure 3.1: *The heat flow from the heat spiral to the tank*

The heat flowing from the spiral to the AdBlue in the tank can be writen as [10]:

$$\dot{Q}_{cool} = \dot{m}_{cool} \cdot c_{p,cool} \cdot (T_{in,cool} - T_{out,cool}) \tag{3.1}$$

where $T_{in,cool}$ is the coolant temperature into the spiral, $T_{out,cool}$ is the temperature out from the spiral, $\dot{m}_{cool}$ is the coolant mass flow and $c_{p,cool}$ is the specific heat capacity for the coolant. By measuring the temperature of the coolant in and out of the tank and the mass flow $\dot{m}_{cool}$, the amount of heat transfer between the tank and the spiral can be determined. An assumption made here is that the heat-change will only take place between AdBlue and the spiral due to the higher thermal conductivity compared to the air in the tank, which will be seen as insulation.

Unknown Parameters

All parameters are known, $c_{p,cool}$ is a constant, T_{out}, T_{in} and $\dot{m}_{cool}$ are measured.

3.1.2 Hoses and Pump

The dosing pump starts circulating AdBlue after a certain time or when the calculated mass of AdBlue reaches a certain level. The hoses transporting the AdBlue through the dosing system are electrically heated to prevent freezing. The circulation of AdBlue in the tank will help the thawing behavior by adding forced convection, so the goal in the real system is to start the pump as early as possible. The heat is added only when the pump is active and will therefore be controlled by a status parameter.

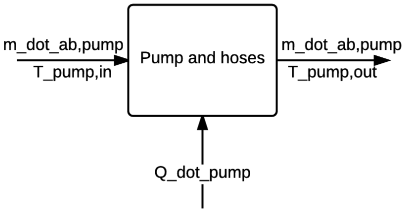


Figure 3.2: *The heat added to AdBlue through the pump*

Figure 3.2 shows the flow of AdBlue through the pump and added heat from coolant warming the hoses and heat losses from the pump. The added heat from the pump and hoses can be described as [10]:

$$\dot{Q}_{pump} = \dot{m}_{ab,pump} \cdot c_{p,ab} \cdot (T_{pump,in} - T_{pump,out}) \tag{3.2}$$

where $\dot{m}_{pump}$ is the massflow of AdBlue into the pump, $c_{p,ab}$ is the specific heat for AdBlue, $T_{pump,in}$ the temperature of Adblue from the tank and $T_{pump,out}$ is the temperature after the pump. This will give an estimation of the amount of heat exchange between AdBlue and the pump due to heat losses and added electric heat from the hoses.

Unknown Parameters

All parameters are known, $c_{p,ab}$ is a constant, $\dot{m}_{pump}$, $T_{pump,in}$, and $T_{pump,out}$ is measured.

3.1.3 AdBlue Tank

The AdBlue tank transfers heat with the surrounding environment which affects the behavior of the medium. If the medium inside the tank is warmer than the outside the heat will flow from the AdBlue to the surrounding and vice versa.

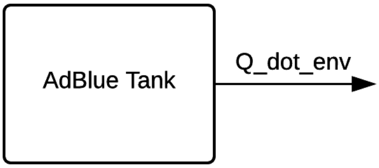


Figure 3.3: *The heat flow from the tank to the environment*

Figure 3.3 shows the heat exchange with the environment and the heat flow can be described as followed:

$$\dot{Q}_{env} = A_{tank,effective} \cdot U \cdot (T_{tank} - T_{env}) \tag{3.3}$$

where U is the combined heat transfer coefficient [15]:

$$U = \frac{1}{\frac{1}{h_{ab,solid}} + \frac{x_t}{\lambda_t} + \frac{1}{h_{env}}} \tag{3.4}$$

and $A_{tank,effective}$ is the area in the tank covered by AdBlue, T_{tank} the tank temperature and T_{env} the environment temperature. $A_{tank,effective}$ can be calculated as a function of the level of AdBlue in the tank as long as the geometry of the tank is known. When calculating heat transfer from a liquid through a tank wall to the environment it is very practical to use the combined heat transfer coefficient. It consists of the heat transfer coefficient for solid AdBlue, $h_{ab,solid}$, the heat transfer coefficient for the surrounding environment, h_{env}, and the heat conductivity for the tank wall with thickness x_t, λ_t.

Unknown Parameters

The unknown parameters in equation (3.4) are $h_{ab,solid}$ and h_{env} which will be used for tuning the model against measurement data.

3.1.4 Heat Flow Inside the Tank

When thawing is active in the tank heat will travel from the liquid medium to the mushy region and from that region to the solid. When temperatures are low, radiation can be neglected since it is more significant for warmer bodies [11]. This heat flow can be described as:

$$\dot{Q}_{liquid} = A_{melt,effective} \cdot h_1 \cdot (T_{liquid} - T_{mushy}) \tag{3.5}$$

where h_1 is the combined heat transfer coefficient, $A_{melt,effective}$ is the area between the liquid phase and the mushy region, T_{liquid} is the temperature in the liquid Adblue and T_{mushy} is the temperature in the mushy region.

The heat will then travel to the solid area from the mushy region and the heat flow can be described as:

$$\dot{Q}_{solid} = A_{solid,effective} \cdot h_2 \cdot (T_{mushy} - T_{solid}) \tag{3.6}$$

where h_2 is the combined heat transfer coefficient, $A_{solid,effective}$ is the area between the mushy region and the solid phase, T_{mushy} is the temperature in the mushy region and T_{solid} is the temperature in the solid Adblue.

Unkown Parameters

The unknown parameters are h_1 and h_2 which will be used as design parameters.

3.2 AdBlue Thawing Behavior

In previous sections the different mechanism that affects the heat flowing in and out of the tank is identified.

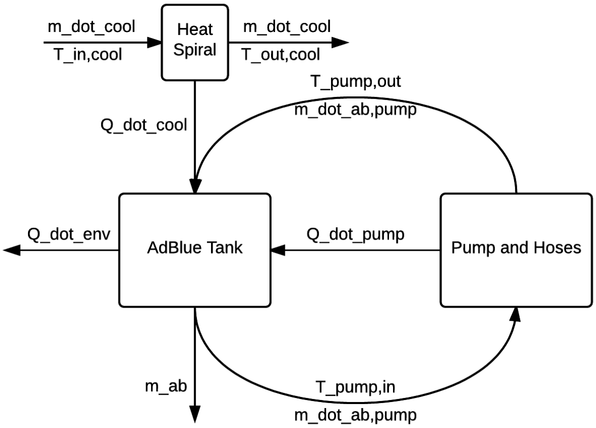
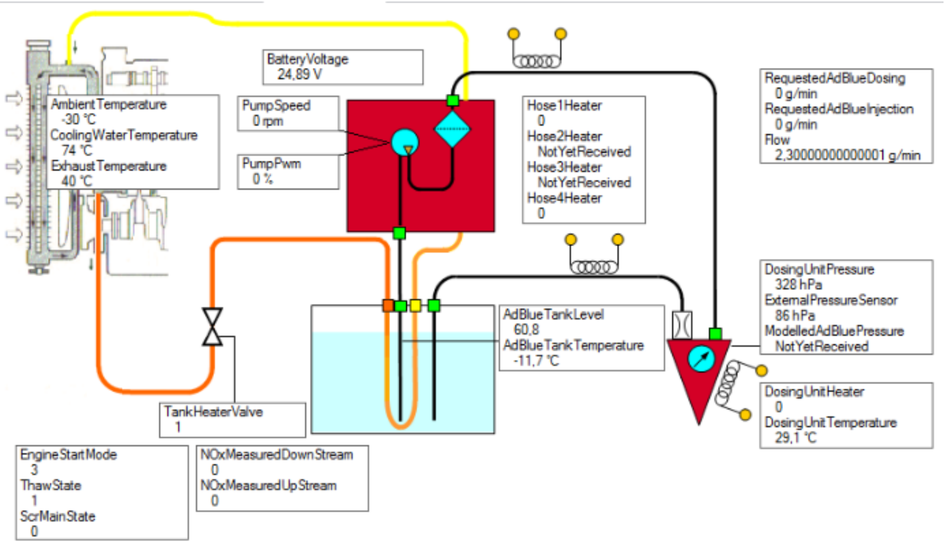


Figure 3.4: *The complete flow for the complete system*

Figure 3.4 shows every system together and how the heat flows between the different systems affecting the AdBlue tank. All these flows are then used to derive two kinds of models, one static model considering constant temperature throughout the tank, and one dynamic temperature model considering that the temperature is different depending on time and phase.


BatteryVoltage
24,89 V

AmbientTemperature
-30 °C
CoolingWaterTemperature
74 °C
ExhaustTemperature
40 °C

PumpSpeed
0 rpm

PumpPwm
0 %

Hose1Heater
0
Hose2Heater
NotYetReceived
Hose3Heater
NotYetReceived
Hose4Heater
0

RequestedAdBlueDosing
0 g/min
RequestedAdBlueInjection
0 g/min
Flow
2,30000000000001 g/min

DosingUnitPressure
328 hPa
ExternalPressureSensor
86 hPa
ModelledAdBluePressure
NotYetReceived

AdBlueTankLevel
60,8
AdBlueTankTemperature
-11,7 °C

TankHeaterValve
1

DosingUnitHeater
0
DosingUnitTemperature
29,1 °C

EngineStartMode
3
ThawState
1
ScrMainState
0

NOxMeasuredDownStream
0
NOxMeasuredUpStream
0

Figure 3.5: *Graphical representation of the system*

Figure 3.5 shows the graphical representation of the system taken from the

EEC3 logger software.

3.2.1 Static Temperature Model

The easiest way to get an approximation of the behavior in the tank is to consider a static temperature model. This means that as long as there is frozen AdBlue left in the tank the energy added will go to transforming the solid AdBlue to liquid and no energy will go to heating the two phases. Therefore the temperature is considered constant at the phase shift temperature -11°C.

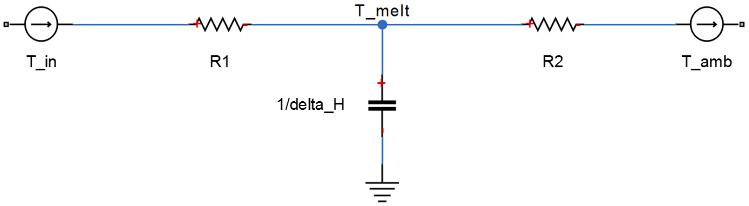


Figure 3.6: *Resistance analogy constant temperature model*

Figure 3.8 shows the resistance analogy of the simple model where the capacitor is the mushy region describing the phase shift and:

$$R1 = \frac{1}{\dot{m}_{cool} \cdot c_{p,cool}} \tag{3.7}$$

$$R2 = \frac{1}{h \cdot A} \tag{3.8}$$

The mass is calculated by premise that the differential in the heat flow into the tank and out of the tank is the energy used for the phase change and therefore the mass can be calculated as follows:

$$m_{static} = \frac{1}{\Delta H_{ab}} \int_0^t (\dot{Q}_{in} - \dot{Q}_{out})\, dt \tag{3.9}$$

where ΔH_{ab} is the specific latent heat of AdBlue, $\dot{Q}_{in} - \dot{Q}_{out}$ is the differential between heat flow into and out of the tank.

Unknown Parameters

The unknown parameters in the constant temperature model is the specific heat capacity h, which is a design parameter.

3.2.2 Dynamic Temperature Model

By doing some simple measurements on the real system, the approximation that the temperature would be constant can be considered too simple. In the real system there are quite large differences in temperatures between the liquid and the solid AdBlue. To get a better estimation of the behavior in the tank a model with estimated temperatures are considered. The model takes into account that the temperature is not constant during the melting process and therefore estimates the temperatures in the solid and liquid phases. Still, the temperature in the region between the two, the mushy region, is considered having a constant temperature of -11°C. By keeping track of the temperature over time, the different heat flows can be better estimated and the model gives a better approximation of the real system.

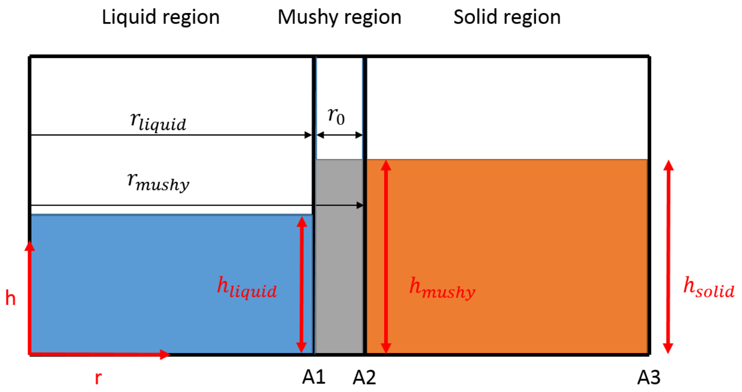


Figure 3.7: *Schematic view over the different areas*

Figure 3.7 shows the two radius in the tank and the three different areas used in the calculations. The different areas are calculated as follows when assumptions are made considering a cylindrical volume around the heat spiral:

$$A_1 = 2\pi \cdot h_{liquid} \cdot r_{liquid} \tag{3.10}$$

$$A_2 = 2\pi \cdot h_{mushy} \cdot r_{mushy} \tag{3.11}$$

$$A_3 = 2 \cdot (l \cdot h_{solid}) + 2 \cdot (b \cdot h_{solid}) + b \cdot l \tag{3.12}$$

where the level and radius of liquid AdBlue, h_{liquid} and r_{liquid}, are depending on the liquid volume of AdBlue, h_{mushy} is the level of the mushy region, $r_{mushy} = r_{liquid} + r_0$ is the radius of the outer part of the mushy region, $r0$ is the thickness of the mushy region, h_{solid} is the level of the solid region, b is the tank base and l is the tank length. Assumptions are made that $h_{mushy} = h_{solid}$ and r_0 are constant meaning that A2 is constant unless all solid AdBlue becomes liquid, area A3 is the surface area of the tank and are constant. Due to different density in liquid and solid AdBlue, h_{liquid} and h_{solid} can differ depending on the melted mass AdBlue. To deal with the level difference h_{liquid} is initially calculated as follows:

$$h_{liquid,0} = \frac{m_{ab,liquid,0}}{r^2_{liquid,0} \cdot \rho_{ab,liquid} \cdot \pi} \tag{3.13}$$

where $m_{ab,liquid,0}$ is the amount of AdBlue melted at $t = 0$, $r_{liquid,0}$ is the radius of the volume of liquid AdBlue at $t = 0$ and $\rho_{ab,liquid}$ is the density of liquid AdBlue. h_{liquid} is then dependent on the actual melted mass and used for calculating the contact area between liquid AdBlue and the mushy region, A1.

The radius of the cylinder in the tank is calculated from the estimated melted mass in the tank and the level of liquid AdBlue:

$$r_{liquid} = \sqrt{\frac{m_{ab,liquid}}{\pi \cdot \rho_{ab,liquid} \cdot h_{liquid}}} \tag{3.14}$$

A summary of the geometry assumptions made in the tank can be seen in table 3.1.

Table 3.1: *Summary of geometry assumptions for the tank*

Variable	Dependency
A1	h_{liquid},r_{liquid}
A2	r_{mushy}
A3	Constant
b,l	Constant
r_0	Constant
$h_{mushy} = h_{solid}$	Constant
r_{liquid}	$m_{ab,liquid}$
h_{liquid}	$m_{ab,liquid}$
r_{mushy}	r_{liquid}

The temperature in the liquid is dependent on the heat flow from the heat spiral $\dot{Q}_{in}$, the pump heat $\dot{Q}_{pump}$, and the heat flow from the liquid to the mushy region, $\dot{Q}_2$:

$$\dot{Q}_{cool} = \dot{m}_{cool} \cdot c_{p,cool} \cdot (T_{in,cool} - T_{out,cool}) \tag{3.15}$$

$$\dot{Q}_{pump} = \dot{m}_{pump} \cdot c_{p,ab,liquid} \cdot (T_{liquid} - T_{pump,out}) \tag{3.16}$$

$$\dot{Q}_{in} = \dot{Q}_{cool} + \dot{Q}_{pump} \tag{3.17}$$

$$\dot{Q}_2 = A1 \cdot h_1 \cdot (T_{liquid} - T_{mushy}) \tag{3.18}$$

where in $\dot{Q}_{cool}$, $T_{in,cool}$ is the coolant temperature into the spiral, $T_{out,cool}$ is the temperature out from the spiral, $\dot{m}_{cool}$ is the coolant mass flow and $c_{p,cool}$ is the specific heat capacity for the coolant. In $\dot{Q}_{pump}$, $\dot{m}_{pump}$ is the mass flow of AdBlue into the pump, $c_{p,ab,liquid}$ is the specific heat for AdBlue, T_{liquid} the temperature of liquid Adblue in the tank and $T_{pump,out}$ is the temperature after the pump. The total amount of heat flow added to the tank is the sum of $\dot{Q}_{cool}$ and $\dot{Q}_{pump}$ called $\dot{Q}_{in}$. In $\dot{Q}_2$, h_1 is the combined heat transfer coefficient between liquid region and mushy region, T_{mushy} is the temperature in the mushy region. The temperature in the solid is dependent on the heat flow from the mushy region, $\dot{Q}_3$, and to the environment, $\dot{Q}_4$, which are calculated as follows:

$$\dot{Q}_3 = A2 \cdot h_2 \cdot (T_{mushy} - T_{solid}) \tag{3.19}$$

$$\dot{Q}_4 = A3 \cdot h_3 \cdot (T_{tank} - T_{env}) \tag{3.20}$$

where h_2 is the combined heat transfer coefficient between mushy region and solid region, $A2$ is the area between the mushy region and the solid phase, T_{mushy} is the temperature in the mushy region and T_{solid} is the temperature in the solid Adblue, h_3 is the combined heat coefficient between the solid region and the environment, T_{tank} is the tank temperature and T_{env} is the environment temperature. An overview of the heat flows in the tank can be described with an electrical circuit such as:

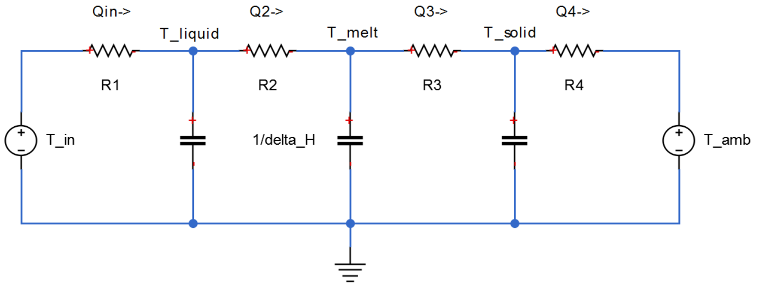


Figure 3.8: *Resistance analogy temperature dependent model*

The resistors in the circuit are equivalent to:

$$R1 = \frac{1}{\dot{m}_{cool} \cdot c_{p,cool}} \tag{3.21}$$

$$R2 = \frac{1}{h_1 \cdot A_1} \tag{3.22}$$

$$R3 = \frac{1}{h_2 \cdot A_2} \tag{3.23}$$

$$R4 = \frac{1}{h_3 \cdot A_3} \tag{3.24}$$

The dynamics of the liquid AdBlue mass can be calculated considering the heat flow into the tank ,$\dot{Q}_{in}$, and out of the tank ,$\dot{Q}_4$, as follows:

$$\frac{d}{dt} m_{ab,liquid} = \frac{1}{\Delta H_{ab}} (\dot{Q}_2 - \dot{Q}_3) \tag{3.25}$$

where ΔH_{ab} is the specific latent heat of AdBlue. Using the assumption that r_0 and h_{mushy} are constant over time, it is concluded that the mass of mushy region remains unchanged and therefore the conservation of mass results in:

$$\frac{d}{dt} m_{ab,liquid} = -\frac{d}{dt} m_{ab,solid} \tag{3.26}$$

The temperatures in the liquid and solid regions are dependent on the heat flows. The temperature in the liquid can be modeled as:

$$\frac{dT_{liquid}}{dt} \cdot m_{ab,liquid} \cdot c_{p,ab,liquid} = \dot{Q}_{in} - \dot{Q}_2 \tag{3.27}$$

The temperature in the solid can be modeled as:

$$\frac{dT_{solid}}{dt} \cdot m_{ab,solid} \cdot c_{p,ab,solid} = \dot{Q}_3 - \dot{Q}_4 \tag{3.28}$$

In the mushy region the temperature will be constant at $T_{mushy} = -11°C$ due to the assumption that the energy used are only for phase transition at this specific location.

Unknown Parameters

The unknown parameters in the dynamic temperature model is the specific heat capacity $h1$, $h2$, $h3$ and $r0$. These will be used as design parameters.

4

Experiment Equipments

This section describes the equipment used for being able to freeze and melt AdBlue with purpose of data measurement which will later be used for model validation.

4.1 Tank

The purpose of the tank used in the experiments is to simulate the one used in the trucks. It needs to handle a variety of AdBlue in both solid and liquid form and handle temperatures between -40°C and +30°C and fast changes in temperature without breaking. The tank dimensions should be selected such that desired number of thermocouples with specific height can be mounted on it. The thermocouples shall be mounted in a matrix formation so that the boundary between liquid and solid AdBlue can be estimated.

Figure 4.1: *The tank used in the experiments*

Figure 4.1 shows the tank used. The sides have been cut off to be able to fit the tank in the freezer. The tank has four holes on the top for holding of the sensor plates to have a reliable connection during the freezing.

4.1.1 Sensor Holder

A plate with holders for the thermocouples is made to fit as a cap on the tank. The purpose is to be able to mount the thermocouples in exactly the same configuration in different experiments.

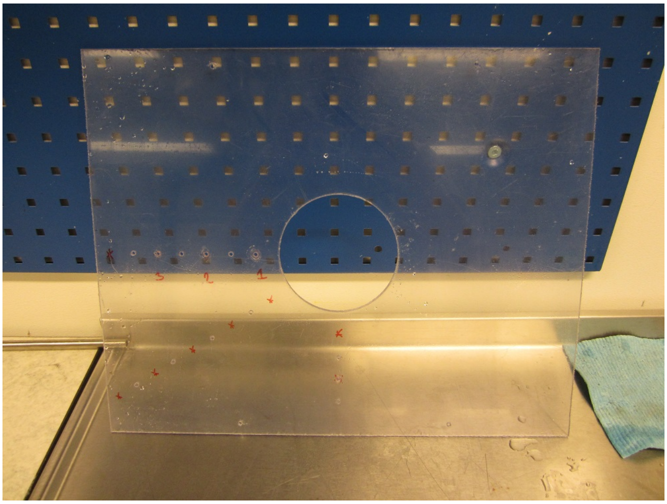


Figure 4.2: *Plate for mounting the thermocouples in the tank*

Figure 4.2 shows the plate made of Plexiglas with the purpose to hold sticks with thermocouples. The big hole is to fit the heating armature with the diameter of ca 120mm, the small holes barely visible due to transparent plastic are drilled with 4mm diameter and used for fitting the sensor sticks.

4.1.2 Sensor sticks

The thermocouples are mounted on a threaded rod to be able to control the length and height of the sensors.

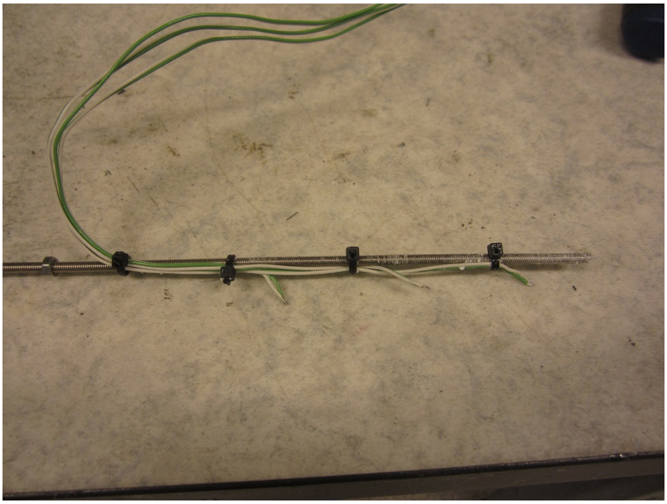


Figure 4.3: *Threaded rod for with sensors*

Figure 4.3 shows the positions of the thermocouples mounted on a stainless steel threaded rod.

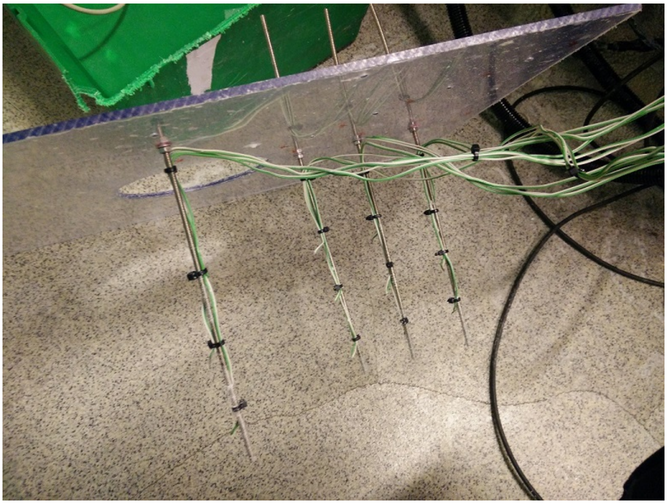


Figure 4.4: *Sensor plate with mounted sensors*

Figure 4.4 shows the manufactured holder together with the sticks with three thermocouples each on a different level.

4.2 Heating Armature

The heating armature is of type 500s and is a combined heating spiral and AdBlue pickup unit. The pickup unit is used for delivering AdBlue to the SCR and recirculate the unused AdBlue. The heating armature is connected to the coolant, the pickup unit to the AdBlue pump, and the built-in temperature and level sensors are used to collect data.

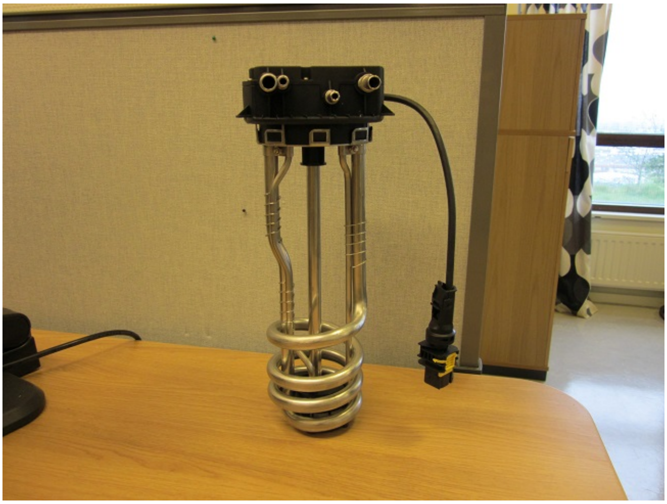


Figure 4.5: *The combined heating armature and AdBlue pickup*

4.2.1 Heating Fluid

The heating fluid is a mix between water and glycol consisting of 49% ethylene glycol and 51% water. The temperature of the inlet engine coolant can be varied during the test but the software is set to start heating when temperatures drops under 65 °C and stop heating at 75 °C.

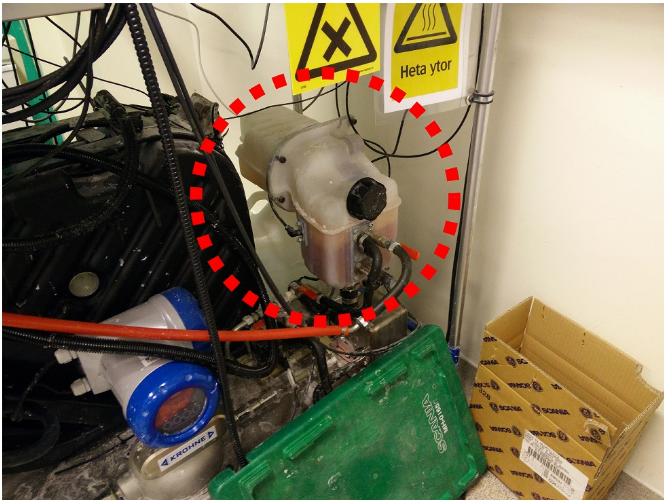


Figure 4.6: *The tank containing coolant*

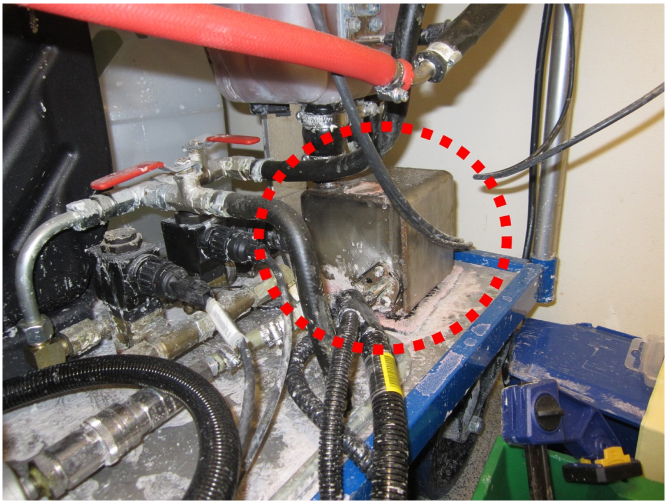


Figure 4.7: *The coolant heater*

Figure 4.6 shows the coolant tank which contains the glycol and water mixture. Below it, the heater is placed in a steal box at which the coolant is circulated for heating as can be seen in figure 4.7. The coolant can be directed in such a way that it only circulates in the tank and heater. This is useful in order to heat the coolant without thawing the ongoing freezing experiments and to have all the liquid in the system at the same initial temperature. The mass flow from the coolant pump is held constant and are determined by filling up a predetermined volume and measuring the time.

4.2.2 Dosing Pump

The dosing pump is used for transporting the liquid AdBlue from the tank to the dosing unit. It is also used for AdBlue circulation in the tank during thawing in order to speed up the process. The hoses connecting the pump to the tank are heated to prevent freezing. The mass flow from the dosing pump is held constant and are determined by filling up a predetermined volume and measuring the time.

Figure 4.8: *The dosing pump*

Figure 4.8 shows the pump used for dosing AdBlue and circulating AdBlue during the thawing session.

4.3 AdBlue Pump

After every thawing experiments the melted AdBlue is pumped out for measuring the melted volume using an external pump connected to the delivery hose.

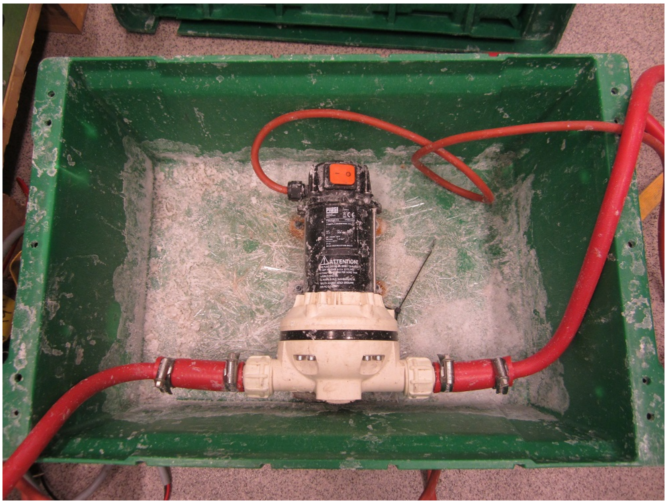


Figure 4.9: *External pump*

Figure 4.9 shows the pump used for pumping out AdBlue after each thawing session. The pump is driven by 24 volts taken from the test rig.

4.4 Freezers

Two different types of freezers are used for the experiments which are introduced in the following sections.

4.4.1 Soft Drink Cooler

A small soft drink cooler is available where it can produce temperatures as low as -12°C and fulfills the criteria to freeze AdBlue. This cooler is to be used for cooling AdBlue during experiment setups to speed up the freezing process.

Figure 4.10: *The softdrink cooler used for smaller samples*

4.4.2 Freezer

A bigger freezer made for freezing is also available. The freezer has a temperature range down to -40°C so it is useful for testing extreme environments and to be able to freeze larger samples on a manageable time basis.

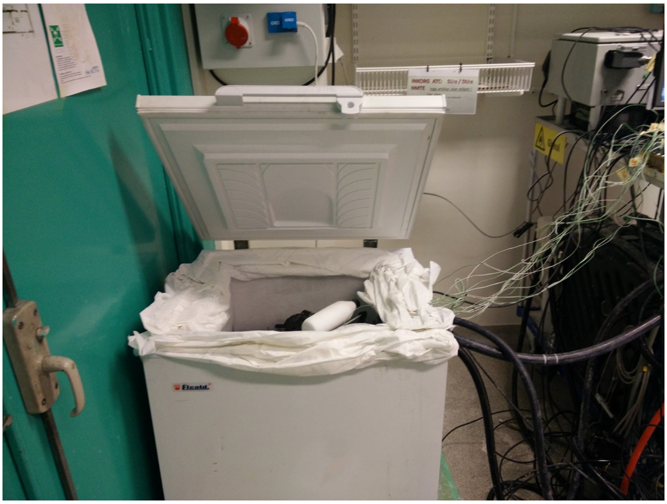


Figure 4.11: *The freezer*

Figure 4.11 shows the freezer containing a sample for freezing. The paper around the edges are used for extra isolation during a freezing due to the amount of cables running from the test rig to the sample.

4.5 Sensors and Measurement Equipment

This section defines the different sensors and the equipment used to be able to carry out the experiments.

4.5.1 Thermocouple Elements

The task of the thermocouples is to determine different temperatures in the system for the respective placement. The thermocouples will be placed in a matrix configuration as described above to determine the distribution of the moving boundary in AdBlue. They are also placed so that the coolant and the pump temperature can be determined. The thermocouples is of type K and are isolated with PVC. They have the article number 04-20010 and are manufactured by Pentronic.

The thermocouples are manufactured by cutting sensor wire to the correct length and then welding them together in one end and adding a contact in the other.

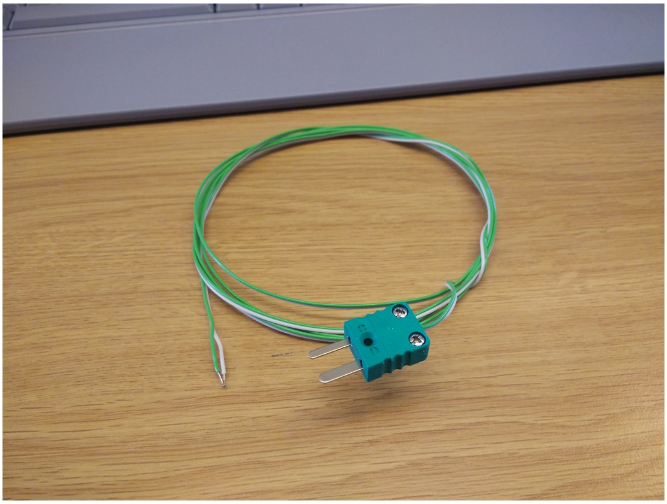


Figure 4.12: *The thermocouples used for measuring temperature*

Figure 4.12 shows the thermocouples used for temperature measurements. The thermocouples are build up by two different materials and the known voltage difference between them is translated to temperatures.

4.5.2 Thermocouples Placement

The thermocouples are mounted on a threaded rod using cable ties to avoid damage and impact from the mounting equipment. Each threaded rod contains three separate thermocouples on a given height from the bottom of the tank. In total there are twelve thermocouples measuring temperatures in the liquid and solid AdBlue states during an experiment. The thermocouples are mounted 35mm above the bottom and two more are mounted with 35mm distance between, above the first, see figure 4.4. On the mounting plate the first rod is mounted 75mm from the middle and the rest with 50mm distance in between. In the tank they are mounted in two directions as shown in figure 4.4 due to circular symmetry assumptions.

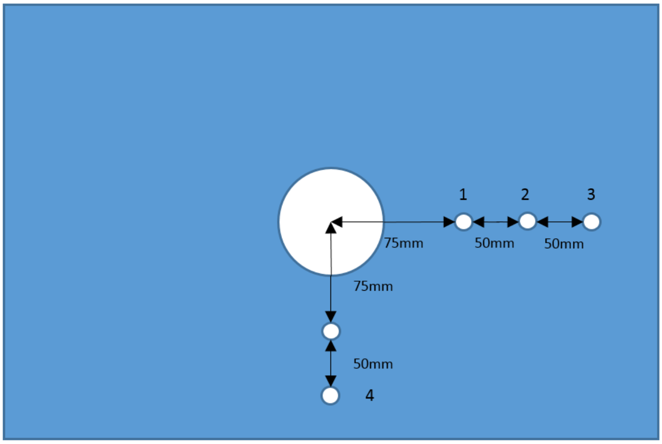


Figure 4.13: *The locations of the thermocouples from above*

Figure 4.13 shows the locations of the threaded rods on the holding plate seen from above the tank.

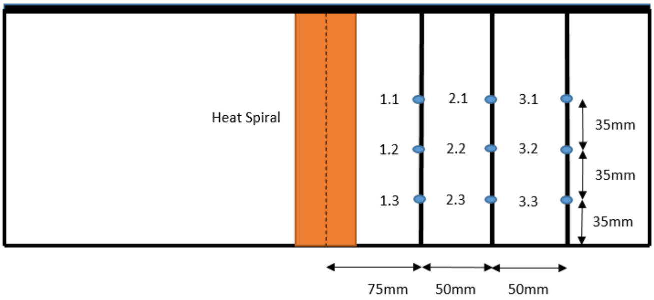


Figure 4.14: *The locations of the thermocouples from the side*

Figure 4.14 shows the locations of the thermocouples on the holding plate seen from the cross section of the tank. The thermocouples on location 4 in figure 4.13 is not present in the cross section.

Table 4.1: *Number of thermocouples in the experiments*

Thermo element placement	Number of thermocouples
Heat spiral middle	1pcs.
Tank	12pcs.
Enviromental temperature	1pcs.
Heat spiral, coolant in	1pcs.
Heat spiral, coolant out	1pcs.
Pump input	1pcs.
Pump output	1pcs.

Table 4.1 lists the number of thermocouples at different positions in the tank and on the equipment mounted in the tank. The temperature in and out of the pump are measured by adding thermocouples to the input and output from the pump.

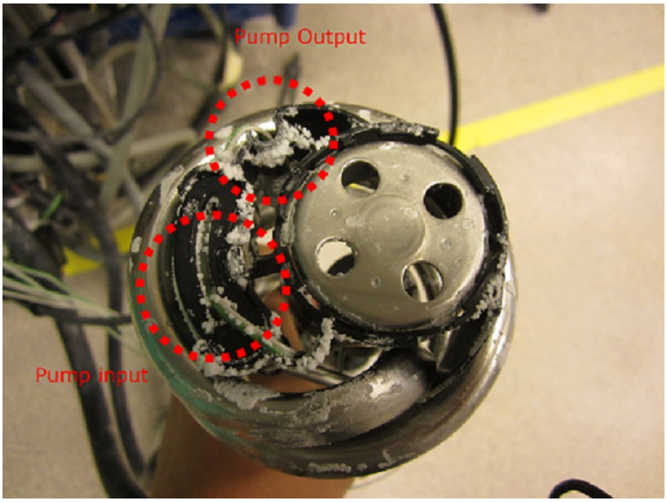


Figure 4.15: *Temperatures in and out from pump*

Figure 4.15 shows the placement of the thermocouples measuring the input temperature of AdBlue into the tank and the temperature out of the pump in the output hose. The hoses used for transporting AdBlue to and from the pump are heated themselves to prevent freezing in the delivery system and by measuring the temperature at the end of the input and output, the heat from the hoses can be included in the pump heat calculations.

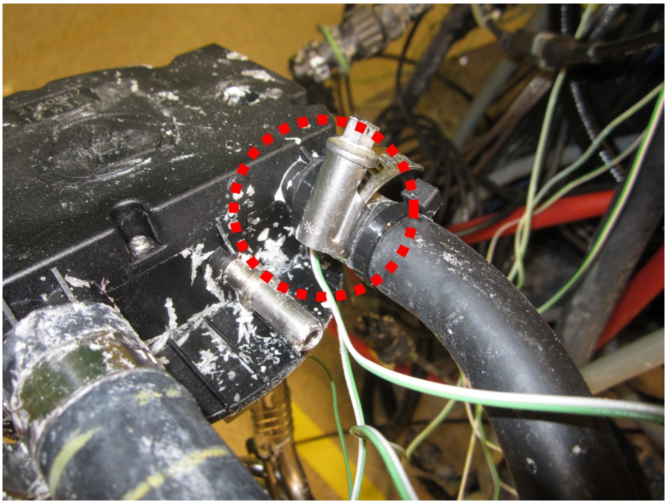


__Figure 4.16:__ Thermocouple placement into the spiral

Figure 4.16 shows the initial placement of the thermocouple inside the connection to the spiral which led to unreliable readings of the sensor due to big impact of the environmental temperature.

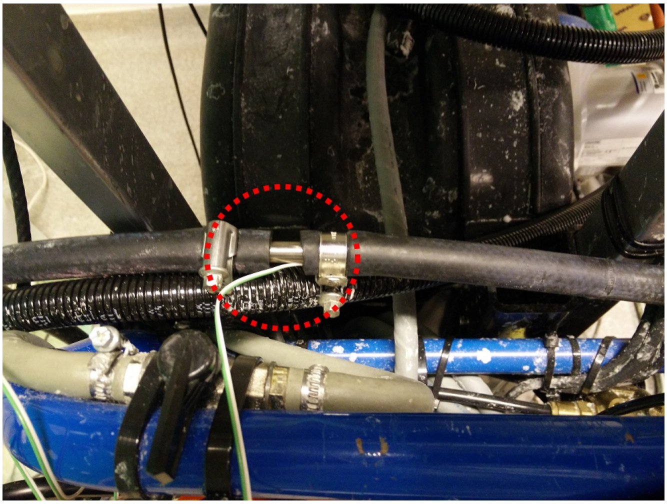


__Figure 4.17:__ The improved placement of the thermocouple

Figure 4.17 shows the improved position of the thermocouple measuring temperature of the coolant into the heating spiral. The sensor is moved from the end of the hose to the middle of the hose for easier installation and to avoid affection from the surroundings. To isolate the sensor from the room temperature, the sensor should be placed in the middle of the hose cross section area. Since it was not possible in the location seen in figure 4.16, it is placed as seen in seen in figure 4.17.

Figure 4.18: *Coolant temperature sensor out of the spiral*

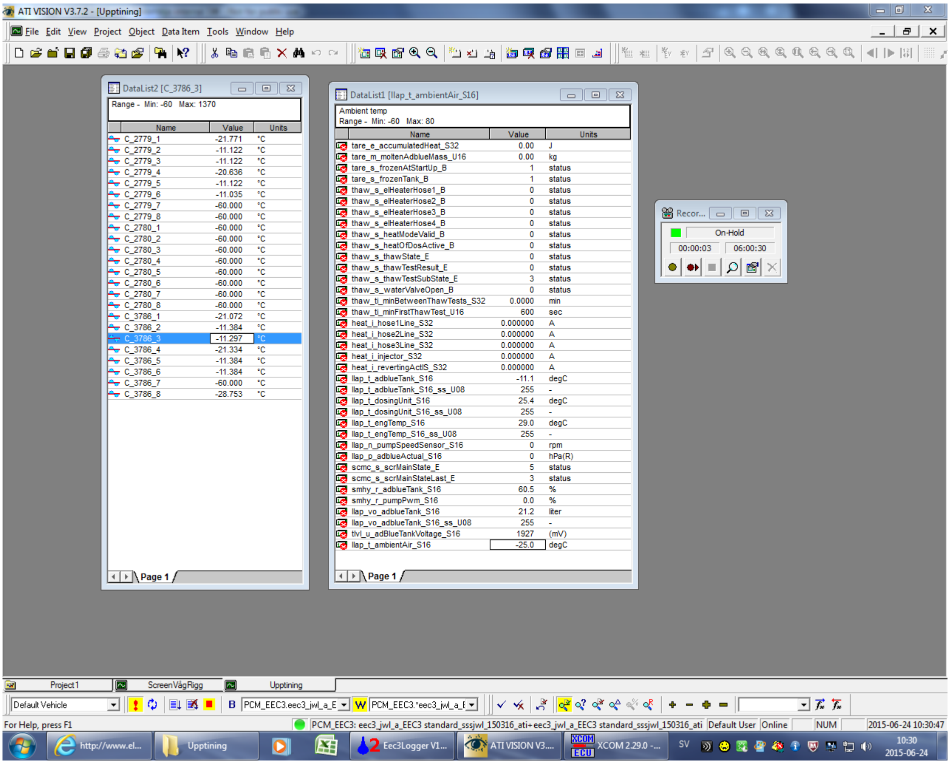
Figure 4.18 shows the thermocouple placement measuring the temperature out of the spiral.

4.6 Mass Flow

To be able to estimate the heat flowing from the spiral to the AdBlue in the tank the mass flow of coolant is needed. This is measured by filling up a tank with predetermined volume and measuring the time it takes. By knowing the volume and the time filling the constant massflow can be calculated.

4.7 Computer Equipment

The computer equipment on set comprises of a computer with associated IPETRONIK-modules [1] to be able to connect sensors. The computer in turn is equipped with software to be able to log data and export for analysis. The software in first hand used to log sensor data on the computer is Ati Vision [2].



DataList2 [C_3786_3]

Range - Min: -60 Max: 1370

Name	Value	Units
C_2779_1	-21.771	°C
C_2779_2	-11.122	°C
C_2779_3	-11.122	°C
C_2779_4	-20.636	°C
C_2779_5	-11.122	°C
C_2779_6	-11.035	°C
C_2779_7	-60.000	°C
C_2779_8	-60.000	°C
C_2780_1	-60.000	°C
C_2780_2	-60.000	°C
C_2780_3	-60.000	°C
C_2780_4	-60.000	°C
C_2780_5	-60.000	°C
C_2780_6	-60.000	°C
C_2780_7	-60.000	°C
C_2780_8	-60.000	°C
C_3786_1	-21.072	°C
C_3786_2	-11.384	°C
C_3786_3	-11.297	°C
C_3786_4	-21.334	°C
C_3786_5	-11.384	°C
C_3786_6	-11.384	°C
C_3786_7	-60.000	°C
C_3786_8	-28.753	°C

Page 1

DataList1 [llap_t_ambientAir_S16]

Ambient temp
Range - Min: -60 Max: 80

Name	Value	Units
tare_e_accumulatedHeat_S32	0.00	J
tare_m_moltenAdblueMass_U16	0.00	kg
tare_s_frozenAtStartUp_B	1	status
tare_s_frozenTank_B	1	status
thaw_s_elHeaterHose1_B	0	status
thaw_s_elHeaterHose2_B	0	status
thaw_s_elHeaterHose3_B	0	status
thaw_s_elHeaterHose4_B	0	status
thaw_s_heatModeValid_B	0	status
thaw_s_heatOfDosActive_B	0	status
thaw_s_thawState_E	0	status
thaw_s_thawTestResult_E	0	status
thaw_s_thawTestSubState_E	3	status
thaw_s_waterValveOpen_B	0	status
thaw_ti_minBetweenThawTests_S32	0.0000	min
thaw_ti_minFirstThawTest_U16	600	sec
heat_i_hose1Line_S32	0.000000	A
heat_i_hose2Line_S32	0.000000	A
heat_i_hose3Line_S32	0.000000	A
heat_i_injector_S32	0.000000	A
heat_i_revertingActIS_S32	0.000000	A
llap_t_adblueTank_S16	-11.1	degC
llap_t_adblueTank_S16_ss_U08	255	-
llap_t_dosingUnit_S16	25.4	degC
llap_t_dosingUnit_S16_ss_U08	255	-
llap_t_engTemp_S16	29.0	degC
llap_t_engTemp_S16_ss_U08	255	-
llap_n_pumpSpeedSensor_S16	0	rpm
llap_p_adblueActual_S16	0	hPa(R)
scmc_s_scrMainState_E	5	status
scmc_s_scrMainStateLast_E	3	status
smhy_r_adblueTank_S16	60.5	%
smhy_r_pumpPwm_S16	0.0	%
llap_vo_adblueTank_S16	21.2	liter
llap_vo_adblueTank_S16_ss_U08	255	-
tlvl_u_adBlueTankVoltage_S16	1927	(mV)
llap_t_ambientAir_S16	-25.0	degC

Page 1

PCM_EEC3.eec3_jwl_a_E
PCM_EEC3.*eec3_jwl_a_E

PCM_EEC3: eec3_jwl_a_EEC3 standard_sssjwl_150316_ati+eec3_jwl_a_EEC3 standard_sssjwl_150316_ati

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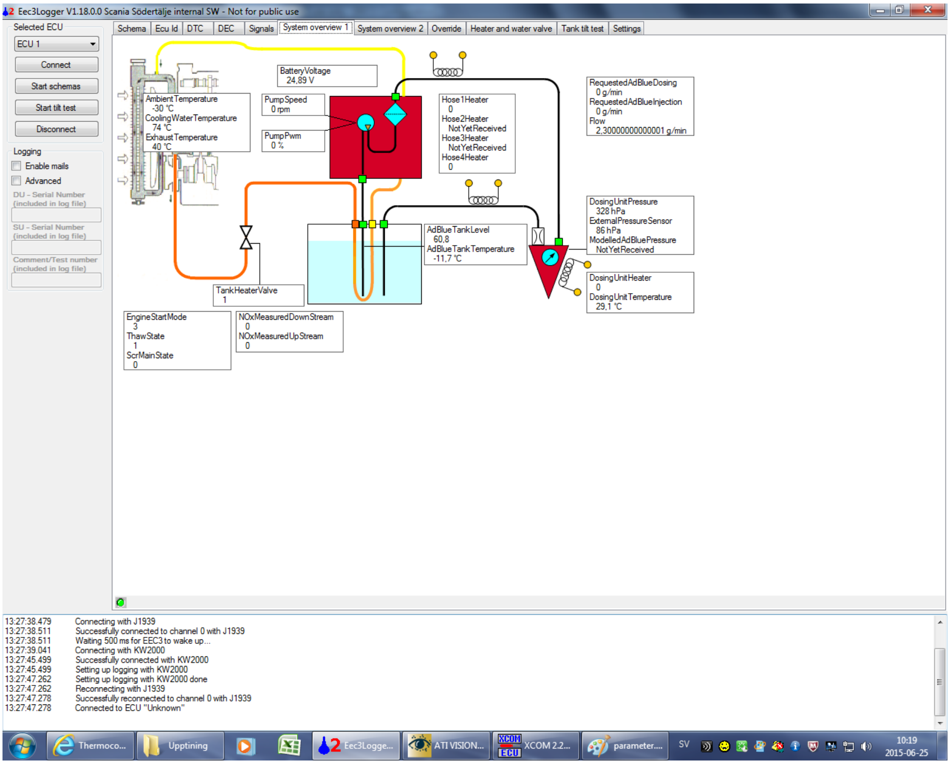
Figure 4.19: *Vision GUI*

Figure 4.19 shows the GUI used for recording and reading the active parameters in the system. The left part of the window shows the signals from the IPETRONIK-modules which measures the temperatures in AdBlue and the middle part shows all the parameters that are available from the EEC3 unit. The right window controls the recordings and the settings over which variables should be recorded. The software used to controll the EEC3 system while running is called the EEC3logger.



AmbientTemperature
-30 °C
CoolingWaterTemperature
74 °C
ExhaustTemperature
40 °C

BatteryVoltage
24,89 V

PumpSpeed
0 rpm

PumpPwm
0 %

Hose1Heater
0
Hose2Heater
NotYetReceived
Hose3Heater
NotYetReceived
Hose4Heater
0

RequestedAdBlueDosing
0 g/min
RequestedAdBlueInjection
0 g/min
Flow
2,30000000000001 g/min

DosingUnitPressure
328 hPa
ExternalPressureSensor
86 hPa
ModelledAdBluePressure
NotYetReceived

AdBlueTankLevel
60,8
AdBlueTankTemperature
-11,7 °C

DosingUnitHeater
0
DosingUnitTemperature
29,1 °C

TankHeaterValve
1

EngineStartMode
3
ThawState
1
ScrMainState
0

NOxMeasuredDownStream
0
NOxMeasuredUpStream
0

```
13:27:38.479    Connecting with J1939
13:27:38.511    Successfully connected to channel 0 with J1939
13:27:38.511    Waiting 500 ms for EEC3 to wake up...
13:27:39.041    Connecting with KW2000
13:27:45.499    Successfully connected with KW2000
13:27:45.499    Setting up logging with KW2000
13:27:47.262    Setting up logging with KW2000 done
13:27:47.262    Reconnecting with J1939
13:27:47.278    Successfully reconnected to channel 0 with J1939
13:27:47.278    Connected to ECU "Unknown"
```

Figure 4.20: *EEC3logger GUI*

Figure 4.20 shows the GUI used for controlling the EEC3 system during system runs. The software can overrun preprogrammed functions in the EEC3 so there can be manual control over for example the coolant pump and the heater and the complete system ignition. The GUI also gives a good graphical representation of the system.

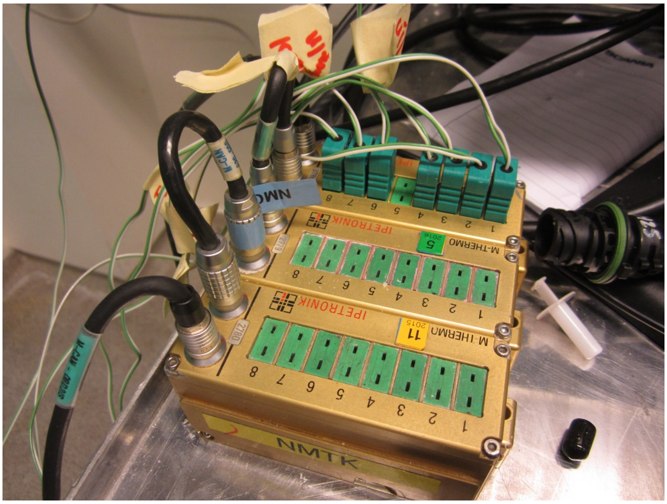


Figure 4.21: The modules used for connecting sensor to the computer

Figure 4.21 shows the modules used for connecting the sensors for temperature measurement. Three of the same kind were available so a total of twenty four thermocouples could be used simultaneously. The IPETRONIK-modules where connected to the computer through a virtual CAN interface.

Figure 4.22: The virtual can interface adapter

Figure 4.22 shows the virtual can interface that translates the signals from the IPETRONIK-modules through a CAN interfaces to USB. This is connected to the computer and the signals can be read by the VISION software.

5

Measurement Description

The purpose of this section is to describe the approach which is used in order to obtain reliable data from the measurements.

5.1 Set Up

The equipment described in the previous section are all assembled together on a test rig. The purpose of the test rig is to simulate the truck environment in a laboratory.

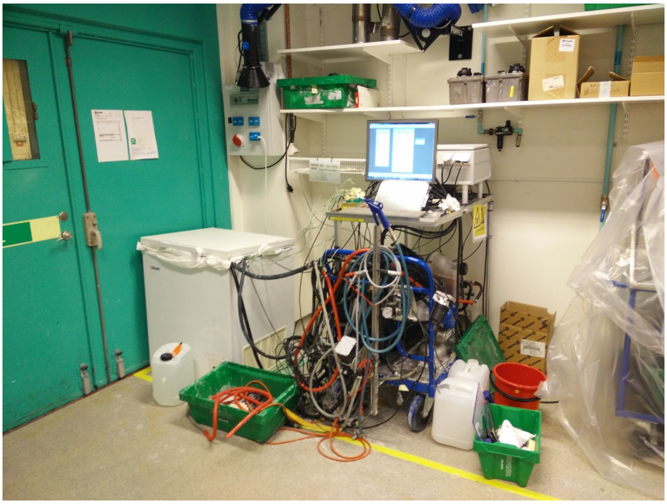


Figure 5.1: *The experiment setup*

Figure 5.1 describes the complete test rig equipped for a measurement session. The hoses between the rig and the freezer are the coolant hoses connected to the heat spiral.

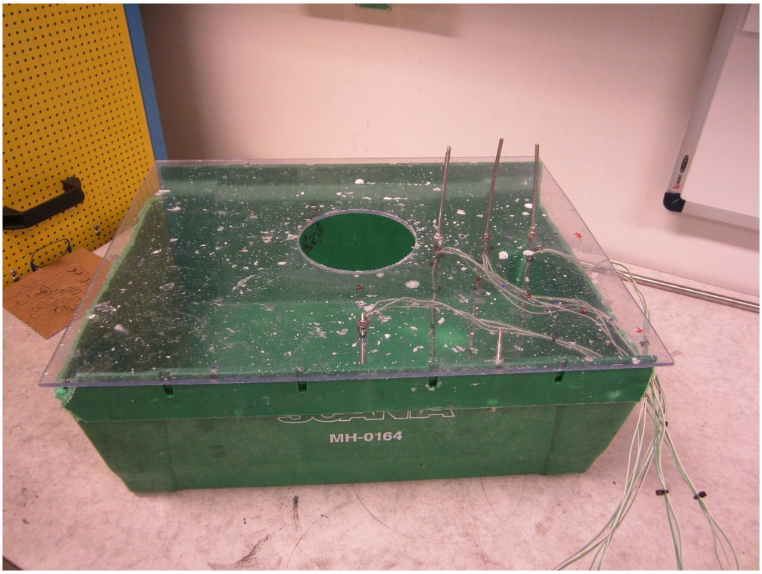


Figure 5.2: *The tank with holder*

Figure 5.2 shows the tank with sensor holder and sensor sticks mounted as such it will be placed in the freezer. The tank is filled with 20 liters of liquid AdBlue and put in the freezer up to two days to achieve a homogeneous solid sample. To determine when the sample is completely frozen the thermocouples are monitored to see that every measurement point is below freezing temperature.

Before starting a melting experiment, the coolant in the tank is preheated. This is done by rerouting the coolant so it will only circulate between the heater and the tank. By doing this, results of the measurements will be more consistent and the time for heating up the coolant can be removed from the experiment time. The main reason to preheat is the limited power from the electric heater so the system will be a bit more relaxed by preheating.

Figure 5.3: *Sample during recording*

Figure 5.3 shows a sample of AdBlue in the freezer during a recording.

5.2 Procedure

When the rig is complete and the sample is frozen Vision is prepared for recording. The Eec3 software is in override mode to keep the system from starting. When turning the ignition on, in other words letting the EEC3 software work as if a truck is running, the software will if the ambient temperature is below freezing start adding heat to the tank. At this point the coolant valves are opened and the coolant flows through the spiral. In Vision, the recording is started and all sensors and valuable data from the EEC3 is recorded. The EEC3 software will then try to start the dosing pump depending on how much AdBlue is thawed using the current model. If the pump is not able to reach a certain pressure, namely AdBlue is still frozen in the pump inlet, the pump will stop and try again after 10 minutes. This will proceed until a certain pressure is reached, the pump will then stop and measure if the pressure drops correctly and there is free flow of AdBlue. If so the pump will start circulating AdBlue in the tank.

If the melting process succeeds and the AdBlue starts melting, the measurement goes on for 70 minutes before aborting. Directly after a finished measurement series, the external pump is connected to the pickup unit and the melted AdBlue is pumped out of the tank to measure the melted mass. The melted mass is recorded to be able to calibrate the models if needed so they can show the correct amount of melted AdBlue. If the melting process does not succeed, it will be aborted and the process will be restarted with a new sample. A series were the melting process does not succeed is recorded to be able to see how the model behaves during abnormal melting behaviors. Abnormal melting behavior means that the small amount of AdBlue melted at the beginning is used for filling up the dosing system, this will cause the spiral from losing all physical contact with the AdBlue in the tank and therefore heat transfer is significantly slower than when liquid Adblue is present.

6

Results

This section reports the results and verification from the two models created during different conditions and the comparison between them and the implemented model used today.

6.1 Temperature Measurements

Here are the raw temperature measurements from the thermocouples in the tank showed. Two different melting behaviors are investigated and a separate data set for verifying the models are presented.

6.1.1 Normal Melting Behavior

The normal conditions is when the melting procedure works as supposed to, namely heat is added to the tank and AdBlue begins to melt, after a certain time the pump starts the circulation of AdBlue in the tank. The ambient temperature in the freezer were -29°C and 20 liters of liquid AdBlue had been frozen for approximate 36 hours, leading to a mean initial temperature of -12.5°C in the tank and the sample frozen solid. The control values during the experiments is the temperatures into and out of the spiral and the temperature into and out of the dosing pump. The mass flow of coolant and Adblue from their respectively pump are considered constant and the duration of the experiment are 4200 seconds (70 minutes).

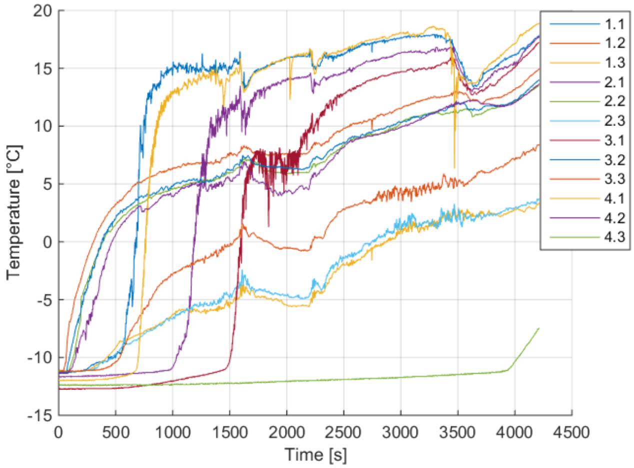


Figure 6.1: *Plot showing the temperatures in the tank*

Figure 6.1 shows the temperature distribution in the tank at different coordinates around the spiral during an normal melting session. The purpose of the experiment is to see the distribution of the temperatures in the tank and determine the behavior of the moving boundary. As can be seen in the figure the temperatures behaves different depending on their location in the tank. The thermocouples closest to the spiral, for example 1.2 shows that AdBlue melts almost instantly while the further away takes more time or are still in solid state, for example 4.3.

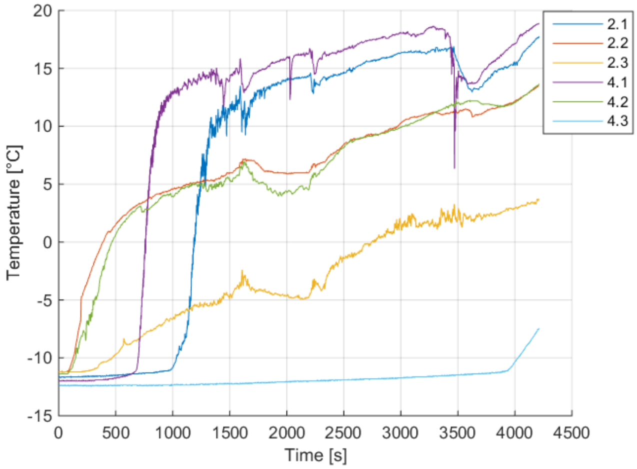


Figure 6.2: *Temperature measurements at position* 2.1 *to* 2.3 *and* 4.1 *to* 4.3 *around the heating spiral*

The calculations made are based on cylindrical symmetry of the melting process through the whole tank. As can be seen in figure 6.2 the temperatures at two different coordinates at the same distance and height, 2.2 and 4.2, are compared and their behavior are very similar. This strengthens the assumption that cylindrical symmetry is a good approximation to use when the melting is studied. The differences in temperature on the other positions for example 4.1 and 2.1, can be explained by small differences in thermocouple placement or the fact that the experiment tank is rectangular in shape and therefore a larger isolation layer are effecting the thermocouple on the long side. The temperatures still show the same behavior and the symmetry seems reasonable. Other modeling approaches have also been using symmetry approximations during similar measurements [7].

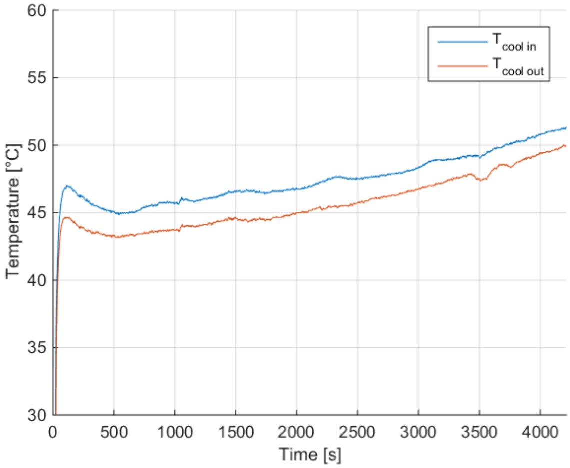


Figure 6.3: *Temperatures in and out of the heating spiral*

Figure 6.3 shows the temperature measurement from the temperature into the tank. The purpose of the experiment is to determine the difference between the temperature in to the spiral and out, to be able to calculate the delivered heat flow from the heating spiral to the tank. When the validation of the models started to take place a large error in the temperature measurements on the heating armature where found. The temperature difference between $T_{cool,in}$ and $T_{cool,out}$ were to small leading to bad results from the models. This problem where solved by measuring the temperature at other positions in the system and therefore be able to calculate the actual difference in temperature. The data sets with the faulty measurements could then be used by adding a calibration parameter with magnitude of 12 °C to increase the difference between $T_{cool,in}$ and $T_{cool,out}$, leading to correct heat flow to the tank. The first position are described in figure 4.16 and the modified placement in figure 4.17. Reviewing the thermocouple after dismounting the rig showed that the isolation of the thermocouple had been damaged which probably contributed to misleading measurements because of metal contact at other places than the tip of the thermocouple.

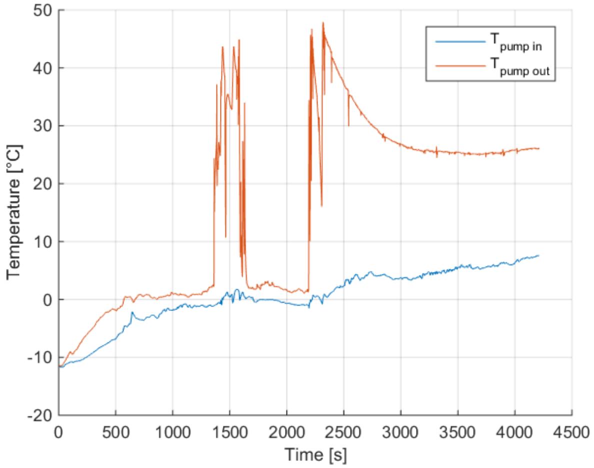


Figure 6.4: *Temperatures in and out of the dosing pump*

Figure 6.4 shows the temperatures in the input of the dosing pump and the output temperature from the circulation. The purpose of this measurement is to decide the heat flow added from the dosing pump and the heated hoses in the system. The first peak in the figure shows the first attempt to start the pump and the second is the attempt where it succeeds and circulation starts.

6.1.2 Abnormal Melting Behavior

This section describes a data set where the melting of the sample is not successful meaning that when the legislated 70 minutes has passed and the sample is still not melted. The experiment duration is 7800 seconds (130 minutes). The control values during the experiments is the temperatures into and out of the spiral and the temperature into and out of the dosing pump. The mass flow of coolant and Adblue from their respectively pump are considered constant. The starting volume is 20 liters of liquid AdBlue and the sample is frozen down to -16°C in the middle of the tank and -23°C at the coolest point. The ambient temperature is -30°C. The implemented model in the system overestimates the melting performance in such conditions which leads to the software starting the dosing pump too early and therefore drying the tank completely. This prevents heat flow from the heating spiral to the tank and the melting slows down or stops completely.

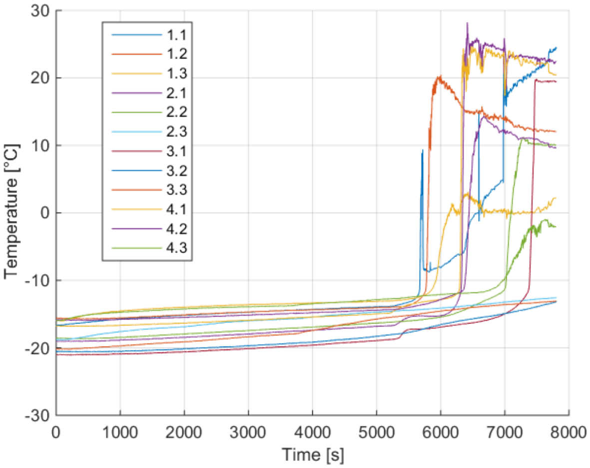


Figure 6.5: *Temperatures in tank*

Figure 6.5 shows the temperatures in the tank during a 7800 seconds long measurement. The purpose of the experiment is to examine the temperatures in the tank and the models behavior when heat flow is not delivered as expected.

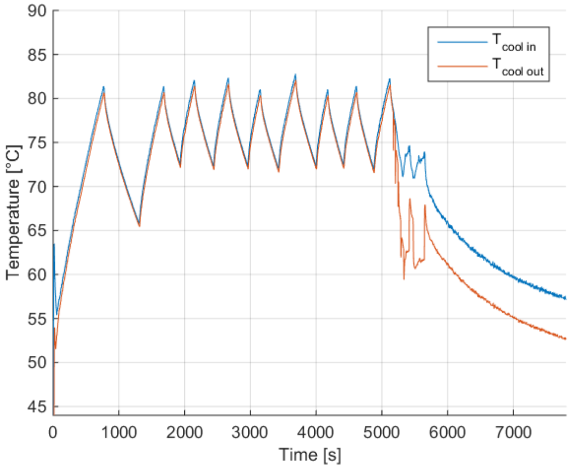


Figure 6.6: *Temperatures in and out of the heating spiral*

Figure 6.6 shows the temperatures in and out of the heating spiral. The purpose of the experiment is to trace the heat flow to the tank. As can be seen in the figure there is almost no difference in temperature between $T_{cool,in}$ and $T_{cool,out}$ until more than 4980 seconds has passed. This means that heat flow between the heating spiral and the tank is not present.

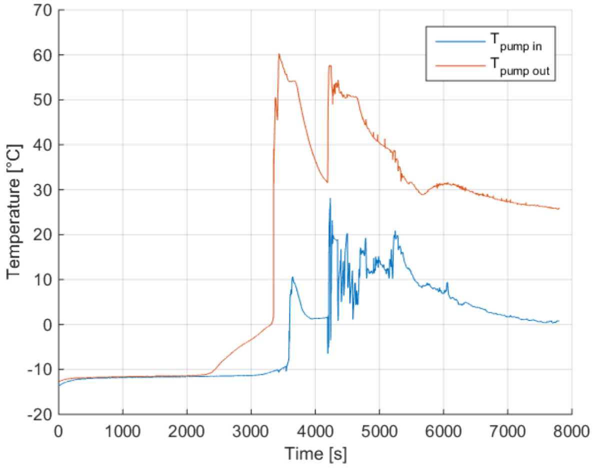


Figure 6.7: *Temperatures in and out of the dosing pump*

Figure 6.7 shows the temperatures into and out of the heated hoses and dosing pump. The purpose of the experiment is to see how the heat flow from the pump behaves. As can be seen in the figure there is no successful start of the pump until the temperature in the intake rises above -11 °C. The pump is not able to fully start until after 4200 seconds has passed when also the output is free from solid AdBlue.

6.1.3 Verifying Data Set

To examine the models performance under a different scenario they are tested with another data set with a slightly higher mean temperature in the tank at -11.5°C and with measured mass melted AdBlue at 17kg. The duration of the experiment is still 4200 seconds (70 minutes). Unfortunately, the ambient temperature were not measured in this data set so this signal is estimated. This leads to an error factor in the result to count on when discussing the alternative data set. In the alternative data set the temperature in the solid is higher than in the data set used for creating the models. The leads to a faster melting process due to less energy needed to heat the sample before phase transition.

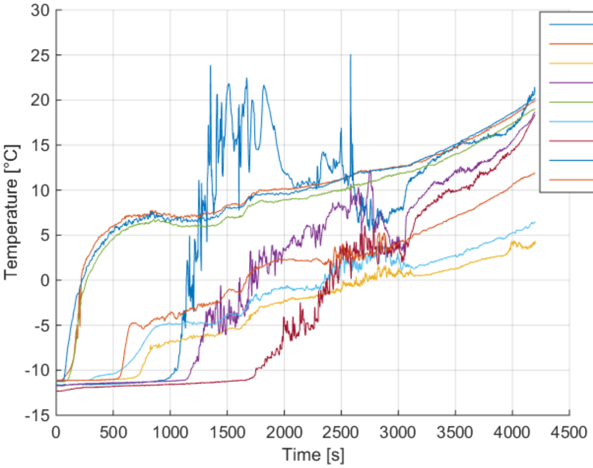


Figure 6.8: *Plot showing the temperatures in the tank*

As can be seen in figure 6.8 all thermocouples are above freezing temperature after approximately 1700s compared to the previous data set seen in figure 6.1.

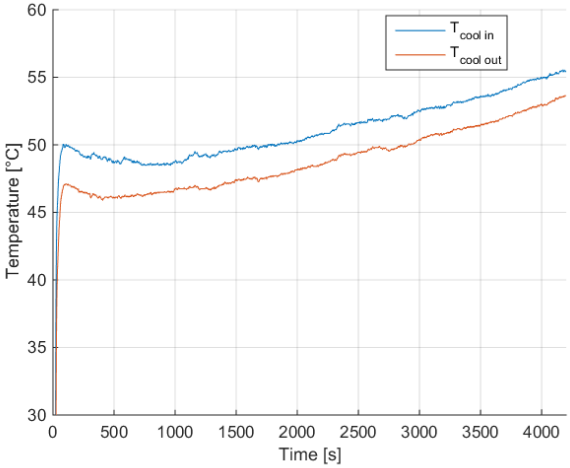


Figure 6.9: *Temperatures in and out of the heating spiral*

As can be seen in figure 6.9 the temperatures into and out from the heat spiral behaves similar to the previous data set seen in figure 6.3.

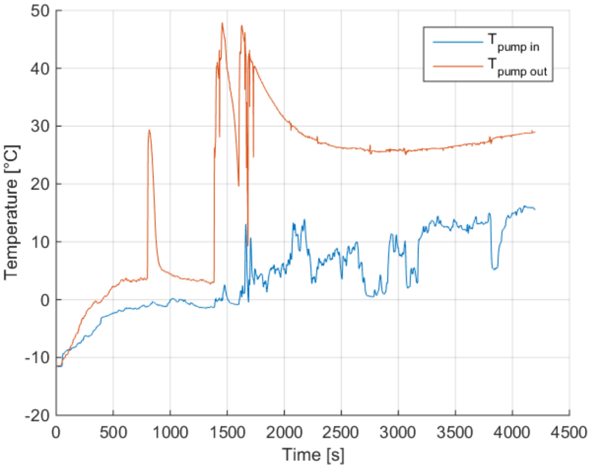


Figure 6.10: *Temperatures in and out of the dosing pump*

As can be seen in figure 6.10 the pump circulating AdBlue is started ca 1000s earlier compared to previous data set seen in figure 6.4. This leads to a faster melting procedure due to the added heat from the pump circulating AdBlue reaches the system earlier.

6.2 Constant Temperature Model

This section shows the results from simulation of the constant temperature model derived from the temperature measurements above.

6.2.1 Normal Conditions

The constant model is first evaluated when using the measurement data from section 6.1.1

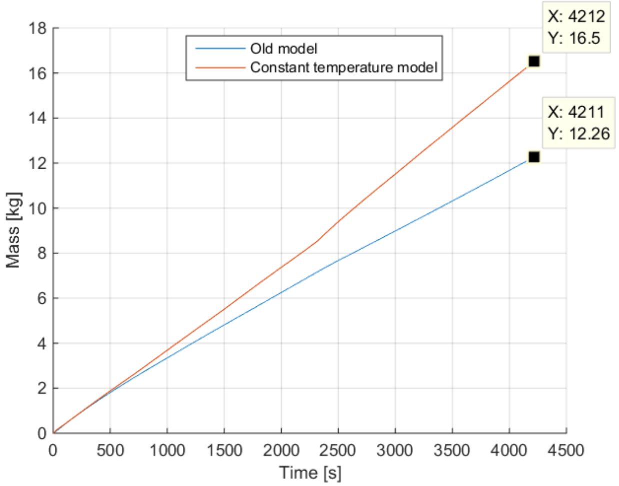


Figure 6.11: *Comparison between the static model and the old model implemented today while measuring 16.5kg melted mass liquid*

As can be seen in the result for the static model, figure 6.11, it can calculate the mass with good results compared to the measured 16.5kg of melted AdBlue. The model implemented in the system today tends to underestimate the mass and a reason is the simplification made when not using the added heat from the dosing pump and heated hoses. The added heat is in the magnitude of $70J/s$ compared to the heat spiral at a magnitude of $600J/s$, this means an increase of around 10% heat into the tank which is a large quantity of heat the model implemented today does not consider. The static model is tuned to this performance by adjusting the heat capacity constant h in equation 3.8. The model is validated against the measured mass liquid AdBlue after the experiment.

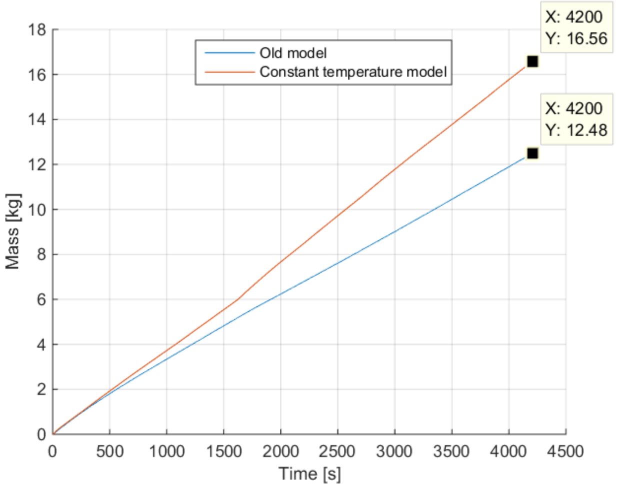


Figure 6.12: *Comparison between the static model and the model implemented today while measuring 17kg melted mass liquid*

As can be seen in figure 6.12 the performance of the model when using the verifying data set presented in section 6.1.3 is acceptable. As stated earlier the ambient temperature in this data set is estimated which can affect the performance of the model. The model is underestimating the mass melted, probably because of the heat flow is not linear as the model states.

6.2.2 Abnormal Conditions

This section shows the results from the constant model when using the measurement data from section 6.1.2

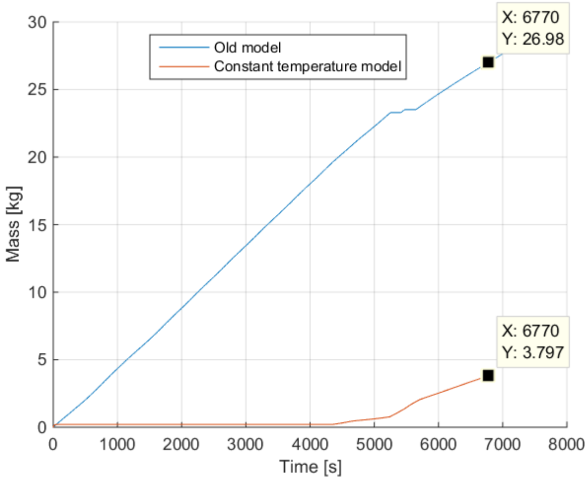


Figure 6.13: *Comparison between the static model and the model implemented today while measuring 5kg melted mass liquid*

Figure 6.13 shows the difference between the model used today and the constant temperature model when there is no heat flow to the tank. The new constante temperature model calculates with the actual heat flow and therefore there is no melted AdBlue. The model used today can not detect this because it is using the difference in temperature between the coolant and the tank to estimate the heat flow. The estimation of melted mass in this measurement series is not as good but the importance is to be able to detect a loss of heat flow.

6.3 Dynamic Temperature Model

This section shows the results from simulation of the dynamic temperature model derived from the temperature measurements above.

6.3.1 Normal Conditions

The dynamic temperature model is first evaluated with the measurement data from section 6.1.1.

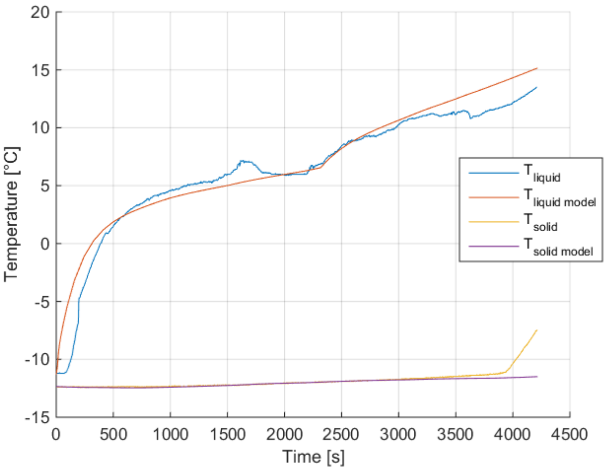


Figure 6.14: *Modeled temperature compared to the actual mean temperature in liquid and solid AdBlue*

As can be seen in figure 6.14 the modeled temperature $T_{liquid,model}$ is in close agreement with the measured data, T_{liquid}. The modeled temperature in the liquid rises faster than the measured which is understandable because of the first temperature measurement occurs away from the heat spiral. The dynamic of the liquid temperature model follows the measured data good and the added pump heat at approximately 2400s is necessary for a good result. The temperature $T_{solid,model}$, shows good accuracy and departs from the measured data, T_{solid}, when the AdBlue surrounding the thermocouple goes from solid to liquid.

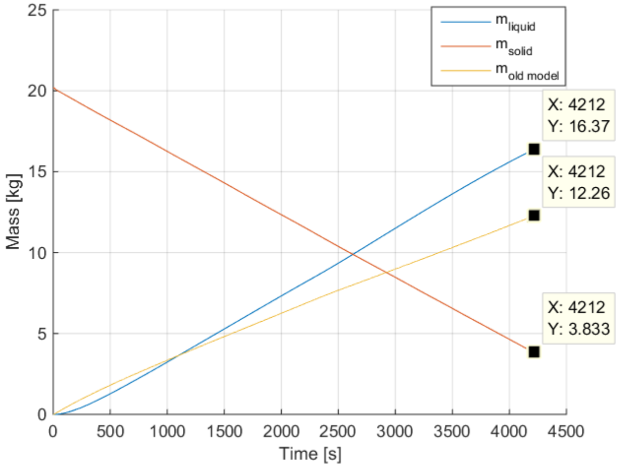


Figure 6.15: *Comparison between the dynamic model and the model implemented today while measuring 16.5kg melted mass liquid*

Figure 6.15 shows that the dynamic temperature model is estimating the melted mass AdBlue, m_{liquid}, closely to the measured value of 16.5kg compared to the model used today, $m_{old,model}$, which underestimates the liquid mass. The dynamic temperature model also takes into account different levels of AdBlue in the tank making it more versatile if other configurations would be used. The parameters h_1, h_2 and h_3 are tuned and validated against the temperature distribution in the tank and the measured amount of AdBlue melted. This gives the model a high level of security due to it being validated against more data.

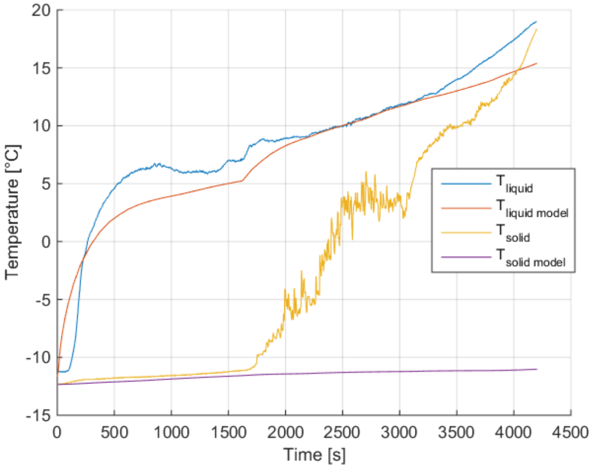


Figure 6.16: *Temperature model in liquid and solid*

Figure 6.16 shows modeled temperatures, $T_{liquid,model}$ and $T_{solid,model}$ compared to the actual temperatures, T_{liquid} and T_{solid}, when using the alternative data set. The dynamics of the temperature in the liquid phase is still good but is underestimated in the beginning of the measurements. The solid temperature is still good until the liquid phase reaches the thermocouple and there is no temperature to verify against.

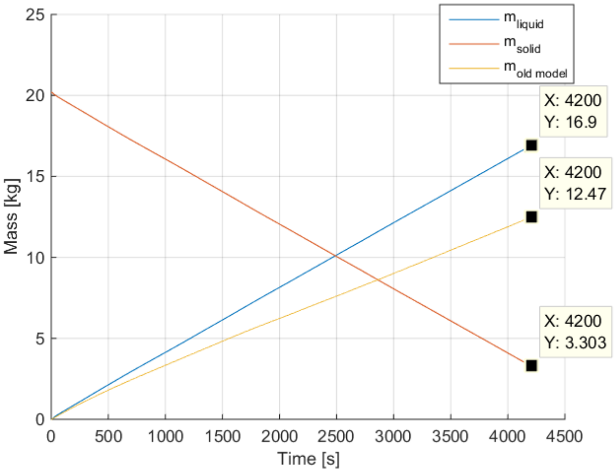


Figure 6.17: *Comparison between the dynamic model and the model implemented today while measuring 17kg melted mass liquid*

Figure 6.17 shows the performance of the model when using the alternative data set. The estimation of liquid mass, m_{liquid}, is 16.9kg compared to the measured 17kg which proves good accuracy in the model in the validation data set. Compared to the constant temperature model, the dynamic model approximates melted AdBlue better, this is because of the nonlinearity in the tank which is present in the dynamic model.

6.3.2 Abnormal Conditions

This section shows the results from the dynamic temperature model when using the measurement data from section 6.1.2.

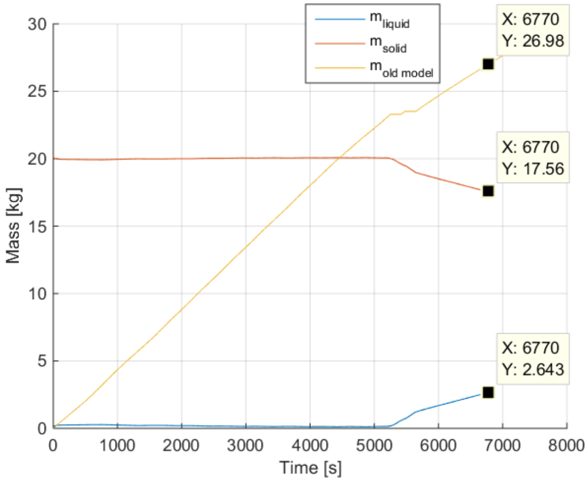


Figure 6.18: *Comparison between the static model and the model implemented today while measuring 5kg melted mass liquid*

As can be seen in figure 6.18, the estimated mass, m_{liquid}, is not good when the heat flow is disturbed into the tank. Still, as was mentioned for the constant temperature model, the lack of heat flow into the tank is easily detected when the temperatures in the heating spiral are known.

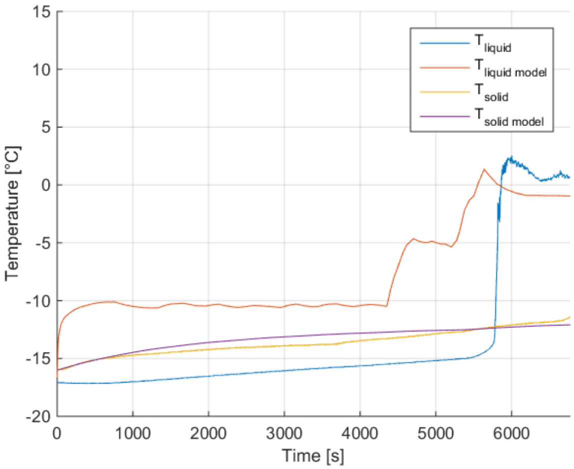


Figure 6.19: *Modeled temperature compared to the actual mean temperature in liquid and solid AdBlue*

As can be seen in figure 6.19 the temperature in the liquid region, $T_{liquid,model}$, are not close compared to the measured temperature, but the model is calculating temperature in liquid AdBlue, which is not present at that time so the temperature in the liquid cannot be verified. Still, the temperature is below melting temperature for AdBlue which is in the correct region of what the temperature should be. When liquid AdBlue is present after approximate 6000 seconds the model shows the temperature in the liquid phase better compared to the measurements. The solid temperature $T_{solid,model}$ is still estimated good with preserved dynamics compared to T_{solid} as can be seen in the figure.

6.4 Sensitivity

This section shows result form when alternating the parameters in the models.

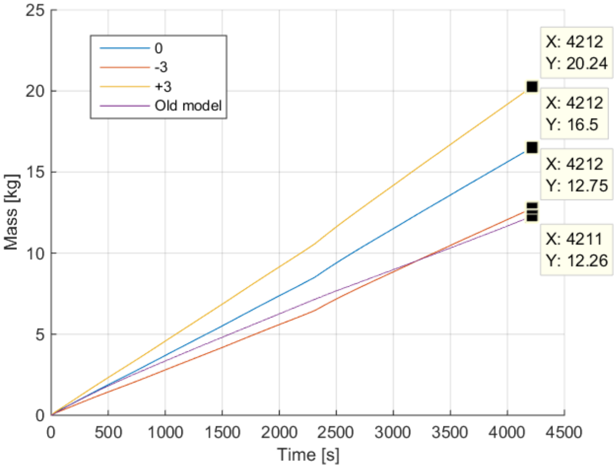


Figure 6.20: *Calcualted mass with different error on the temperature measurement on the heat spiral*

The heat flow affecting the static model the most is the one from the heating spiral. As can be seen in figure 6.20 the estimated mass is very different when applying an error on the measurements. The error in this case is ± 3°C. The error is choosed to compare how big the fault can be before the model is performing as the old one. The sensors used in the truck have an error at approximately 1% leading to a fault of less than ± 0.5°C at room temperature and the model will perform good even with the error in mind.

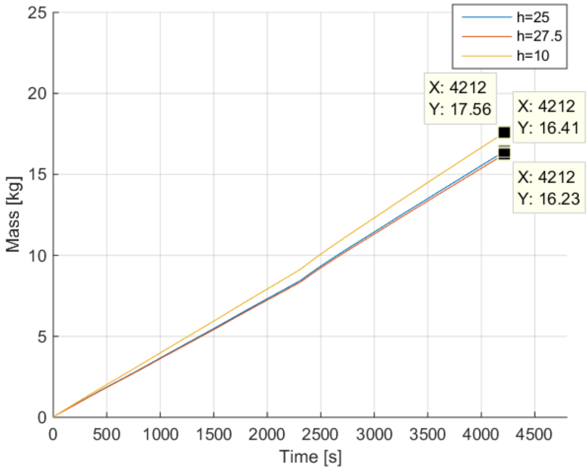


Figure 6.21: *Calcualted mass with different heat capacity h*

The static model are calibrated using the heat capacity h and verifying against the measured mass melted AdBlue. Figure 6.21 shows the result when alternating h. As can be seen in the figure when lowering h the model overestimate the melted mass and when increasing h the mass is underestimated. When changing h 10% the differences in estimated mass is roughly 1% while a 60 % change shows a 10% differences in estimated mass which means that quite large changes in the heat capacity is needed to affect the performance of the model.

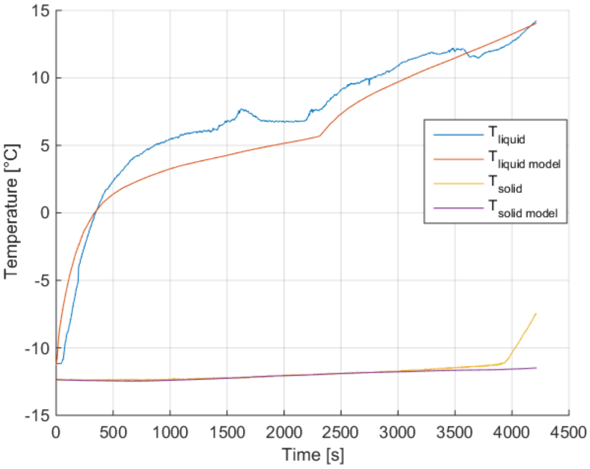


Figure 6.22: *Calculated temperature with $h1$ increased by 10%*

In the dynamic temperature model the heat capacity with the most influence is $h1$. If $h1$ is increased with 10% as can be seen in 6.22, the temperature is slightly underestimated but not with any significant magnitude.

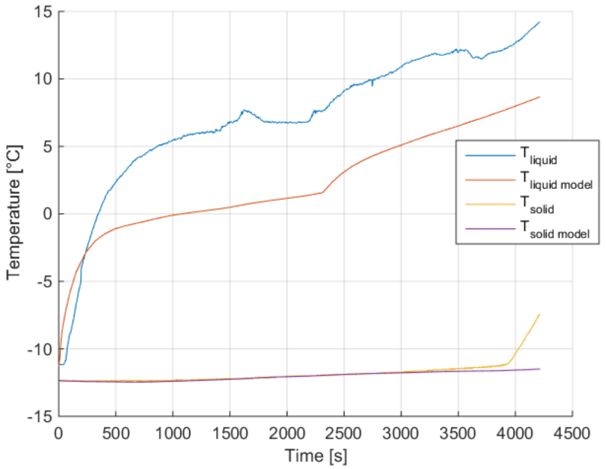


Figure 6.23: *Calculated temperature with $h1$ increased by 50%*

In figure 6.23 $h1$ is increased by 50% and there is a large drop in accuracy in the model. When looking at a change on the parameter up to 10% there is still a good temperature estimation. Above 10% the model start deviate to much from measured data.

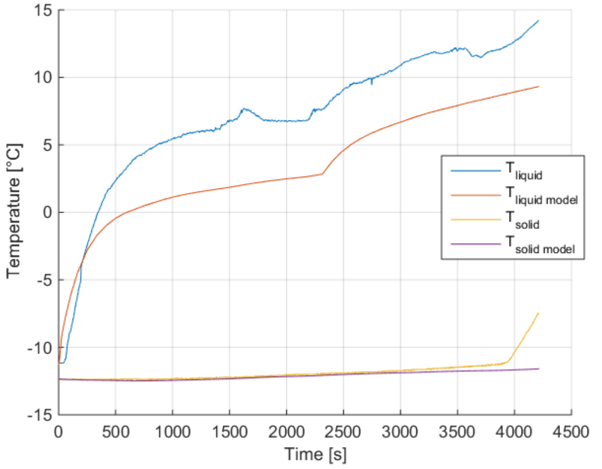


Figure 6.24: *Temperature estimation with a 3 degree lower temperature in*

A fault of 3 °C is implemented, lowering $T_{cool,in}$ to simulate a lower difference in between the temperatures in the heat spiral. A problem which could occur if unreliable thermocouples are used. As can be seen the temperature affects the model such that the temperature in the liquid is underestimated and a deviation leading to more than 3 °C lower difference between $T_{cool,in}$ and $T_{cool,out}$ leads to bad performance.

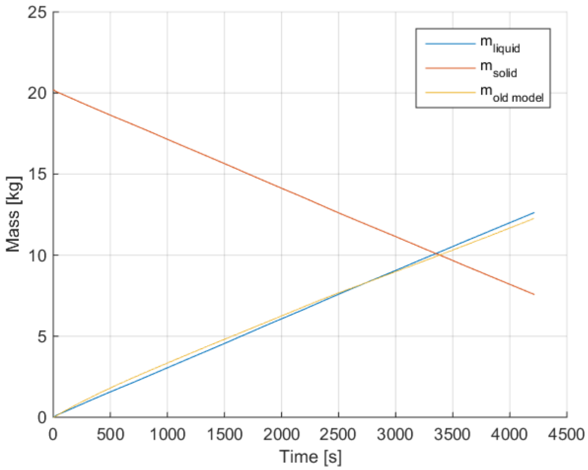


Figure 6.25: *Mass estimation with a 3 degree lower temperature in*

As can be seen in figure 6.25 lowering the temperature difference in the heating spiral leads to underestimating the mass melted AdBlue. Lowering the difference more than 3 °C leads to worse performance than the model used today. If the opposite occurs, and the difference between $T_{cool,in}$ and $T_{cool,out}$ gets higher, the model will overestimate both the temperature in the liquid phase and the melted mass AdBlue which could lead to the software trying to start the dosing pump to early and slowing down the melting procedure. The sensors used in the truck have an error at approximately 1% leading to a fault of less than ± 0.5°C at room temperature and the model will perform good even with the error in mind.

7

Conclusions and Future Works

During this master thesis two different models have been created. Both shows good results and are able to determine the amount of melted AdBlue after a certain time with good accuracy.

The constant temperature model is simple and easy to use while still evolving the present model with added heat from the dosing pump and heated hoses. Still, the constant temperature model is not dependent on the level of AdBlue in the tank, leading to less good performance at operating points far away from the one used for calibration of the model.

The dynamic temperature model uses the modeled temperatures in the tank and takes in to consideration the level of AdBlue in the tank when melting is initiated. This leads to a more physically correct model which is calibrated only after measured values in the system. This means more parameters to calibrate but they are simple to obtain if the temperatures in the tank are accessible for calibration. By considering the level of AdBlue in the tank the model is not as dependent on a operating point for calibration and should give more reliant information of mass melted for different operating points.

Even though the level in the tank is calculated when building these models, there was not enough time or space in the freezer to test with different amount of AdBlue, which would be interesting to see how much it affects the melting behavior, especially for the dynamic temperature model. The tank used was manufactured to fit in the available freezer and contain the measurement equipment and heating spiral. Due to the limited space inside the freezer, the volume of AdBlue could not be larger than 20 liters before overflowing. The shape of the tank also made it hard to test small quantities of AdBlue cause of the low hight which made it hard to mount thermocouples in a good way.

To follow up this thesis there would be interesting in the future to see how forced convection is affecting the thawing behavior of AdBlue. In the real system on a truck the tank is always exposed to wind and other environmental effects. The vibration caused by a moving truck could also affect the behavior and stir around in the melted AdBlue causing the process to speed up. The tank used in this thesis is purposely build for fitting in the freezer and fitting the equipment needed. If more time is spent, the same experiments could be done in an environment with equipment more like the real system.

8

Recommendations

The model implemented today can only access the temperature on the coolant entering the heating spiral and the temperature in the tank. If possible it is recommended to install another temperature sensor to measure temperature out of the heat spiral. By doing this it is possible to keep track of the amount of heat actually added to the tank and will make the model for the melted mass AdBlue much more reliant. This temperature are made available in this thesis and the results compared to the model used today are better. An alternative is to try to find a connection between the temperature of the coolant and the temperature measured in the tank and use them to try to model the temperature out of the heating spiral. The software should be updated so when encountering ambient temperatures below -20 °C, the dosing pump starts later to give the melting procedure more time to initiate, preventing draining of melted AdBlue that leads to insulation of the heating spiral.

As can be seen by the results in this master thesis a better estimation of the melted AdBlue can be made by updating the model with pump heat and ambient heat losses. To make it even more exact and less reliable on calibration for each and every operating mode, the dynamic temperature model should be considered where the calculation are more dependent on the physical relations in the tank and should perform better in different setups without calibration for every operating point.

Appendix

A

Measurement equipments

Name	Type	Numbers	Comment
Thermocouples	Sensor	30pcs.	24 pcs. for the tank, 2pcs., for temperature of coolant, 1pcs for temperature corresponding the built in meter, 2pcs. for pump circulation, 1pcs.for environmental and a few for spares.
Big Tank	AdBlue tank	1pcs.	Ex. 50l, ca600x400x270mm.
Small Tank	AdBlue tank	1pcs.	Ex. Regular 10l, (ca diameter 265mm, hight 275mm) bucket.
Mass Flow Meter	Sensor	1pcs.	If possible measuring mass flow, otherwise calculate it.
Lid, small tank	Tank lid	1pcs.	A round plate, ca 280mm in diameter for mounting sensor sticks.
Lid, big tank	Tank lid	1pcs.	Rectangular plate, ex ca600x400x270mm, for mounting sensor sticks.
Sensor holder	Holder	8pcs.	Stick, ca 250mm, with the possibility to fasten it perpendicular against the lid.
Nut	Nut	8pcs.	Nut for mounting stick to holder
Bolt	Bolt	8pcs.	Bolt for mounting stick to holder

B

Simulink

B.1 Static Model

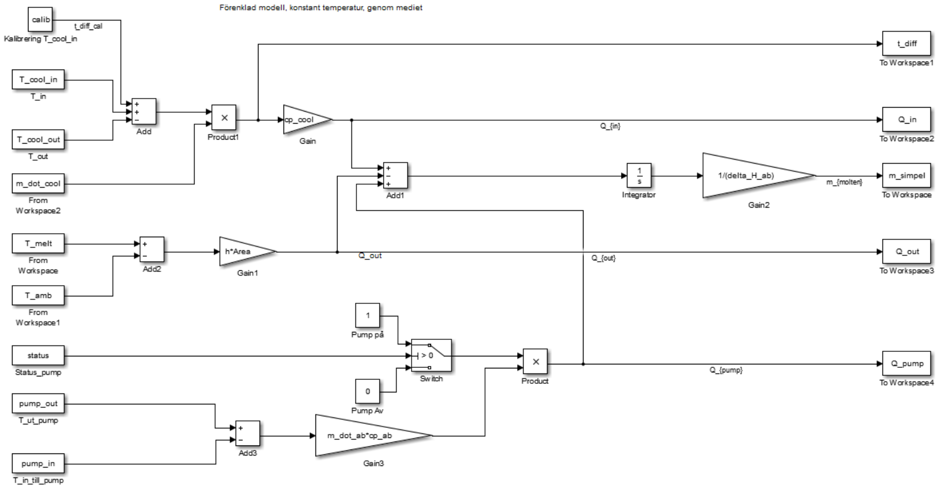


Figure B.1: *Static simulink model*

B.2 Dynamic Temperature Model

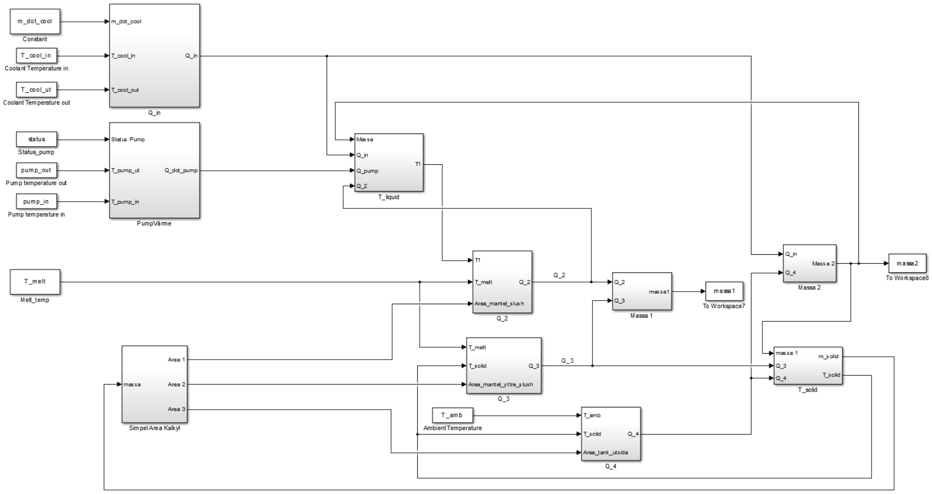


Figure B.2: Dynamic simulink model

Bibliography

[1] IPETRONIK measurement equipment. `https://www.ipetronik.com/en`. Accessed: 2015-09-07. Cited on page 37.

[2] VISION Software software. `https://www.accuratetechnologies.com/ECUCalibration/VISIONSoftware`. Accessed: 2015-09-07. Cited on page 37.

[3] Nitrogen Dioxide Health united states enviromental protection agency. `http://www.epa.gov/oaqps001/nitrogenoxides/health.html`. Accessed: 2015-05-07. Cited on page 2.

[4] Emission Standards regulatory framework. `http://www.dieselnet.com/standards/eu/hd.php`. Accessed: 2015-05-05. Cited on page 1.

[5] Vehicular Systems linköpings university. `http://www.vehicular.isy.liu.se/`. Accessed: 2015-05-05. Cited on pages vii and 1.

[6] Scania CV AB. `www.scania.com`. Accessed: 2015-05-05. Cited on pages vii and 1.

[7] Stefan aus der Wiesche. Numerical heat transfer and thermal engineering of adblue (scr) tanks for combustion engine emission reduction. *Applied thermal engineering*, 27(11):1790–1798, 2007. Cited on pages 9, 10, and 47.

[8] Theodore L Bergman, Frank P Incropera, and Adrienne S Lavine. *Fundamentals of heat and mass transfer*. John Wiley & Sons, 2011. Cited on page 11.

[9] Y Cengel, J Cimbala, and R Turner. *Fundamentals of thermal-fluid sciences (SI units)*, volume 430733322. McGraw-Hill, Europe, Middle East and Africa. ISBN, 2008. Cited on page 8.

[10] Byung-Chul Choi, Young Kwon Kim, Woo-Nam Jhung, Chang-Hwan Lee, and Chan-Yeon Hwang. Experimental investigation on melting characteristics of frozen urea–water-solutions for a diesel scr de-nox-system. *Applied Thermal Engineering*, 50(1):1235–1245, 2013. Cited on page 14.

[11] Rikard Dyrsch and Carl Moqvist. Temperature modeling and control in scr-systems for heavy trucks. 2009. Cited on pages 8 and 16.

[12] Alaa E El-Sharkawy, Panagiotis D Kalantzis, Muqsid A Syed, and David J Snyder. Thermal analysis of urea tank solution warm up for selective catalytic reduction (scr). Technical report, SAE Technical Paper, 2009. Cited on page 9.

[13] Lars Eriksson and Lars Nielsen. *Modeling and control of engines and drivelines*. John Wiley & Sons, 2014. Cited on page 11.

[14] Ola Hall. Thawing of adblue calculations with regards to legal demands eu6. Technical report, Scania CV AB, 2012. Cited on page 4.

[15] John H Lienhard IV. Jh lienhard v, a heat transfer textbook. *Cambridge massachussets*, 2006. Cited on pages 7, 9, and 15.

[16] Indrajit N Yadav. Adblue: An overview. *International Journal of Environmental Sciences*, 2(2):756–764, 2011. Cited on pages 3 and 4.

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