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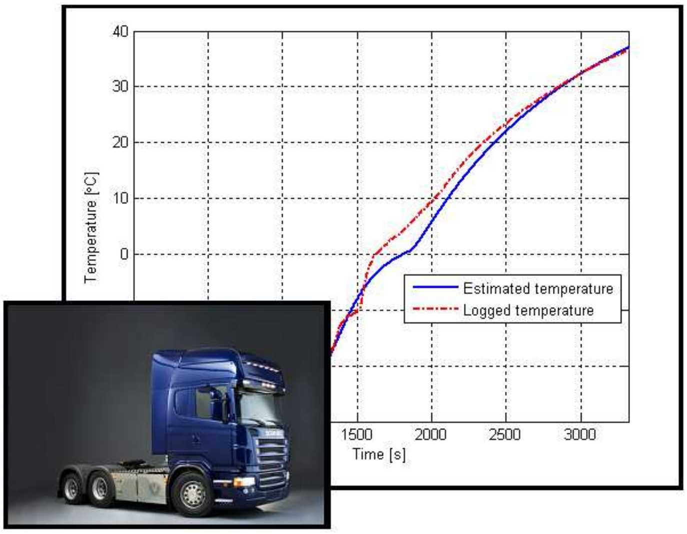

Temperature Modeling and Control in SCR-systems for Heavy Trucks

Master of Science Thesis

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Abstract

Growing demands on emission reductions in the vehicle industry require the need of better after treatment methods by the truck manufacturers. One method of NO_x reduction is by after treatment of the exhausts with a so called SCR-system; Selective Catalytic Reduction. An SCR-system injects AdBlue, a mixture of urea and deionized water, into a catalytic reactor in which the urea reduces NO_x to nitrogen gas and water.

One problem with AdBlue is the fact that it freezes at $-11\,^{\circ}\mathrm{C}$. To prevent it from freezing, the components in the SCR-system may be heated, both electrically and with hot coolant water from the engine. Due to lack of temperature sensors it is hard to know if the AdBlue in all components are liquid and installing more sensors is very expensive. In this thesis work it is examined if it is possible to estimate the temperature in the SCR-system with the use of the available temperature sensors. The estimation is done by using physical relations as well as measurement data to determine unknown parameters. The components that have been dealt with are the AdBlue tank, the pump unit and the suction, pressure and backflow hoses.

The work resulted in a model constructed in Matlab/Simulink, in which it is possible to simulate the temperatures during different circumstances. The model explains available data well, but more measurements are required to make a thorough validation.

Using the model, different control concepts for the electrically heated pressure hoses are evaluated to see if it is possible to improve the currently used on/off-control regarding thawing time and energy consumption. Simulations indicate that a feedback controller is not profitable due to the high cost in a new sensor which can not be motivated by the energy saving. Instead a proportional open-loop controller is suggested where the knowledge of the hose's static gain is used to compensate for environmental disturbances.

Keywords: SCR, AdBlue, model, Matlab/Simulink, heating control

Sammanfattning

Växande emissionskrav inom fordonsindustrin ställer krav på förbättrade metoder för avgasrening hos dagens lastbilstillverkare. En metod för att rena NO_x gaser är genom efterbehandling av avgaserna med hjälp av ett SCR-system; Selective Catalytic Reduction. Ett SCR-system injicerar AdBlue, en blandning av urea och avjoniserat vatten, in i en katalysator där urean reducerar NO_x till att bli kvävgas och vatten.

Ett problem med AdBlue är det faktum att det fryser vid $-11\,^{\circ}\mathrm{C}$. För att undvika att det fryser kan man värma SCR-systemets ingående komponenter, både elektriskt och med hjälp av kylarvatten från motorn. På grund av få temperatursensorer är det dock svårt att veta om AdBluen i alla komponenter är flytande och investeringar i nya sensorer är mycket dyra. I följande examensarbete undersöks därför om temperaturen i SCR-systemet går att skatta med hjälp av de sensorer som redan finns att tillgå. Skattningen är gjord med hjälp av fysikaliska samband tillsammans med mätdata för att bestämma okända parametrar. De komponenter som undersökts är AdBlue tank och pumpenhet samt sug-, tryck och returslang.

Arbetet resulterade i en modell i Matlab/Simulink, där man genom enkla simuleringar kan undersöka vilken temperatur SCR-systemets komponenter har under olika omständigheter. Modellen beskriver tillgänglig data väl men fler mätningar krävs för att man ska kunna göra en grundlig validering.

Med hjälp av modellen undersöks även ett antal olika regulatorer för el-värmningen av tryckslangen för att se om den nuvarande on/off regleringen går att förbättra avseende uppvärmnings tid och energiåtgång. Simuleringar indikerar att en återkopplad regulator inte är lönsam då investeringen i den sensor som krävs inte skulle betalas av mängden sparad energi. Istället föreslås en öppen styrning där man använder sig av kunskap om slangens statiska förstärkning för att kompensera mot störningen från omgivningstemperaturen.

Nyckelord: SCR, AdBlue, modell, Matlab/Simulink, värmereglering

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Södertälje, February 22, 2009

RIKARD DYRSCH
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CONTENTS

NOTATION

The following notations are used throughout the report.

Capital Letters

A	area $[m^2]$
C_p	specific heat capacity $[J/kgK]$
L	length $[m]$
P	power $[W]$
Q	heat flow rate $[W]$
T	temperature $[K]$
U	overall heat transfer coefficient $[W/m^2K]$
W	energy $[J]$

Lower-case Letters

e	energy flux $[W/m^2]$
h	heat transfer coefficient $[W/m^2K]$
l	level [%]
m	mass $[kg]$
q	heat flux $[W/m^2]$
t	time $[s]$
x	thickness $[m]$

Greek Letters

λ	thermal conductivity $[W/mK]$
ρ	density $[kg/m^3]$

Symbols

$\varnothing$	diameter [m]

Subscripts

Ab	Adblue
c	coolant
co	cold
$cond$	conduction
$conv$	convection
cr	cross sectional area
$elec$	electrical
env	environment
h	hose
l	liquid
n	non-black
p	pump unit
s	solid
t	tank
sa	surface area
seg	segment
set	setpoint
tot	total
wa	warm

1 INTRODUCTION

In this chapter a background to the work and specified requirements are given together with objective and methods used. A general introduction to SCR-systems is also given.

1.1 Background

Constantly growing demands on emission control require more efficient ways of taking care of the emissions. During combustion in a diesel engine the main emissions are hydrocarbons, carbon dioxide, nitrogen oxides, sulphur oxides and particles (Nilsson 2006). The goal for Scania CV AB is of course to be able to limit the amount of emissions that the vehicles produce but this is also regulated by rules in the different continents. In Europe the current regulation is called Euro IV and is valid until October 2008 when Euro V will be in effect. Euro V and even more Euro VI, which will be valid from 2012, focuses in particular on nitrogen oxides, see Figure 1.1 (Nilsson 2006). To be able to meet these demands, improvements on the current exhaust treatment is required.

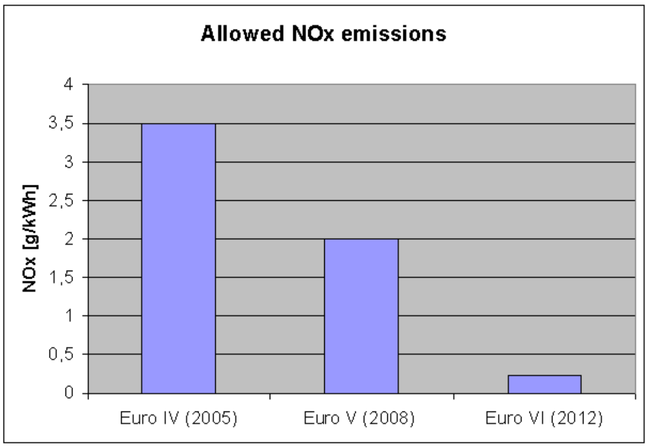


Figure 1.1. Allowed NO_x in the European emission standards.

A common way of solving this in the heavy truck industry is by after treatment of the exhausts. Since many years both heavy trucks and personal cars use catalytic converters to reduce the emissions. These are placed in the exhaust pipe and are used to convert the raw emissions into less harmful substances.

One specific type of catalytic converter is SCR; Selective Catalytic Reduction. By adding ammonia into the exhausts, nitrogen oxides can be turned into water and nitrogen gas which are not harmful to the environment. Since ammonia is considered poisonous and has an unpleasant smell the chemical compound urea is used instead. On the market this is sold as AdBlue which is a combination of urea and deionised water.

One drawback with AdBlue is the fact that its freezing-point is at a temperature of $-11\,^{\circ}\mathrm{C}$ which makes it difficult to handle in a cold environment. AdBlue itself is not damaged by the freezing and the SCR-system is also constructed to stand it, but the crystallization of the liquid makes it impossible to inject the frozen AdBlue into the exhausts. To prevent freezing and for thawing of a frozen system, heating is required. The heating can be based either on electrical energy, hot coolant water from the engine or both.

When AdBlue is frozen in the system it is important that it can be thawed as fast as possible to get the system started again. But since heating of the SCR-system is energy demanding there is a trade-off between fast thawing of the AdBlue and an energy-saving method of doing it.

To control the heating of the SCR-system in an energy effective way, information about the temperature in specific points of the system is needed. Due to lack of sensors a physichal model has to be used to estimate the temperature in important parts of the system.

1.2 Objective

The primary objective with the project is to construct a model in Matlab/Simulink that describes the temperature in different parts of an SCR-system used at Scania. The model should be constructed in such a way that even those with limited knowledge about Matlab/Simulink are able to interpret the results and configure parameters. The model should also be on a general form, so that it is easy to adjust it to different physical setups and heating concepts. The model should focus on temperatures in different parts of the system under cold circumstances, i.e. when the AdBlue is frozen or is under risk of freezing.

The secondary objective is to present a concept of how the system should be thawed in an efficient way with respect to both time and power usage when the AdBlue is frozen. This includes a study of the current used method and to develop and examine new methods that could be used instead.

1.3 Requirements

Some requirements were set up to be able to evaluate the work after the project was finished.

Model requirements:

- The temperature in all relevant parts of the SCR-system must be estimated.
- There must be a Simulink model presented for each SCR-system of interest, e.g. systems from different manufacturers.
- Properties of different components in the system such as hose dimensions and AdBlue tank volume shall be adjustable.
- Coolant water heating and electrical heating must be available in the model.
- The model shall be built such that people with only basic skills in Matlab can use it and interpret the results.
- The model must be well documented.

Control requirements:

- Evaluate the current control method and give suggestions of possible improvements regarding thawing time and energy consumptions.

1.4 Method

The model is based on physical relations. However, to get the model to behave according to the real system, measurement data is used for parameter adjustments. The model is implemented in Matlab/Simulink which is widely used both at Chalmers University of Technology and at Scania CV AB.

Using knowledge from the modeling, alternative control methods were developed. These were then compared to each other and with today's thawing method with respect to thawing time and energy consumption.

1.5 SCR - Selective Catalytic Reduction

Of the currently available techniques for reduction of NO_x in diesel engines, selective catalytic reduction, or SCR, is one of the most powerful. The technology was first used in the 1970's but then only in power plants and other stationary installations. After further development of the technology it was in the 1990's adapted to mobile applications, first in the marine industry and as late as in 2004 the first commercial heavy truck with SCR was available on the market. (Ericson 2007)

This section will give a brief introduction to SCR in heavy trucks in general and at Scania in particular.

1.5.1 General about SCR

The SCR technology is based on a chemical reductant that is applied in the exhaust flow upstream of the catalyst. The active chemical reagent is ammonia, NH_3, but as mentioned before this is, due to its unpleasant properties, used in the chemical compound known as urea, $(NH_2)_2CO$. Injected in the hot exhausts the urea resolves into ammonia and carbon dioxide as

$$(NH_2)_2CO + H_2O \rightarrow NH_3 + CO_2 \tag{1.1}$$

In the catalyst the ammonia reacts with nitrogen oxide and forms nitrogen gas and water as (Engman 2006)

$$NH_3 + NO_x \rightarrow N_2 + H_2O \tag{1.2}$$

In addition to the fact that AdBlue freezes at $-11\,°C$ there are a few difficulties with the SCR system. First of all it is under many conditions not possible to reach 100% NO_x reduction. Partly this is due to the fact that the catalyst has much slower dynamics than the engine; the catalyst typically requires several minutes to get to chemical equilibrium, compared to a few milliseconds for the diesel engine. Also the catalyst has a relatively small temperature window in which a high conversion rate can be achieved, below $200\,°C$ and above $450 - 500\,°C$ the conversion is severely decreased. Another important factor that has to be taken into account is the so called ammonia-slip. The ammonia-slip is a measurement of how much ammonia that passes the catalyst without being converted. This is unwanted because of the unpleasant smell and also because there are laws that regulate the amount of allowed ammonia-slip. (Ericson 2007)

1.5.2 Mobile SCR-systems

When used in mobile applications the main components of the SCR-system are the AdBlue tank, pumping unit, dosing unit, SCR catalyst and a control unit. The flow of AdBlue and information (e.g. sensors signals) is illustrated in Figure 1.2.

The SCR-system has sensors for temperature and level in the AdBlue tank and exhaust temperature before the catalyst. There is also a NO_x sensor placed after the catalyst. Information about the current working point (torque and rpm) of the engine is also of use and available for the SCR-system.

Based on measurements of the temperature of the exhausts as well as information about the current working point of the engine, the amount of produced NO_x and the potential to reduce this can be calculated by the electric control unit, ECU. The ECU then calculates the amount of AdBlue that should be injected and sends this information to the dosing unit. To further increase the performance the ECU can correct the amount of injected AdBlue by feedback of the difference between measured NO_x after the catalyst and the setpoint of allowed NO_x .

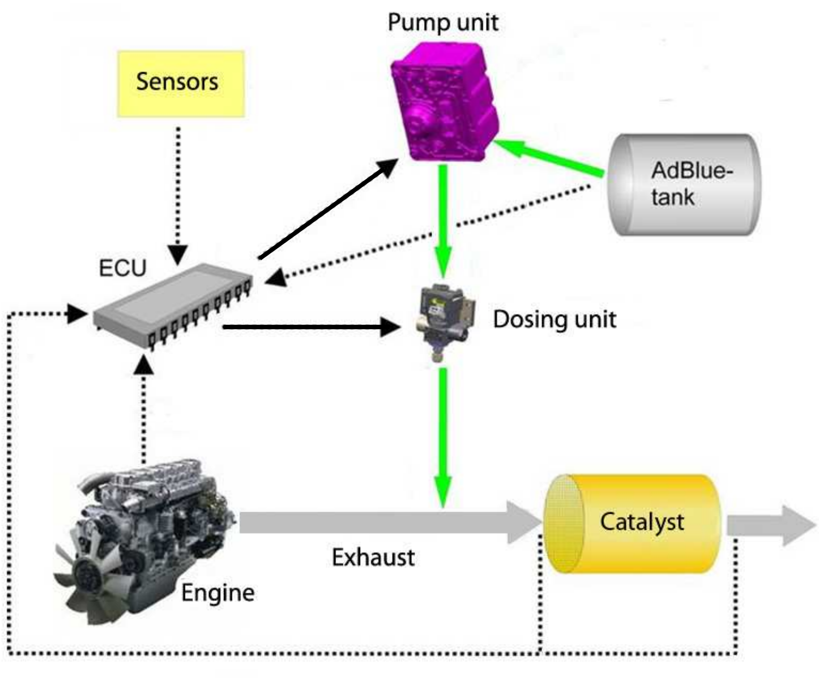


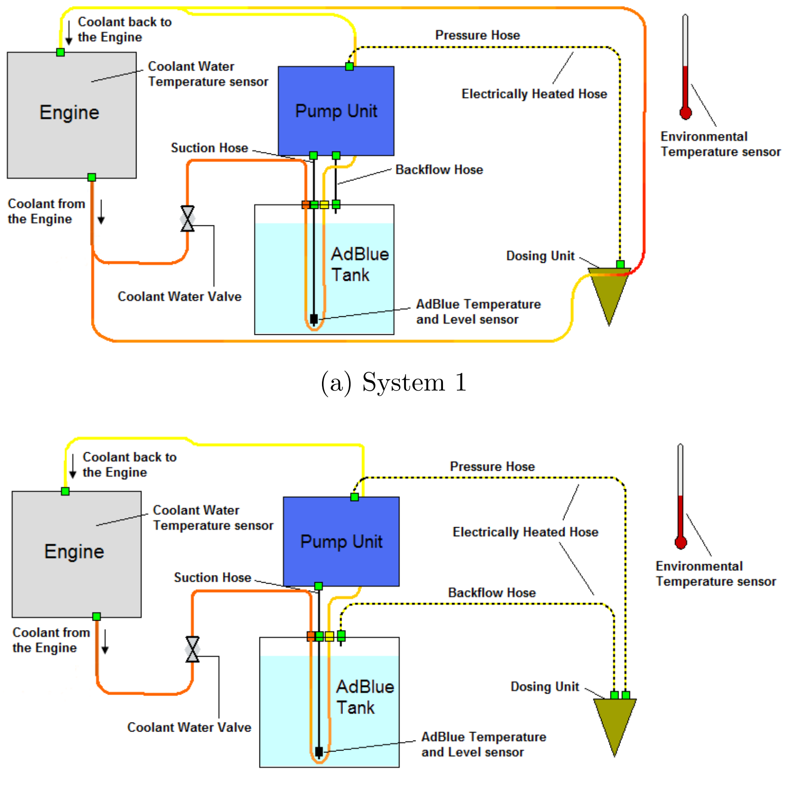
Figure 1.2. Flow of AdBlue and information in an SCR-system. The green arrows are flow of AdBlue, the solid black arrows control signals and the dotted arrows are sensor signals. © Christian Künkel, Scania CV

1.5.3 The SCR-systems at Scania

Two SCR-systems have been dealt with during this project, from now on referred to as *System 1* and *System 2*. These systems work in principle rather similarly but differ at some points. The main components are the AdBlue tank, pump unit, dosing unit, suction hose, backflow hose and pressure hose. The main difference between the systems lies in the way the temperature in the dosing unit is controlled, see Figure 1.3. Due to the placement of the unit, in connection with the hot exhaust pipe prior to the silencer, both cooling and heating of the dosing unit have to be taken into account.

In System 1 coolant from the engine is used to cool the dosing unit. This flow is uncontrollable and pumped to the dosing unit as long as the engine is running. The heating of the dosing unit relies on the hot temperature from the silencer. Therefore both the suction and backflow hoses are connected to the pump unit and redundant liquid is directly pumped back to the tank.

In System 2 another method is used for the temperature control in the dosing unit. Instead of using coolant water from the engine, System 2 takes advantage of the cooling effect from the AdBlue liquid by having the backflow hose connected to the dosing unit instead of to the pump.



(a) System 1

(b) System 2

Figure 1.3. The heating and cooling concepts of System 1 and System 2.

Due to the placement of the dosing units at the exhaust silencer these are automatically heated and therefore not taken into consideration in this project.

1.5.4 Heating Concepts

Two methods are available to thaw frozen AdBlue, and heat up AdBlue which is liable of freezing; electrical heating and coolant water heating. In this project the coolant from the engine is used to heat the AdBlue tank and the pump unit while there are both coolant water heated and electrically heated hoses used. The coolant is controlled with a water valve which can only be in the states on and off and the electrical heating can be controlled by a PWM-signal.

2 MODELING OF THE SCR-SYSTEM

The model of the SCR-system is based on both physical properties and measurement data and mainly structured as described in the three phases of modeling (Ljung and Glad 1994). According to this method the system is first divided into smaller subsystems and the degree of approximations are determined. The different subsystems are then examined further and the basic equations are formulated. In the last phase the equations are structured and suited for simulations.

In this chapter an introduction to heat transfer gives the fundamental equations and relations that the modeling is based on. A detailed description of how each part of the SCR-system is modeled then follows.

2.1 Introduction to Heat Transfer

Heat transfer between different media or within a medium is basically dependent on two things; *temperature* and *heat flow*. Temperature is a measure of the stored energy and heat flow is a measurement of the movement of thermal energy from one place to another. There are several material properties that affect temperature and heat flow. The most important of these includes specific heat capacity, thermal conductivity and material density. For more advanced calculations, fluid velocities and viscosity must also be taken into account but that will not be dealt with in this report. (Lienhard IV and Lienhard V 2008)

2.1.1 Relation between Temperature and Heat Flow

The laws governing heat transfer are typically relationships between the quantities temperature T and heat flow rate Q. Heating an object means that temperature increases as a function of the energy flow into the object. This gives the relation

$$Q(t) = C\frac{d}{dt}T(t) \tag{2.1}$$

where C is the thermal capacity. The temperature as function of the heat flow rate is then

$$T(t) = \frac{1}{C}\int_0^t Q(s)ds + T(0) \tag{2.2}$$

In some cases the thermal capacity C depends on the temperature and the temperature function is then replaced by a nonlinear expression. (Ljung and Glad 1994)

2.1.2 Modes of Heat Transfer

There are three different types of heat transfer that can occur in a heat transfer process, either by themselves or in combinations; *conduction*, *convection* and *radiation*.

Conduction

Conduction occurs when thermal energy flows from one region of higher temperature to a region with lower temperature due to molecular contact *in a medium* or *between mediums in direct physical contact*. Different materials have widely different thermal conductivities which are due to the big variations in molecular structures. Generally conduction increases with density because of the decreased distances between the molecules.

The fundamental law of heat conduction, *Fourier's law*, states that heat flow through a material is proportional to the negative temperature gradient and the area through which the heat is flowing. If the constant of proportionality is called λ, then Fourier's law can be stated as:

$$q_{cond} = -\lambda \frac{dT}{dx} \tag{2.3}$$

where q_{cond} is the heat flux, λ is called thermal conductivity , T is temperature and x is the direction in which heat flows.

In one dimensional heat conduction problems Fourier's law can be written in simple scalar form as

$$q_{cond} = \lambda \frac{\Delta T}{L} \tag{2.4}$$

where L is the thickness of the material in which heat flows and ΔT is the temperature difference. The variables q_{cond} and ΔT are written as positive quantities, i.e when expressing the heat flux on this form one must remember that heat always flows from hotter to colder regions.

The total heat flow rate Q_{cond} in a material is the heat flux multiplied by the area A, through which the heat flows. This gives the relationship

$$Q_{cond} = q_{cond} A = \lambda A \frac{\Delta T}{L} \tag{2.5}$$

(Lienhard IV and Lienhard V 2008)

Convection

Unlike heat transfer by conduction where the heat flows only by direct molecular contact, heat transfer by convection involves moving and mixing of small portions of a fluid or gas. Since convection involves motion of matter, convection can not occur at all in solids. There are two types of convection; natural and forced convection. Natural convection occurs when the motion and mixing is caused by density variations resulting in different temperatures inside the fluid. Forced convection is caused by an outside force e.g. a fan or a pump.

Heat transfer by convection involves no single property of the heat transfer medium; instead properties like fluid velocity, fluid viscosity, and surface roughness all affect the mechanism of convection. Therefore convection is usually treated empirically because of all the varying factors.

The basic relationship for convective heat transfer is

$$q_{conv} = h\Delta T \tag{2.6}$$

where q_{conv} is the heat flux, h is called the convective heat transfer coefficient and ΔT is the temperature difference between two mediums. In the same way as for conduction the total heat flow, Q_{conv}, can be stated as

$$Q_{conv} = hA\Delta T \tag{2.7}$$

where A is the area in which the two mediums are in contact. (Lienhard IV and Lienhard V 2008)

Radiation

Thermal radiation is the temperature flow from an object caused by electromagnetic radiation from the object's surface. Any object with temperature different from absolute zero will emit thermal radiation, which is generated when the kinetic energy within atoms is converted to electromagnetic radiation.

According to Stefan-Boltzmann's law, the energy flux e radiated from a non-black body is

$$e(T) = \epsilon\sigma T^4 \tag{2.8}$$

where $\sigma = 5,670400 \times 10^{-8}$ $[W/m^2K^4]$ is called the Stefan-Boltzmann constant and ϵ, $0 < \epsilon \leq 1$, is the emittance for the body, i.e the proportion of energy flux radiated from a non-black body in comparison to a black body with the same temperature. For black bodies, which are perfect emitters and absorbers, $\epsilon = 1$.

The heat transfer due to radiation from this body is then

$$Q = eA = \epsilon\sigma AT^4 \tag{2.9}$$

where A is the area of body. (Lienhard IV and Lienhard V 2008)

Since the heat transfer is proportional to the temperature to the power of four, the heat transfer due to radiation is significant for warm bodies. For colder bodies however the emitted energy from radiation can often be neglected compared to convection and conduction. Therefore heat transfer by radiation will not be treated further in this report.

2.1.3 Overall Heat Transfer Coefficient

In many practical applications a heat transfer process involves a combination of both conduction and convection. To deal with this the *overall heat transfer coefficient* is commonly used. This can be thought of as the general conductance to the heat transfer rate. A relevant example is a tank containing liquid and surrounded by air, see Figure 2.1. The heat transfer through the tank wall is mainly affected

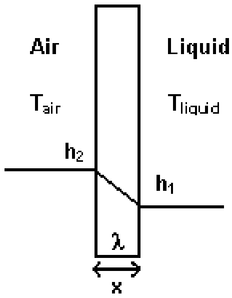


Figure 2.1. Heat flow through a tank wall with thickness x and thermal conductivity λ.

by three things; convection between the liquid and the wall characterized by h_1, the heat transfer in the wall determined by the wall thickness x and the thermal conductivity λ and the convection by air on the outside of the tank, represented by h_2. The overall heat transfer coefficient U can then be stated as

$$U = \frac{1}{\frac{1}{h_1} + \frac{x}{\lambda} + \frac{1}{h_2}} \tag{2.10}$$

The total heat transfer rate, Q_{tot}, is then

$$Q_{tot} = UA_{sa,t}(T_l - T_{air}) \tag{2.11}$$

where $A_{sa,t}$ is the tank surface area, T_l the bulk temperature of the liquid and T_{air} the temperature of the surrounding air. (Lienhard IV and Lienhard V 2008)

2.2 Parts in the SCR-system

The three main parts of the system that are modeled are the hoses, the AdBlue tank and the AdBlue pump. All system parts have one thing in common, AdBlue, which properties are described first. A detailed description of how the different parts are modeled then follows and here the different heat flows are explained. A description of the Simulink implementation is also presented.

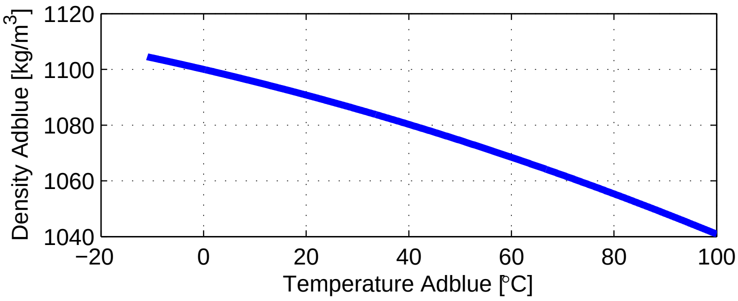


Figure 2.2. Change of density as function of temperature.

2.2.1 Properties of AdBlue

AdBlue, the mixture between urea and deionised water, is chosen at its eutectic composition which means the point with the lowest freezing temperature. For Ablue this is a composition of 32,5% urea and 67,5% deionised water and a freezing point at $-11\,^{\circ}\mathrm{C}$. (BASF Aktiengesellschaft 2005)

The *specific heat capacity* C_p for AdBlue varies with the temperature. This change however is very small within each phase. The big difference occurs at the phase change between liquid and solid why two mean values can be used to approximate the specific heat capacity within the phases: (aus der Wiesche 2007)

$$C_{p,l} \approx 3.4 \; [J/kgK]$$
$$C_{p,s} \approx 1.6 \; [J/kgK]$$

A larger temperature dependence can be seen for the density ρ_{Ab} of liquid AdBlue. This dependence is shown in Figure 2.2 and described by

$$\rho_{Ab,l} = 1100.01 - 0.428345T - 1.62819 * 10^{-3}T^2 \tag{2.12}$$

where T is the temperature in °C (BASF Aktiengesellschaft 2005). The small density change in the solid phase can be neglected, assuming that the behaviour of frozen Adblue is similar to that of frozen water. The expansion coefficient for ice is a factor ten smaller than for water. (Nordling and Österman 2004)

Another important variable used for thermal calculations is the conductivity, λ_{Ab}, which also differs depending on the phase, liquid or solid: (aus der Wiesche 2007)

$$\lambda_{Ab,l} = 0.57 \; [W/mK]$$
$$\lambda_{Ab,s} = 0.75 \; [W/mK]$$

In addition to the variable changes dependent of the AdBlue phase mentioned above is a property called enthalpy of fusion. This is the amount of energy required to create disorder among the structured molecules in the solid state and causes the temperature around the melting point to be constant until the enthalpy of melting is reached. The same behaviour can be seen in the opposite direction, in crystallization of liquid, which then is the amount of energy required to order the molecules (Sandler 2006). The specific melting heat of AdBlue is 270 $[J/g]$ (BASF Aktiengesellschaft 2005).

2.2.2 Hose Models

For both System 1 and System 2 there are three hoses present; suction hose, backflow hose and pressure hose. There are several different types of hoses and therefore models over all, at the time, available types of hoses are made. The concept of modeling hoses is independent of the type of hoses used, even though the physical properties of the hoses differ in some aspects.

To be able to estimate the temperature in several parts of the hose, it is divided into n segments with a specific length L. In this project $n = 4$ has been used. The model of the hose is then based on the different heat flows into and out from each segment as described in Figure 2.3. For simplicity the heat flow along the hose material is neglected since the effect from this is assumed to be very small.

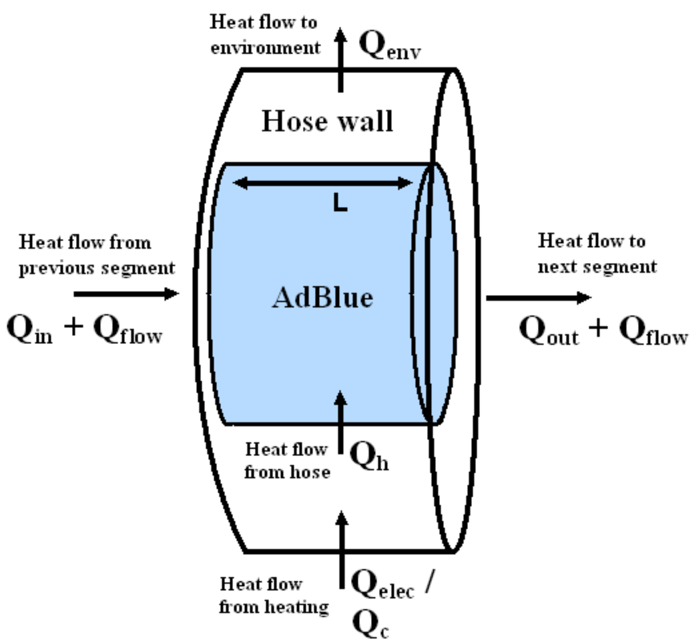


Figure 2.3. A segment of the hose and the direction of heat flow defined.

Because the thickness of the hose wall is large compared to the diameter of the AdBlue channel it must be taken into account when designing the model. The model is based on the assumption that the heating does not directly affect the AdBlue in the hose, instead the heating whether it is electric or coolant acts to heat the hose itself which in turn heats the AdBlue.

The heat flow into each segment Q_{in} and the flow out from each segment Q_{out} is the conductive heat flow that depends on the cross-sectional area A_{cr}, the length of the segment L, the thermal conductivity of AdBlue λ_{Ab}, and the temperature difference between the segments. Let $T_{Ab,seg}$ be the temperature of the AdBlue in current segment and $T_{Ab,seg-1}$, $T_{Ab,seg+1}$ the temperatures in the previous and next segment respectively. With this notation, the heat flow rate in and out of the segment can be described as in Equation (2.5) which gives

$$Q_{in} = \frac{\lambda_{Ab}}{L} A_{cr} (T_{Ab,seg-1} - T_{Ab,seg}) \tag{2.13}$$

$$Q_{out} = \frac{\lambda_{Ab}}{L} A_{cr} (T_{Ab,seg} - T_{Ab,seg+1}) \tag{2.14}$$

In the first segment $T_{Ab,seg-1}$ is the temperature from the previous component back to the AdBlue tank which can be denoted T_0. In the same way $T_{Ab,seg+1}$ in the last segment is the temperature in the next component.

The convective heat flow between the hose wall and the environment, Q_{env}, is calculated as in Equation (2.7) which gives

$$Q_{env} = h_{env} A_{sa} (T_{h,seg} - T_{env}) \tag{2.15}$$

where h_{env} is the convective heat transfer coefficient between the hose surface and the environment, A_{sa} is the outer surface area of the segment, $T_{h,seg}$ is the hose material temperature of the segment and T_{env} the ambient temperature.

As discussed earlier, two methods are available for external heating of the hoses; electrical heating and coolant water heating. Depending on the method used the properties of the hose is changed regarding material and number of channels. The hose with electrical heating has a single channel with a metal wire winded around it conducting heat to the AdBlue homogenously. The calculation of Q_{elec} is then simply based on the power into the segment as

$$Q_{elec} = \frac{P_{tot}}{n} \tag{2.16}$$

where P_{tot} is the total electric power delivered to the hose.

The coolant heated hoses has two channels as shown in Figure 2.4. In this case, the heat flow from the coolant to the hose material can be described as

$$Q_c = h_c A_{sa,c} (T_c - T_{h,seg}) \tag{2.17}$$

where h_c is the convective heat transfer coefficient between the coolant and the inner surface area of the coolant channel in the segment, $A_{sa,c}$. T_c is the temperature of the coolant from the engine. For simplification the coolant water temperature is considered constant through the entire hose.

The hose is in turn heating the AdBlue as

$$Q_h = h_{Ab} A_{sa,Ab} (T_{h,seg} - T_{Ab,seg}) \tag{2.18}$$

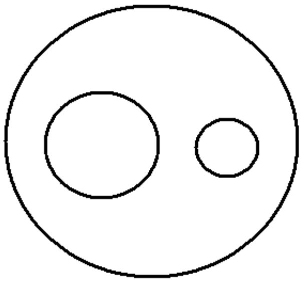


Figure 2.4. Cross section of a double channel hose. The large channel is for coolant water and the small one for AdBlue.

where h_{Ab} is the heat transfer coefficient between AdBlue and the inner surface area of the AdBlue channel $A_{sa,Ab}$. Here, depending on the phase of the AdBlue in the hose, h_{Ab} can either describe the conductive heat transfer between the hose and solid AdBlue or, when the AdBlue is liquid, the convective heat transfer between the hose and the AdBlue.

$T_{h,seg}$ is, with signs defined as in Figure 2.3, determined by

$$\dot{T}_{h,seg}(t) = \frac{1}{m_h C_{p,h}}(Q_{added}(t) - Q_h(t) - Q_{env}(t)) \tag{2.19}$$

where m_h is the mass of the hose segment material and $C_{p,h}$ is its specific heat capacity. Q_{added} can either be Q_{elec} as in Equation (2.16) or Q_c as in Equation (2.17).

There is also a heat transfer caused by the physical flow of AdBlue liquid, Q_{flow}, calculated as

$$Q_{flow} = k_{flow}(T_{Ab,seg-1} - T_{Ab,seg}) \tag{2.20}$$

where k_{flow} $[W/K]$ is determined by measurement data. In reality k_{flow} is dependent on the flow speed of the liquid. However, as long as the flow is turned on it is relatively constant through the system why the variations to flow speed can be neglected. There are ways to describe this flow more accurately, but since the flow is not relevant for the main problem in this project the above simplification is considered a good enough approximation.

By adding the heat flows in Equation (2.13)-(2.14) and Equation (2.18)-(2.20) the temperature of the AdBlue in each segment can be determined by

$$\dot{T}_{Ab,seg}(t) = \frac{1}{m_{Ab} C_{p,Ab}}(Q_{in}(t) - Q_{out}(t) + Q_h(t) + Q_{flow}(t)) \tag{2.21}$$

where m_{Ab} is the mass of AdBlue in the segment.

Tuning Parameters

In addition to k_{flow} there are for both the coolant heated and the electrically heated hoses parameters that can not be acquired from tables or datasheets. These parameters are the ones that are adjusted to get the right behavior of the model. For the electrically heated hoses the convective heat transfer coefficient h_{Ab} is unknown and for the coolant heated hoses the convective heat transfer coefficients h_{Ab} and h_c are unknown. Both of the hose types also have the unknown parameter h_{env}.

2.2.3 AdBlue Tank Model

Due to the fact that there is a temperature sensor in the AdBlue tank this part of the SCR-system is not necessary to model to be able to control the temperature. However, there is still interest in having a model for the tank as well. The model could be used to get a hint of how the coolant pipes should be configured to get a sufficiently fast heating. Another scenario is that the temperature sensor is malfunctioning. This can be more easily detected if there is a model that can predict the tank temperature based on the ambient and coolant temperature together with the time the truck has been turned on.

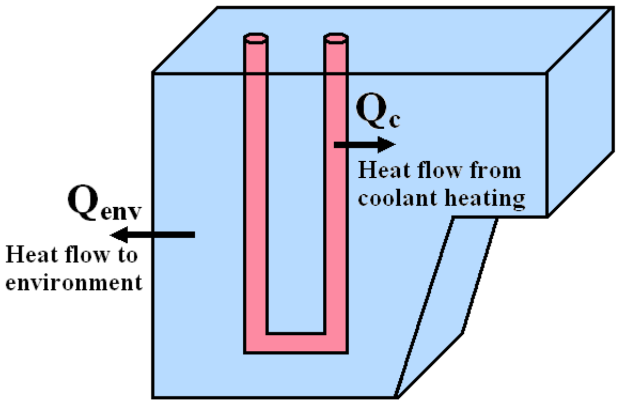


Figure 2.5. The heat flows as they are defined for the AdBlue tank.

There are two important heat flows in the tank; heat flow from the coolant to the AdBlue, Q_c, and heat flow from the AdBlue through the tank wall to the environment, Q_{env}, see Figure 2.5. The tank is heated by coolant that goes through a metalpipe from the top of the tank to the bottom and back again. This means that the amount of heat that is transferred to the AdBlue depends mainly on two things; the surface area of the coolant pipes submerged in AdBlue, i.e the surface area as function of the level l in the tank $A_{sa,c}(l)$, and the coolant temperature T_c. The coolant pipe is made of metal with thickness x_p and heat conduction coefficient λ_p. With the convective heat transfer coefficient h_c between coolant and pipe and the heat transfer coefficient h_{Ab} between pipe and AdBlue, the overall heat transfer coefficient can be stated as

$$U_c = \frac{1}{\frac{1}{h_c} + \frac{x_p}{\lambda_p} + \frac{1}{h_{Ab}}} \tag{2.22}$$

The total heat transfer rate from coolant to AdBlue is then

$$Q_c = U_c A_{sa,c}(l)(T_c - T_t) \tag{2.23}$$

where T_t is the tank temperature.

The other significant heat flow is the one from AdBlue to the surrounding air. This depends on the tank material and the wall thickness. If the tank material has the heat conduction coefficient λ_t and thickness x_t, the convective heat transfer coefficient between the tank wall and the environment is h_{env}, and the heat transfer coefficient between the AdBlue and the tank wall is h_{Ab} then the overall heat transfer coefficient can be stated as Equation (2.10) which gives

$$U_{env} = \frac{1}{\frac{1}{h_{Ab}} + \frac{x_t}{\lambda_t} + \frac{1}{h_{env}}} \tag{2.24}$$

Assuming that the area of the tank which on the inside is covered by AdBlue is $A_t(l)$, the total heat flow to the surrounding air is

$$Q_{env} = U_{env} A_t(l)(T_t - T_{env}) \tag{2.25}$$

where T_{env} is the ambient air temperature.

The temperature in the tank is then given by

$$\dot{T}_t(t) = \frac{1}{m_{Ab,t} C_{p,Ab}}(Q_c(t) - Q_{env}(t)) \tag{2.26}$$

where $m_{Ab,t}$ is the mass of the AdBlue in the tank.

Unlike for the hoses, the coolant water temperature is not considered constant during the flow through the tank. An easy way of describing the temperature after the tank is

$$T_{c,out} = T_c - L_c l k_t (T_c - T_t) \tag{2.27}$$

where L_c is the length of the coolant pipe, l is the AdBlue level [%] and k_t is a constant that specifies the heat loss per meter $[m^{-1}]$.

Tuning parameters

The unknown parameters for the tank that will be used for tuning are the three convective heat transfer coefficients h_c, h_{Ab} and h_{env}. The coolant water heat loss constant k_t is also considered unknown.

2.2.4 Pump Unit Model

The two pumps' complex shape and construction makes it hard to accurately model them using physical relations. However, simple relations can be stated and by looking at measurement data, parameters can be adjusted to make the model behave accordingly. As for the hoses it is assumed that the ambient temperature as well as the coolant heating acts on the pump unit which in turn affects the temperature of the AdBlue within the pump. There are then four different heat flows that are of importance; the heat flow due to heating from the coolant water Q_c, the heat flow to the environment Q_{env}, the heat flow between the pump unit and the AdBlue Q_p and the heat flow caused by physical flow of the AdBlue liquid Q_{flow}.

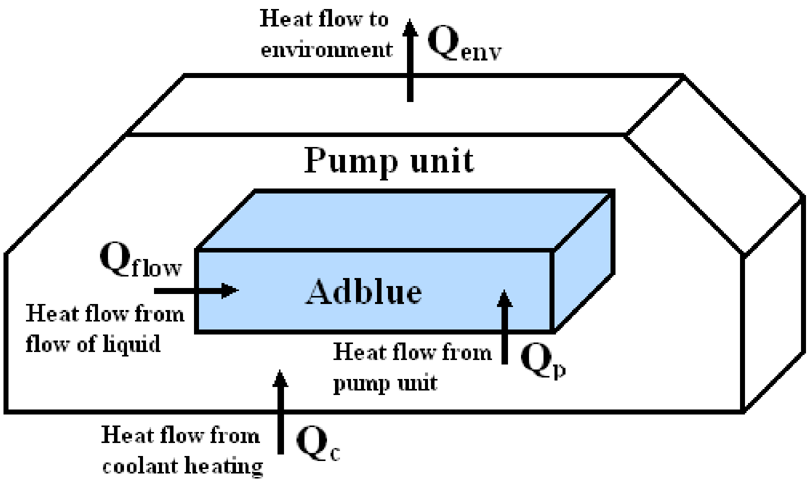


Figure 2.6. Heat flows in to and out from the pump unit.

With directions as shown in Figure 2.6 the heat flows out from and in to the pump unit can be stated as

$$Q_{env} = h_{env}A_{p,out}(T_p - T_{env}) \tag{2.28}$$

and

$$Q_c = h_c A_{p,in}(T_c - T_p) \tag{2.29}$$

where $A_{p,out}$ and $A_{p,in}$ is the outer and inner area of the pumps.

The temperature of the pump unit is in turn affecting the AdBlue temperature as

$$Q_p = h_p A_{sa,Ab}(T_p - T_{Ab}) \tag{2.30}$$

where $A_{sa,Ab}$ is the total inner surface area of the AdBlue channels.

The pump temperature can now be determined by

$$\dot{T}_p(t) = \frac{1}{m_p C_{p,p}}(Q_c(t) - Q_{env}(t) - Q_p(t)) \tag{2.31}$$

where m_p is the mass of the pump unit and $C_{p,p}$ its specific heat capacity.

As with the hoses, the AdBlue temperature is also dependent on the physical flow of liquid described by

$$Q_{flow} = k_{flow}(T_{Ab,in} - T_{Ab}) \tag{2.32}$$

where $T_{Ab,in}$ is the temperature of the AdBlue flowing in to the pump. This, together with Q_p gives the AdBlue temperature in the pump unit as

$$\dot{T}_{p,Ab}(t) = \frac{1}{m_{Ab}C_{p,Ab}}(Q_p(t) + Q_{flow}(t)) \tag{2.33}$$

Tuning Parameters

Due to the complex shape of the pump units, both concerning the outside surface area and the area of the coolant and AdBlue channels on the inside, these are considered unknown. The products $h_{env}A_{p,out}$, $h_cA_{p,in}$, $h_pA_{sa,Ab}$ in Equation (2.28), (2.29) and (2.30) will then be considered to be tuning parameters.

2.2.5 Nonlinearities

Due to the fact that AdBlue has different properties depending on its phase, a number of nonlinearities have to be dealt with in the model. These nonlinearities have in common that they all appear in the zone of phase change between liquid and solid AdBlue.

The first property suits for the specific heat capacity $C_{p,Ab}$ and the thermal conductivity λ_{Ab}. Here the value is held constant within the phase but changed in the phase change, see Section 2.2.1. This change is modeled by switching value when the temperature passes $-11\,°\mathrm{C}$.

The second property is density which is dealt with in a similar way with the difference that it is assumed to be constant as long as the AdBlue is frozen but described by a function in the liquid phase.

The last nonlinearity that has to be taken into account is the melting enthalpy which is described in Section 2.2.1. This property is modeled by holding the temperature at the melting point constant until enough energy is accumulated.

2.3 Calculations of Initial Conditions

To be able to estimate the temperatures of each component in the SCR-system, the corresponding initial temperatures must be known. Since only the AdBlue tank has a sensor installed, the temperatures in the other components must be calculated using known information, and to do this two things are needed: *The time the truck has been turned off* and *the ambient temperature during that time*. The time the truck has been turned off is easily available, but there is no way to logg the ambient temperature during the time the truck's ignition is turned off why an estimation of this is needed. The aim is to find a way to describe the average ambient temperature during the time the truck has been turned off. The estimation can be done in several ways.

The most simple way is to set the ambient temperature to the same value as the ambient temperature at the time of start-up. However, for this to be accurate the assumption must be made that the temperature has been close to the temperature at start-up during the whole time the truck was turned off. Another sligthly more sophisticated method is to save the ambient temperature when the truck is turned off, compare it to the temperature when the truck is turned on and assume that the change has been linear during the time in between. This method would probably be enough in many situations, but in some cases it would give an inaccurate value of the average ambient temperature. One scenario where this method would fail is the following: A truck is parked in a cold environment during the night. The temperature in the afternoon when the engine is turned off and in the morning when it is started up again could be rather similar even though the temperature during the night was much cooler.

To solve this, the inertia of the tank temperature can be used to get a better value of the average ambient temperature during the time the vehicle has been turned off. When the coolant heating is turned off, i.e. $Q_c = 0$, Equation (2.25) and (2.26) yield

$$\dot{T}_t(t) = -\frac{U_{env}A_t}{m_{Ab,t}C_{p,Ab}}(T_t(t) - T_{env}(t)) \tag{2.34}$$

which, by assuming that T_{env} is constant (a mean value over the time the truck is turned off), has the solution

$$T_t(t) = T_{env} + (T_0 - T_{env})e^{-\frac{U_{env}A_t}{m_{Ab,t}C_{p,Ab}}t} \tag{2.35}$$

Here T_0 is the AdBlue temperature in the tank that is saved when the vehicle is turned off and $T_t(t)$ is temperature when the truck has been turned off for t seconds.

Given the time the vehicle has been turned off, t_{off}, and the tank temperature after this time, $T_t(t_{off})$, T_{env} can be determined by

$$T_{env} = \frac{T_t(t_{off})e^{\frac{U_{env}A_t}{m_{Ab,t}C_{p,Ab}}t_{off}} - T_0}{e^{\frac{U_{env}A_t}{m_{Ab,t}C_{p,Ab}}t_{off}} - 1} \tag{2.36}$$

With knowledge of the average ambient temperature and the temperature that each component had when the vehicle was turned off, the initial temperature at start up in the system's components can now be determined. This is done by using the equations in Sections 2.2.2 - 2.2.4 with all heating variables set to zero.

3 PARAMETER TUNING DATA

To be able to adjust and tune the parameters mentioned in Chapter 2 several tests were done early in the project. Three different tests were conducted with the setup of System 1 and (due to lack of time) only one with System 2. The tests included assisted heating of a frozen system, cool down of a warm system and natural heating due to change in ambient temperature. This is then used to adjust the model parameters and get the model to behave similar to the real system.

Due to some problems at the first measurement occasion, e.g. leakage on the pressure hoses and lack of data from the pump unit, some complementary measurements had to be done in a separate test on those components.

3.1 Measurements on a Complete SCR-system

A Scania R560 Highline semi-trailer truck was used for the tests and the tests were conducted in a test cell big enough to contain the whole truck and with the ambient temperature adjustable between $-40\,°C$ and $40\,°C$. The cell is also fitted with a dynamometer so that real road conditions can be tested.

3.1.1 Preparations

The test began with mounting a number of external thermocouple temperature sensors to the truck. The sensors were directly connected to the truck onboard data monitoring system. Almost all previous tests of the temperature on the system were limited to points outside hoses and couplings. To get more accurate and faster responding temperature readings, as many sensors as possible were placed inside the hoses, both in the AdBlue flow as well as in the coolant water. To get the sensors placed in the hoses, the couplings were removed, a thermocouple inserted, and then the coupling was put back. However there are risks with doing this. One is the possibility that the thermocouple gets damaged from the coupling and therefore does not give the right temperature. Another is the risk of leakage, especially in the pressure hoses between the pump unit and the dosing unit.

Due to the long freezing time of the AdBlue tanks, three fully filled tanks were placed in $-30\,°C$ three days before the main tests were done to ensure the supply of fully frozen tanks.

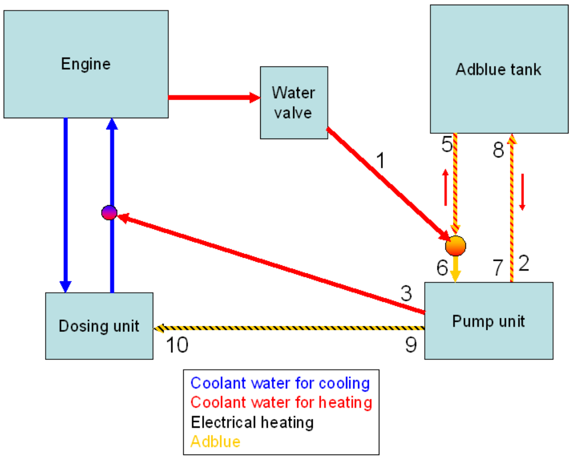


Figure 3.1. Setup of System 1. The placement of thermocouples are marked with the numbers 1-9.

Measurement Setup on System 1

System 1 was fitted with nine thermocouples (of which two had to be removed due to leakage) as shown in Figure 3.1. In this setup an electrically heated pressure hose was used. The other components were heated by coolant from the engine and the suction and backflow hoses was double channeled as shown in Figure 2.4.

Description of external measurement points:

1. Incoming coolant water from engine.
2. Coolant before pump.
3. Coolant after pump.
4. -
5. AdBlue channel in the suction hose at the tank side.
6. AdBlue channel in the suction hose at the pump side.
7. AdBlue channel in the backflow hose at the pump side.
8. AdBlue channel in the backflow hose at the tank side.
9. Pump side of the pressure hose, later removed and used as ambient temperature sensor around the pump
10. Tank side of the pressure hose, later removed.

Except for the external temperature sensors several internal signals are available as long as the truck's ignition is turned on. Some signals of interest are: AdBlue tank

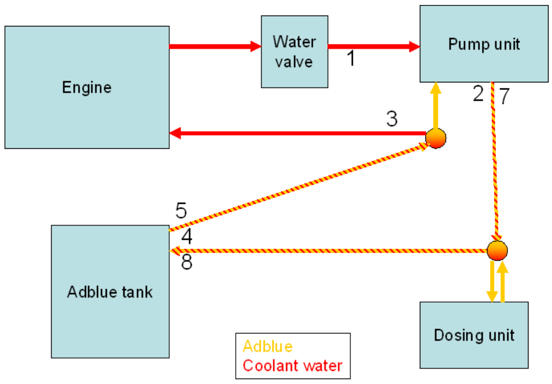


Figure 3.2. Setup of System 2. The placement of thermocouples are marked with the numbers 1-8.

temperature, ambient temperature, status of the water valve and signals indicating if the dosing is turned on or off.

Measurement Setup on System 2

The test on System 2 was made with all components coolant heated. The suction hose was double channeled as in System 1 but the pressure and backflow hoses consisted of two separate hoses lying next to each other, one containing AdBlue and the other containing coolant water. The system was fitted with eight sensors as in Figure 3.2, on roughly the corresponding places as for System 1.

Description of measurement points:

1. Incoming coolant water from engine.
2. Coolant water after pump.
3. Coolant water after pressure hose, backflow hose and tank.
4. Coolant water before tank.
5. AdBlue channel in the suction hose at the tank side.
6. -
7. AdBlue pressure hose at the pump side.
8. AdBlue backflow hose at tank side.

The internal signals that were logged are the same as for System 1.

3.1.2 Performed Tests

As mentioned above three tests were done with System 1 and one with System 2. For simplicity and to get a better overview of the tests, the results and observations from each test will be presented directly after the description of the test.

Test 1: System 1 with Assisted Heating

The first test was done to see how the system behaves when heated from a frozen state under (close to) real conditions. Before the test, to ensure true conditions for a frozen system, the system was left running for a while under normal temperatures. Here leakage on the pressure hose was detected which led to that the two sensors in the hose unfortunately had to be removed. After that a totally frozen tank was fitted, with minimal AdBlue and coolant losses. To give the system time to freeze the truck was left overnight in the test cell at a temperature of $-20\,°\mathrm{C}$.

The main test was done under the following conditions: a constant speed of 30 km/h with a load of 75 kW throughout the whole test cycle. The ambient temperature was held constant at $-20\,°\mathrm{C}$ in about 50 minutes and then changed to $-5\,°\mathrm{C}$ (partly due to some confusion on how to get the pump started). The water valve was fully opened during the whole test. When the tank reached the trigger level $-8\,°\mathrm{C}$ the system started working.

Results and Observations

As can be seen in Figure 3.3 the four different measurement points differ substantially in temperature over time. There can be several reasons for this; one explanation is that the two measurements position at the tank end is rather close to the tank armature, which itself conducts the coolant heat better than the hose itself. Another explanation can be that the amount of frozen AdBlue in the vicinity of the sensors differs. This can be shown by looking at the temperatures in the region around $-11\,°\mathrm{C}$, in point 5 and 8 there is no "plateau" which implies that there were no AdBlue undergoing phase change at that point in the hose. The different length of this plateau in the data for point 6 and 7 can also be due to different amounts of frozen AdBlue. When tuning the model, the "worst-case" should be looked at which means the assumption that any point in the hose has the maximal amount of frozen AdBlue. The large temperature drop on all sensors after about 3100 s is because the system starts up and colder AdBlue from the tank is pumped into the hoses.

In Figure 3.4a it can be seen that the coolant temperature drop is significant between the first two sensors, a reasonable assumption is that the main part of this temperature drop takes place during the flow through the tank. The temperature drop between point 2 and 3 is minimal which is explained by the pump's relatively

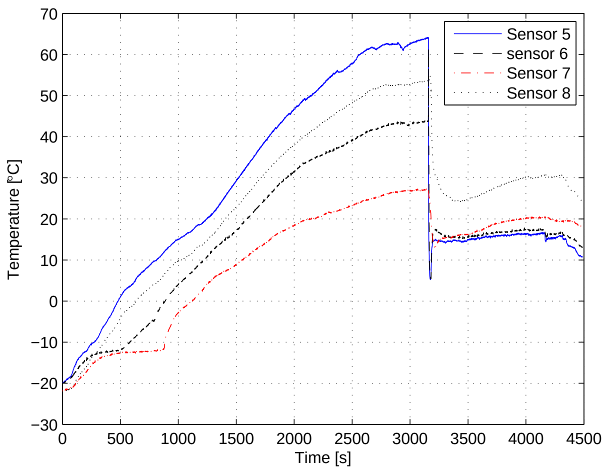
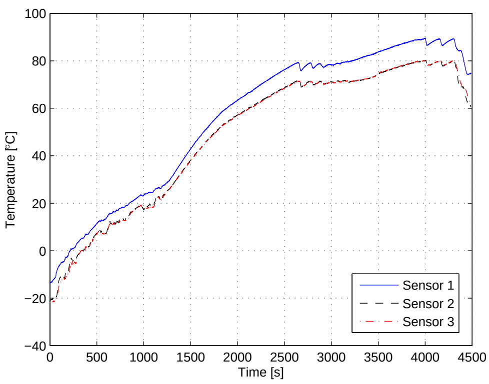
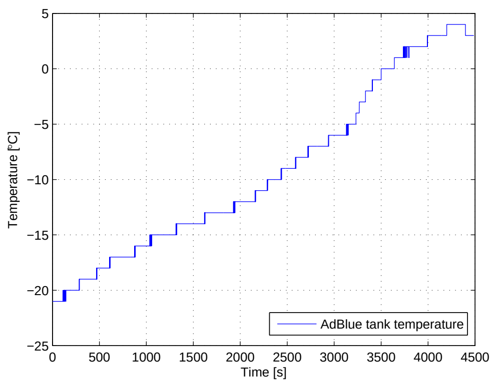


Figure 3.3. AdBlue temperature in measurement point 5-8.

small mass compared to the tank.



(a) Coolant temperature



(b) Tank temperature

Figure 3.4. Coolant and tank temperature measured in System 1.

In Figure 3.4b it is shown that the tank temperature increases a lot slower than in the hoses. This is caused by the much bigger mass. However there is minimal phase change tendencies around $-11\,°C$, probably because there is no stirring in the tank.

Test 2: System 1 Cool Down

Directly after the first test, the cell temperature was set back to $-20\,°C$ and the truck was turned off. This was done to give an estimate of how the AdBlue temperature in the hoses is affected by the ambient temperature. A drawback with this test was that only the external temperature sensors were recorded, which means that sensor 9 has to be relied on to give a proper value of the ambient temperature.

Results and Observations

The main conclusion from this test is that the coolant cools down faster than the AdBlue, which is seen in Figure 3.5. This is probably partly because the AdBlue channel has a smaller diameter which makes it more insulated than the coolant channel.

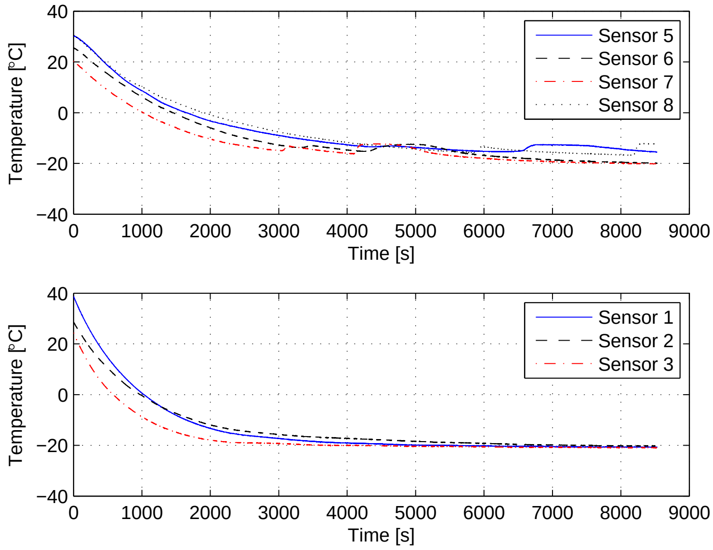


Figure 3.5. The top figure shows AdBlue temperatures from the external measurement points in System 1 and the bottom one shows corresponding coolant temperatures.

Test 3: System 1 with Ambient Heating

When all sensors (except the tank) had reached (−20 °C) the ambient temperature was changed again, this time to 10 °C while the truck was left turned off. This test was done to further give an idea of the system response to ambient temperature changes.

Results and observations

As expected after the second test, just like the cooling the heating of the coolant was faster than for the AdBlue. This can be seen in Figure 3.6.

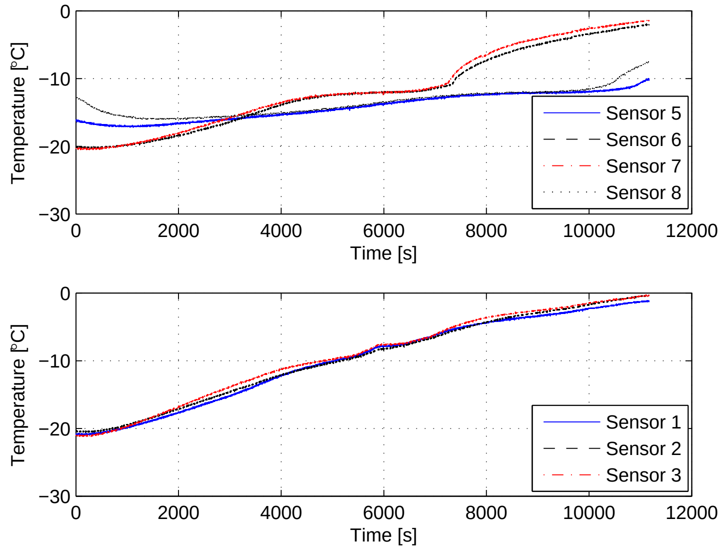


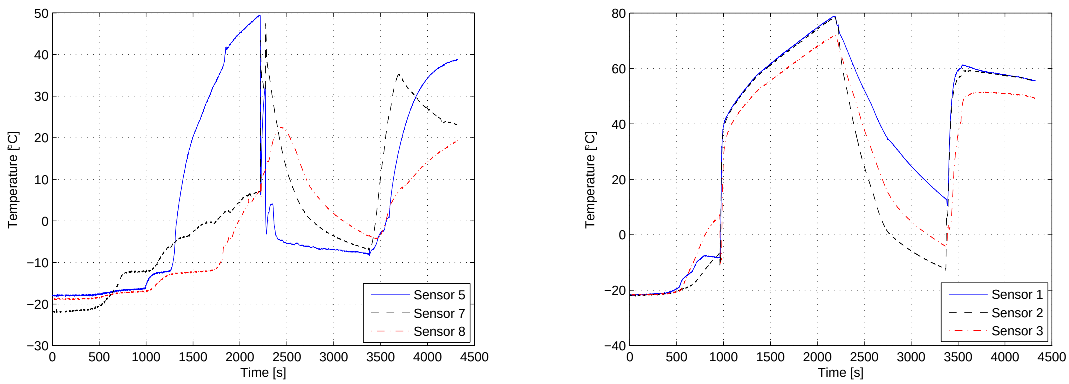
Figure 3.6. The top figure shows AdBlue temperatures from the external measurement points in System 1 and the bottom one shows corresponding coolant temperatures.

Test 4: System 2

The plan was that this test was going to be conducted under the same circumstances as the first System 1 test. However a few events occurred that changed the outcome. The initial conditions were the same; $-20\,^{\circ}$C, 35 km/h and 75 kW load. 16 minutes into the test the water valve was opened and the system started to heat up. After about 30 minutes the test was abruptly stopped after an exhaust leakage had triggered the automatic emergency stop. At the time the pump had just started building up pressure. To get rid of the exhaust the cell doors were opened and fans were started. Due to the increase in temperature it was decided to do the rest of the test outside the cell. The truck was started and was let running on idle, with the pump turned off but with heating turned on, until the temperatures had gone up in the whole system.

Results and observations

Due to the nature of this test the conclusions are not obvious. By looking at Figure 3.7a it can be seen that the AdBlue measurement points have very different temperatures. This is because the pressure and backflow hoses basically just consisted of two hoses lying next to each other. Therefore the heat transfer in those hoses is much less efficient than in the two channel hose which can be seen by the difference in temperature from point 5 to 7 and 8 in the initial heating stage. By looking at the coolant in Figure 3.7b the temperature drop is minimal in the pump but significant after the hoses and tank.



(a) AdBlue temperature

(b) Coolant temperature

Figure 3.7. AdBlue and coolant temperature measured in System 2.

3.2 Complementary Tests

The complementary tests were done on separate components of the SCR-system and therefore the case with flow of AdBlue liquid could not be taken into account during these measurements. This can be compared to the case when the pump unit is still turned off in the complete SCR-system.

3.2.1 Electrically Heated Pressure Hoses

There were no possibilities to test the electrically heated pressure hoses in the test cell. However there was a great need of getting some measurement data on the hoses to be able to adjust the model to behave accordingly.

Setup and Preparations

The tests were done in a standard freezer with the temperature set at $-20\,°C$ and the hoses were powered by a 24 V DC power supply. Three different hoses with different properties were tested and are from now on referred to as *Standard 1*, *Standard 2* and *Prototype*, see Table 3.1. As preparation, the hoses were first fitted with two thermocouple sensors, one in each end, and then to the brim filled with AdBlue. Thereafter they were plugged at each end to prevent spilling. The power output, based on input voltage and current draw, was also measured to examine if the hoses had their specified power output at 18 $[W/m]$. The calculated values were a little

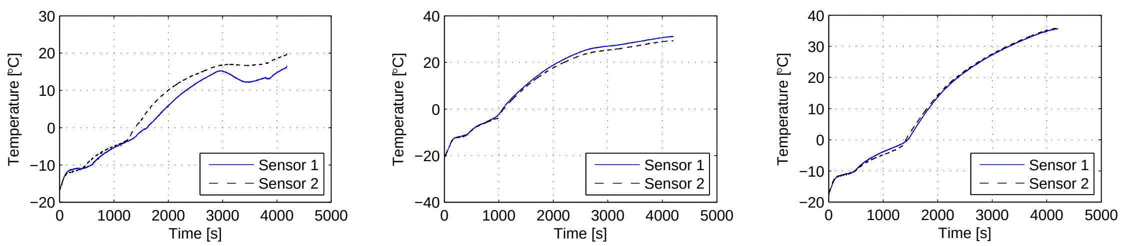
Name	L_{tot} $[mm]$	$\varnothing_{out}$ $[mm]$	$\varnothing_{in}$ $[mm]$	P_{nom} $[W/m]$
Standard 1	2240	15	7.3	16.3
Standard 2	2000	11.5	5.5	17.6
Prototype	680	30	7.3	16.2

Table 3.1. Properties of the electrically heated hoses.

less than this but in all close to the specification. The hoses were then placed in the freezer and left to freeze during the night.

Test and Results

After the hoses had been completely frozen they were one at a time heated until the temperature change had slowed down significantly. The measured temperatures for each hose are shown in Figure 3.8. As can be seen there are differences regarding the stationary temperature and the time to reach this. The main reasons for these differences can be explained by that there are differences between the hoses regarding the insulation to the environment and the electrical heat conducted to the AdBlue.



(a) Standard 1 (b) Standard 2 (c) Prototype

Figure 3.8. The heat up process of the hoses. Each hose has values from its two sensors.

3.2.2 Pump 1 & 2

As well as for the electric hoses there were no possibilities to get readings of the pump temperatures in the tests conducted in the test cell. Therefore tests on the two different pumps had to be done to get data for the pump model parameters.

Setup and Preparations

First both pumps were run in an SCR test rig to fill them with AdBlue under as close to real conditions as possible. The pumps were then removed and plugged to prevent leakage. Thereafter the pumps were fitted with thermocouples sensors in different places inside the pump housing. Pump 1 was fitted with three sensors; one close to the AdBlue filter, one near the circuit board and one in the pressure hose connector. Pump 2 was more difficult to open and therefore only fitted with two sensors, both in the AdBlue filter.

Test and Results

After the pumps had been completely frozen they were one at a time removed from the freezer and connected to a hot water supply. Unfortunately it could only deliver a maximum of 45 °C. Under real conditions the hot coolant water is at a temperature of about $80-90$ °C. In Figure 3.9 the temperatures during the heating process are shown. The water temperature was held constant at 45 °C with a flow rate of three litres per minute. It is clearly shown that the temperatures vary greatly within the pump depending on where the measurement is done.

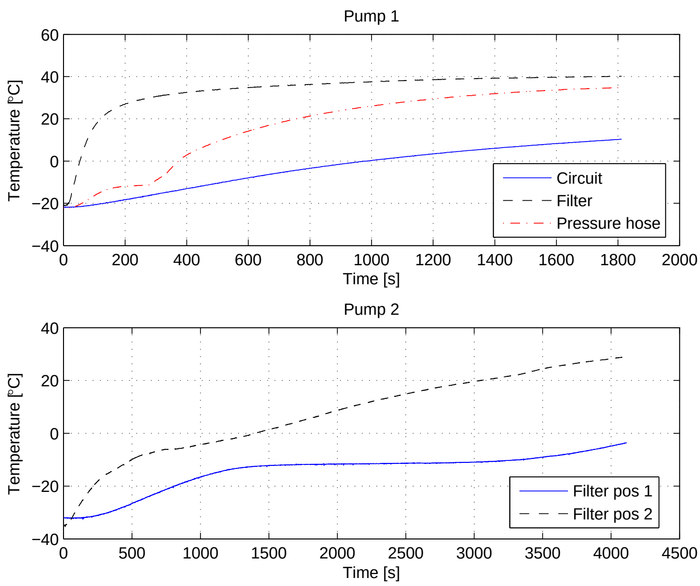


Figure 3.9. The heat up process for two pumps.

4 RESULTS OF THE TEMPERATURE ESTIMATION

The tuning parameters for each part of the system, i.e. the heat transfer coefficients, were tuned manually to fit the data from Chapter 3. No specific method for this tuning was used, but the general idea was to find a combination of the two heat transfer coefficients; from the environment to the AdBlue and from the coolant or electrical heating to the AdBlue. The idea was then to tune the coefficient concerning the effect from the ambient temperature first and that was done in the cases where such data was available, i.e. for the AdBlue tank and the electrically heated hoses.

The validation of the model is made with temperature data from a new measurement occasion. These measurements were made at the end of the project in the same test cell and under the same conditions as the measurements in Chapter 3. The results are presented for each part of the system and shown as figures containing both estimated temperature and measured temperature. Analysis of relevant results are also given for each part.

As will be seen in the results there are two things that have been dealt with in Chapter 2 that are excluded from the results; the temperature in each segment and the effect of the AdBlue flow. Here is an explanation of why that is the case:

- The hose was in Section 2.2.2 divided into segments so that the temperature could be estimated in more than one part of the hose. In the actual system however the length of the hoses was too short for any big differences regarding the coolant water temperature to appear why this could be assumed to be constant over the length. Another argument for the segments was the temperature flow within the liquid Q_{in} and Q_{out} but as this was found to be negligible compared to the other heat flows, the effect of the segments disappeared. However, the functionality is still implemented in the model since if longer hoses would be considered then the temperature loss for the coolant water would be a significant factor.

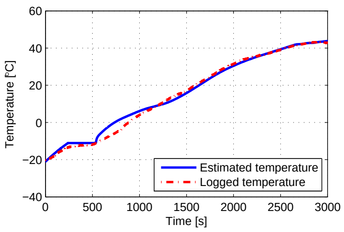
- The physical flow of AdBlue liquid which for example can be seen in the measurements in Figure 3.3 as a significant decrease in temperature was also discussed in Section 2.2.2. However since there cannot be any flow of the AdBlue when it is frozen and the main object of the model is to describe the thawing process, the results from simulations with flow enabled has been left out. As for the segments the functionality is implemented and can be seen as a general behavior when the flow is activated. No effort have been put in parameter tuning though.

4.1 Hose Temperature Estimation

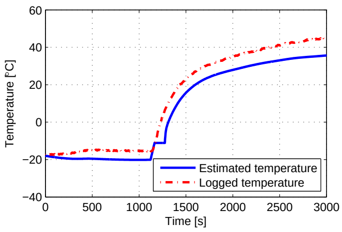
In this section the results from the temperature estimation regarding both the coolant heated hoses and the electrically heated hoses are presented.

4.1.1 Coolant Heated Hoses

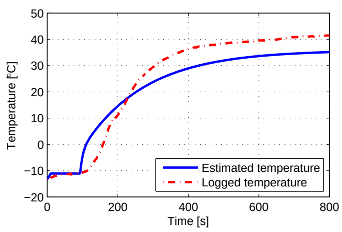
The unknown parameters for the coolant heated hoses were adjusted to give a good fit compared to *Sensor 6* in Figure 3.3. A comparison of the estimated and measured temperature can be seen in Figure 4.1a. Figure 4.1b shows the AdBlue temperature in the corresponding sensor for the new measurements on System 2 compared to the estimated. Unfortunately no measurements on any of the double channelled hoses were made on System 1 on this test occasion. Therefore to get more validation data for the coolant water heated hoses a test similar to the test of the electrically heated hoses was done. The hose was filled with AdBlue, given time to freeze and then connected to a hot water supply with the temperature 45 °C. The estimated temperature compared to the measured in that test is shown in Figure 4.1c.



(a)



(b)

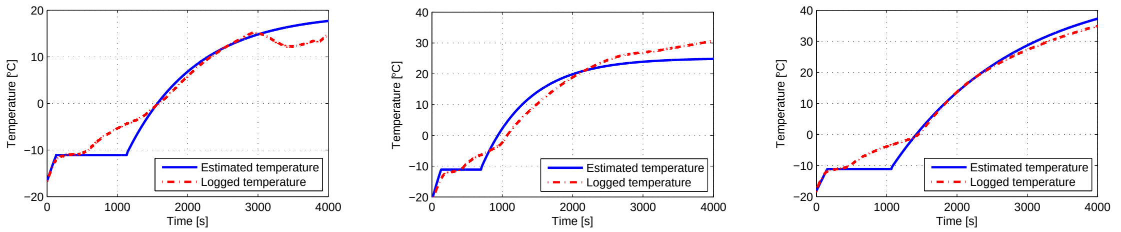


(c)

Figure 4.1. Estimated temperature compared to the measured for the coolant water heated hoses.

4.1.2 Electrically Heated Hoses

As mentioned there were no possibilities to measure the temperature in the electrically heated hoses in the test cell, due to leakage. Therefore no validation data for this part was received. However, to give a picture of how well it is possible to estimate the temperature of this part, the estimated temperature is compared to the data discussed in Section 3.2.1. The results for the three different types of hoses are shown in Figure 4.2.



(a) Standard 1 (b) Standard 2 (c) Prototype

Figure 4.2. Estimated temperature in comparison to the measured for the three different types of electrically heated hoses.

4.1.3 Analysis of the Hose Temperature Estimation

The temperature estimation in the hoses, both electrically heated and double channelled coolant heated, can be made rather well. However, as can be seen from the results there are some differences. These may depend on physical phenomenas that effect the temperature in reality but is not taken into account in the modeling, such as radiation from the exhaust silencer. Some phenomena are also hard to describe with good accuracy. An example of this is the phase change for the electrically heated hoses which does not only occur at $-11\,°C$ but in the interval from $-11\,°C$ to $0\,°C$. The reason for this is probably a combination of the sensor position and the fact that there is no stirring in the hose. If the sensor is close to the hose wall and the amount of AdBlue is big enough, the melting will first be local close to the wall and then cooled by the ice from the centre of the hose during its melting. The temperature during the phase change measured by the sensor is then not as "strict" as the model describes it why a local deviation can be seen in this region.

4.2 AdBlue Tank Temperature Estimation

An accurate model of the tank cool down is important for the calculation of initial conditions discussed in Section 2.3. By examining the cool down it is also possible verify that the impact of the ambient temperature is well modeled. In Figure 4.3, the estimated temperature is compared to measurements. The measurement data is from a winter test where the tank cool down for 10 hours in $-3\,°C$ was logged.

The measurements of the AdBlue tank temperature during heating was made in the climate cell for both System 1 and System 2, with ambient temperature $-20\,°C$. The tank used in the measurements was the same independent of the system used. The coolant water temperature was similar to the one in Figure 3.4a but the water valve was not opened until the coolant temperature had reached $45\,°C$. The results for System 1 and 2 are shown in Figure 4.4a and 4.4b.

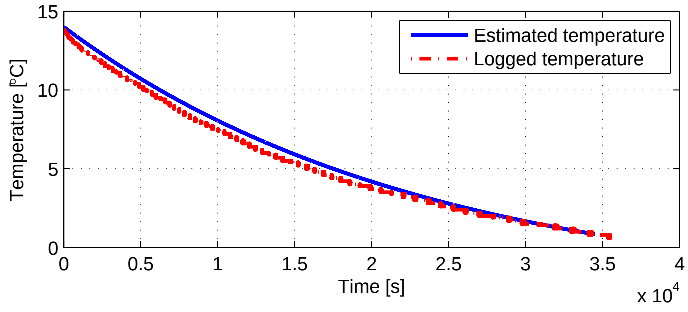
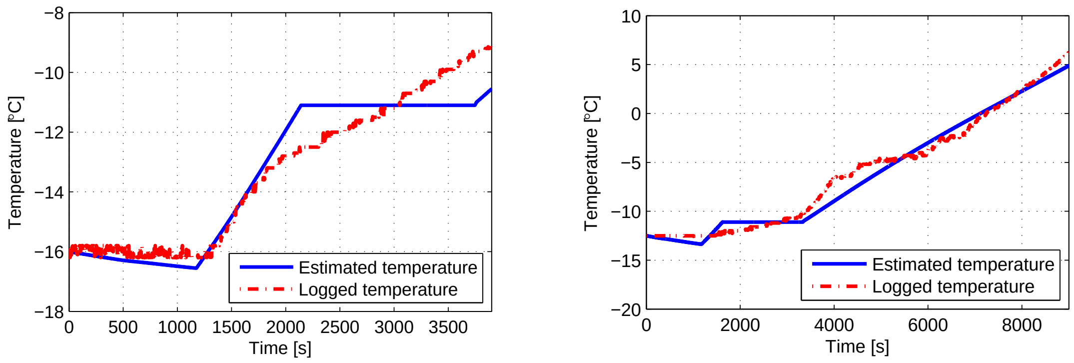


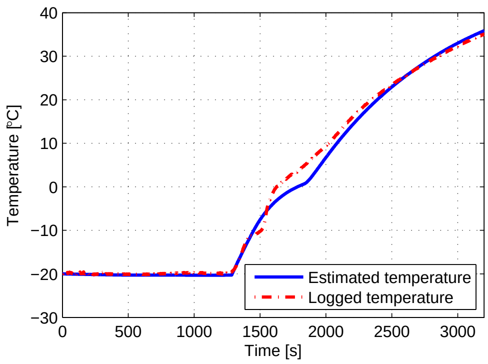
Figure 4.3. Estimated temperature compared to measurements for the cool down of the tank.



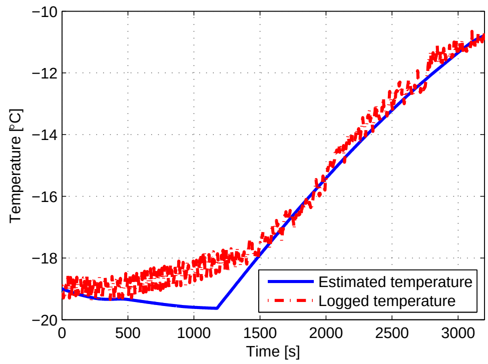
(a) System 1

(b) System 2

Figure 4.4. Estimated temperature for the AdBlue tank compared to measurements during heating.



(a) System 1



(b) System 2

Figure 4.5. Estimated pump temperature in comparison to the measured.

4.2.1 Analysis of the AdBlue Tank Temperature Estimation

As can be seen in Figure 4.4 there are some deviations between the estimated temperature and the measured. The explanations to this are mainly the same as for the hoses; radiation from the exhaust silencer is not taken into account and the phase change is more diffuse in reality than in the theory the model is based on. In the tank however, the sensor is mounted in a known place and the reason for the confusion of the phase change is more dependent on how big the region around the heating armature is that shall be taken into account in the model.

4.3 Pump Unit Temperature Estimation

As was seen in Figure 3.9 in Section 3.2.2 the temperature in the pump unit varied a lot depending on where the measurement was done. In the measurement done for validation data, a hole was drilled into the AdBlue filter in the pump to get more accurate measurements. Since it had been hard to adjust the parameters from the previous data (Figure 3.9), a comparison with that would not be fair. The parameters were therefore adjusted to fit the new measurements and the results for the pump unit can be seen more as a measure of how good fit that is possible by adjusting chosen parameters. The results are shown in Figure 4.5a and 4.5b.

5 CONTROL OF ELECTRICAL HEATING

The electrically heated hoses are controlled by a PWM-signal. This means that the input voltage is modulated as a series of pulses resulting in a specific average voltage over the system. Today a simple on/off control, which triggers on an upper and lower temperature level, is used to control the heating. To examine if this can be improved, two control methods are suggested and compared to the actual method regarding thawing time and energy consumption. Since there are no temperature sensors in the hoses, the output comes from the estimated temperature in the model. The feedback controller calculated in this chapter can be seen as a comparison of how much energy that *could* be saved if a sensor was placed in the hose.

5.1 The Electrically Heated Hose on State Space Form

To be able to design controllers, a transfer function of the electrically heated hose system from PWM-signal P_{PWM} to AdBlue temperature is needed. For simplicity, the most substantial parts for the heat transfer is chosen to express the system on state space form. As mentioned, it was found from simulations that Q_{in} and Q_{out} could be neglected in comparison to Q_{env}, Q_{elec} and Q_h. With notations as in Equation (2.15)-(2.21) and $n = 1$, e.g. calculation on one segment, this gives

$$\begin{aligned}\dot{T}_{h,seg} &= Q_{elec} - Q_h - Q_{env} = \\ &= \frac{1}{m_h C_{p,h}}(P_{seg}P_{PWM} - h_{Ab}A_{sa,Ab}(T_{h,seg} - T_{Ab,seg}) + \\ &\quad - h_{env}A_{sa}(T_{h,seg} - T_{env}))\end{aligned} \tag{5.1}$$

$$\begin{aligned}\dot{T}_{Ab,seg} &= Q_h + Q_{flow} = \\ &= \frac{1}{m_{Ab}C_{p,Ab}}(h_{Ab}A_{sa,Ab}(T_{h,seg} - T_{Ab,seg}) - k_{flow}(T_{Ab,seg-1} - T_{Ab,seg}))\end{aligned} \tag{5.2}$$

A generic state space representation is

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) + Nv(t) \\ y(t) &= Cx(t) + Du(t)\end{aligned} \tag{5.3}$$

Define

$$\begin{aligned}x_1(t) &= T_{h,seg}(t) \\ x_2(t) &= T_{Ab,seg}(t) \\ u(t) &= P_{PWM}(t) \\ v_1(t) &= T_{env}(t) \\ v_2(t) &= T_{Ab,seg-1}(t)\end{aligned} \tag{5.4}$$

Equation (5.1) and (5.2) can be expressed as

$$\begin{aligned}\dot{x}(t) &= \begin{bmatrix} -\alpha-\beta & \alpha \\ \gamma & -\gamma-\zeta \end{bmatrix} x(t) + \begin{bmatrix} \delta \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} \epsilon & 0 \\ 0 & \zeta \end{bmatrix} v(t) \\ y(t) &= \begin{bmatrix} 0 & 1 \end{bmatrix} x(t)\end{aligned} \tag{5.5}$$

where

$$\alpha = \frac{h_{Ab}A_{sa,Ab}}{m_h C_{p,h}}, \quad \beta = \frac{h_{env}A_{sa}}{m_h C_{p,h}}, \quad \gamma = \frac{h_{Ab}A_{sa,Ab}}{m_{Ab} C_{p,Ab}},$$

$$\delta = \frac{P_{seg}}{m_h C_{p,h}}, \quad \epsilon = \frac{h_{env}A_{sa}}{m_h C_{p,h}}, \quad \zeta = \frac{k_{flow}}{m_{Ab} C_{p,Ab}}$$

The transfer function from input u to output y can then be calculated as (Glad and Ljung 2000)

$$\begin{aligned} G(s) &= C(sI-A)^{-1}B + D = \\ &= \frac{\gamma\delta}{s^2 + s(\alpha+\beta+\gamma+\zeta) + \alpha\zeta + \beta(\gamma+\zeta)} \end{aligned} \tag{5.6}$$

As seen in Equation (5.4) there are two different disturbances that has to be taken into account; ambient temperature, $v_1(t)$, which can be seen as a measurable low frequent load disturbance, and the physical flow of AdBlue, $v_2(t)$.

The AdBlue flow is rather complicated to classify and to compensate for. However, this disturbance has no negative impact on the system since the physical flow requires that the AdBlue in the tank is thawed. The temperature of this liquid, which will be a dominating factor, is then not a disturbance that the controller has to compensate for. The controller will therefore only be designed to compensate for the disturbance from the ambient temperature and the physical AdBlue flow will not be taken into account, i.e. $k_{flow} = 0$. With the flow constant to zero, the parameter ζ in Equation (5.5) becomes zero and the new transfer function from input to output is then

$$G(s) = \frac{\gamma\delta}{s^2 + s(\alpha+\beta+\gamma) + \beta\gamma} \tag{5.7}$$

5.2 Properties of the Different Hoses

As mentioned in Section 3.2.1, three different hoses were tested and these are examined when the controllers are designed. However, since the control design is very similar to all hoses, only one hose will be shown for each controller in this report.

From Equation (5.7) the transfer function from PWM-signal to AdBlue temperature for each hose is calculated with parameter values for both solid and liquid phase and the result is shown in Table 5.1. For simplicity, the hoses will from now be referred to their system names given in the same table.

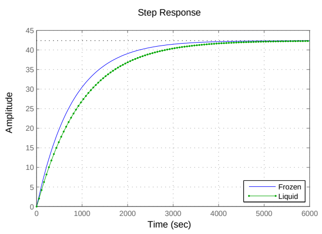
Hose name	*System name*	Transfer func when T $< -11\,°$C	Transfer func when T $> -11\,°$C
Standard 1	G_1	$\frac{0.01521}{s^2+0.2826s+0.0003591}$	$\frac{0.00716}{s^2+0.1668s+0.000169}$
Standard 2	G_2	$\frac{0.01143}{s^2+0.2125s+0.0002293}$	$\frac{0.005379}{s^2+0.1255s+0.0001079}$
Prototype	G_3	$\frac{0.01521}{s^2+0.2819s+0.0001995}$	$\frac{0.00716}{s^2+0.1661s+9.387*10^{-5}}$

Table 5.1. Transfer functions for the electrically heated hoses.

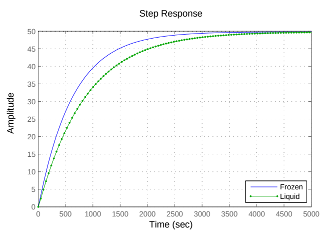
System name	*Poles*	*Static gain*	*Rise time*
G_1, T $< -11\,°$C	-0.2813, -0.0013	42.4	1726
G_1, T $> -11\,°$C	-0.1658, -0.0010	42.4	2151
G_2, T $< -11\,°$C	-0.2114, -0.0011	49.8	2053
G_2, T $> -11\,°$C	-0.1246, -0.0009	49.8	2574
G_3, T $< -11\,°$C	-0.2812, -0.0007	76.3	3102
G_3, T $> -11\,°$C	-0.1655, -0.0006	76.3	3881

Table 5.2. Properties for System G_1, G_2 and G_3.

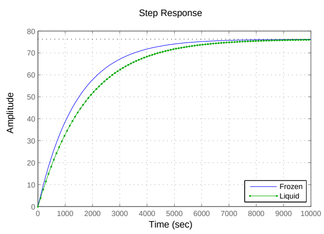
To get more knowledge about the systems' behaviours, the step response is examined (see Figure 5.1). From these it can be seen that all systems seem to be of first order even though it is obvious from the transfer functions that they are actually of second order. This can be explained by looking at the poles, in Table 5.2. Here it is seen that all systems have one dominating pole which gives them a first order behaviour (Lennartsson 2006). The dominating pole depends on that the heat transfer from the hose material to the AdBlue is fast in comparison to the heat transfer from the electrical power to the hose material.



(a) Step response for $G_1(s)$



(b) Step response for $G_2(s)$



(c) Step response for $G_3(s)$

Figure 5.1. Step response for the three different types of electrically heated hoses.

5.3 Control Design

With the hoses described by transfer functions as in Table 5.1, controllers can be designed based on stability and rise time of the system response from reference signal to output. Three different controllers are designed, one that resembles the currently used method and two alternative controllers.

5.3.1 On/off Open-loop Control

The current method used to control the heating of the electric hose is a type of on/off-control. The idea is that the control signal is either turned fully on or off depending on if there is a need to heat the hose or not. The main problem with this method is that the temperature has to be estimated to know when to turn the heating on or off. The advantage is that the control is easy to implement since the control signal only has two values, 0 or 1, which means that no function setting the control signal to an intermediate value is needed. The algorithm is stated as

$$u(t) = \begin{cases} 1 & T_{Ab,seg} \leq T_{low} \\ u^* & T_{low} < T_{Ab,seg} < T_{high} \\ 0 & T_{Ab,seg} \geq T_{high} \end{cases} \tag{5.8}$$

where T_{low} is the temperature when the heating is to be turned on and T_{high} is the temperature when it is turned off. Between these temperatures the control signal is given by u^* which is given by the rule that if $T_{Ab,seg}$ has been greater than T_{high} it will remain 0 until $T_{Ab,seg}$ is lower than T_{low}. When $T_{Ab,seg}$ has been lower than T_{low} the control signal will remain 1 until $T_{Ab,seg}$ is greater than T_{high}.

The estimation of $T_{Ab,seg}$ is in practice based on the ambient and tank temperature together with knowledge about run time and system status. In this report however $T_{Ab,seg}$ will be based on the model output to get a fair comparison between the control algorithms.

5.3.2 Proportional Open-loop Control

Because there is no way to measure the actual AdBlue temperature in the electric hose, a feedback controller can not be used to control the temperature. Instead an open-loop controller can be used. Open-loop controllers can be of many different types but the easiest way in this case is to use the ambient temperature together with knowledge about the properties of the hose to develop the control algorithm.

A simple way to control the heating is to base the delivered power on two things; the time it takes to reach a specific temperature at full electrical power and the power that maintains a specific temperature at the given ambient temperature. With knowledge about this, a simple open-loop controller can be developed.

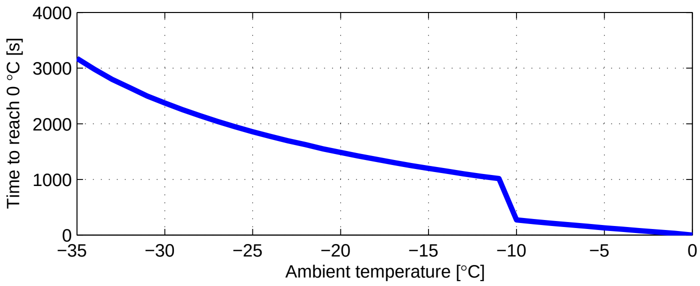


Figure 5.2. The time it takes according to G_1 to reach $0\,°C$ with different ambient temperatures.

The first thing to start with is the gain of the hose when the ambient temperature is set to a constant value and the electrical power is turned fully on. In Table 5.2 it is seen that for the hose Standard 1 the static gain, $|G_1(0)|$, is 42.4. The model assumes that the gain is independent of the ambient temperature, i.e. if the heating is turned fully on the temperature will rise by $42.4\,°C$ from the initial temperature. Because the gain is linear, half the power will give half the temperature. This gives the following relationship for G_1 between the PWM-signal, setpoint temperature and ambient temperature

$$u(t) = \frac{1}{|G_1(0)|}(T_{set} - T_{env}) \tag{5.9}$$

Using the control signal above, which can be seen as feed-forward of the ambient temperature, the output will in time reach the set point. However, since the control signal is calculated based on the difference between the setpoint and the ambient temperature a small difference will result in a small control signal. To get a faster thawing process, the control signal should be set to 1 until the setpoint is reached. Since no feedback is used, the time it takes to reach the setpoint from different ambient temperatures will have to be calculated numerically. This can be done by using Equation (2.21) but in this case the Simulink model is used to do this. Figure 5.2 shows the time it takes to reach a setpoint of $0\,°C$ from different ambient temperatures. The jump at $-11\,°C$ is caused by the phase change.

The results above are combined to form the control algorithm which can be described by

$$u(t) = \begin{cases} 1 & t \leq t_{thaw} \\ \frac{1}{|G_1(0)|}(T_{set} - T_{env}) & t > t_{thaw} \end{cases} \tag{5.10}$$

where t_{thaw} is the time it takes to reach the setpoint at full power. There are several ways to obtain t_{thaw}, one is to save values for the different temperatures in a table and get it from there. Another slightly more sophisticated way is to use polynomials that fit the curve in Figure 5.2. The following function is used for approximating the curve in Figure 5.2

$$t_{thaw} = \begin{cases} -0.10T_{env}^3 - 4.20T_{env}^2 - 109.62T_{env} + 169.85 & T_{env} \leq -11 \\ -0.04T_{env}^3 - 0.37T_{env}^2 - 26.64T_{env} & T_{env} > -11 \end{cases} \tag{5.11}$$

5.3.3 Feedback Control

The feedback control is made without an actual sensor for the AdBlue temperature. To base the control on an estimated output would be unwise since even a small model error would make the temperatures drift. A feedback controller is therefore implemented in the model for comparison with other controllers. The objective is to examine if the investment in a temperature sensor pays off by the energy savings. To be able to compare the results from the feedback control with other controllers, the same hose is used in these calculations namely Standard 1.

A PI-controller is chosen since it reduces the steady-state error that is given by a P-controller, but it is yet easy to design and implement.

Design of a PI-controller

A general formula for a PI-controller is given by

$$F_{PI}(s) = K_i \frac{1 + T_i s}{s} \tag{5.12}$$

A strategy for tuning of a feedback controller is to minimize a performance criteria with demands on stability and the control signal activity (Lennartsson 2006). For the hose we have:

- *Main criteria* for the controller is to compensate for low frequency disturbances, i.e. ambient temperature, which means minimizing J_v as

$$J_v = \frac{1}{K_i} \tag{5.13}$$

  where K_i is the integral gain. The size of K_i is limited by the demands of stability given by

$$M_S = \frac{1}{\min_\omega |1 + L(j\omega)|} \leq 1.7 \tag{5.14}$$

$$M_T = \max_\omega \left| \frac{L(j\omega)}{1 + L(j\omega)} \right| \leq 1.3 \tag{5.15}$$

  where $L(j\omega) = F_{PI}(j\omega)G(j\omega)$ is the open-loop system. Limits on M_S and M_T can be seen as a stability criterion defining the amplitude and phase margin. (Lennartsson 2006)

- *The control signal* is bounded in between 0 and 1 and there are no demands on the control signal activity *within* the limits.

The design method of the PI-controller is based on choice of the phase margin φ_m and the cross-over frequency ω_c. The phase margin can be seen as a measure of how much time delay that can be introduced before the open-loop system gets unstable. The cross-over frequency relates to the response time of the system, where a large cross-over frequency gives a fast system response. Recommended start values are

$$\varphi_m = 45^\circ \tag{5.16}$$
$$\omega_c = 0.4\omega_{G150} \tag{5.17}$$

where ω_{G150} is the frequency when the system's phase is -150°. (Lennartsson 2006)

From this T_i and K_i are calculated as

$$T_i = \frac{1}{\omega_c \tan(-\angle F_{PI}(j\omega_c))} \tag{5.18}$$
$$K_i = \frac{\omega_c}{|G(j\omega_c)|\sqrt{1 + (\omega_c T_i)^2}} \tag{5.19}$$

where

$$\angle F_{PI}(j\omega_c) = -180^\circ + \varphi_m - \angle G(j\omega_c) \tag{5.20}$$

and $|G(j\omega_c)|$ and $\angle G(j\omega_c)$ is the gain and the phase of the system at frequency ω_c, respectively.

To get K_i as large as possible, i.e. minimize J_v, φ_m and ω_c are iterated in an interval around their start values. The values of φ_m and ω_c that give the largest K_i and still fulfill the stability criteria (5.14)-(5.15) are chosen.

From this method K_i and T_i are calculated for a PI-controller on each side of -11 °C as

$$G_1(s), T < -11\,^\circ\mathrm{C} \Rightarrow K_i = 0.14, T_i = 29.7 \tag{5.21}$$
$$G_1(s), T > -11\,^\circ\mathrm{C} \Rightarrow K_i = 0.06, T_i = 49.9 \tag{5.22}$$

with $\varphi_m = 46.7^\circ$ and $\omega_c = 0.37\omega_{150}$. In the controller, the parameters are changed when the temperature passes $-11\,^\circ$C.

Since the ambient temperature is measurable it is common to use a feed-forward gain in combination with the feedback to get a faster compensation of the disturbance. However, the dynamics of the system from PWM-signal to AdBlue temperature is fast in comparison to the change of ambient temperature why feedback control is enough to compensate for the disturbance.

A way to evaluate the controller after the design is to examine the sensitivity function $S(j\omega)$ to see how well process disturbances are compensated for. In Figure 5.3 the magnitude for this function and for the open-loop system are shown for different frequencies. Here it is seen that for low frequencies the magnitude of $S(j\omega)$ is small which means that low frequency disturbances are well attenuated. This is the same as saying that the gain of the system is high for low frequencies which can be seen by looking at $L(j\omega)$.

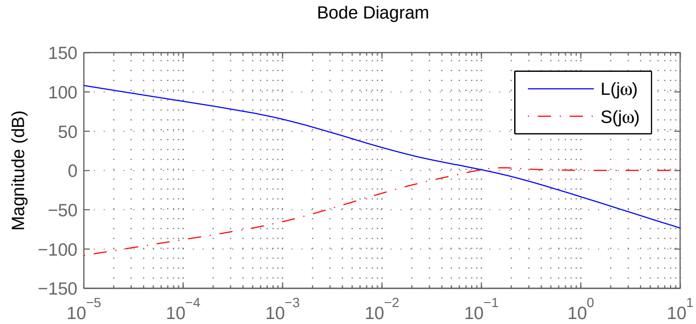
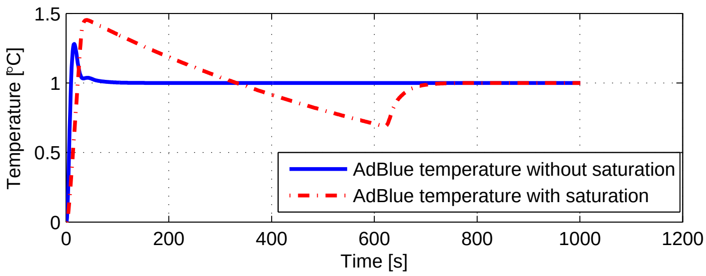
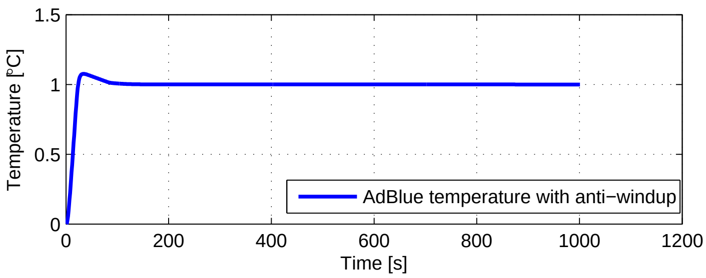


Figure 5.3. Magnitude diagram for $L(j\omega)$ and $S(j\omega)$.

Due to the fact that the PWM-signal can not be more than 1 or less than 0 the control signal becomes saturated if the controller demands values outside these limits. A common problem when this occurs is that the I-part of the controller drifts away to large values since no effect of the changes is seen on the output error. When the control signal is desaturated it will then take time for it to recover which has a negative effect on the output, see Figure 5.4a.



(a) Without anti-windup



(b) With anti-windup

Figure 5.4. The closed-loop system's step response with windup and anti-windup respectively.

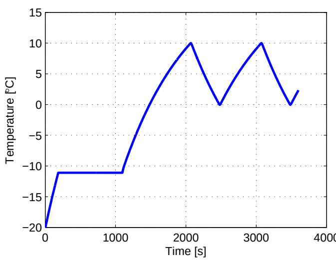
To prevent this phenomenon to happen, anti-windup is implemented which means that the increase of the integrator part is interrupted if the control signal goes outside its limits. The results of this can be seen in Figure 5.4b.

5.4 Results and Analysis of the Control

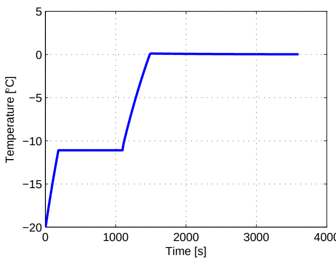
The three controllers described in Section 5.3 are compared regarding thawing time and energy consumption. The comparison is made based on simulations with the following settings:

- Hose Standard 1
- Length 1 m
- Set point = 0 °C
- Ambient temperature = −20 °C
- Pump unit turned off ⇒ No flow of AdBlue in the system

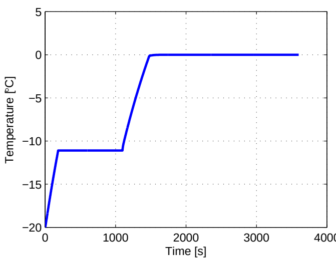
In the case with on/off-control, the trigger values (T_{low} and T_{high}) are set to 0 °C and 10 °C. This to be sure that the temperature is always on ”safe-side” of the lower limit since the temperature in the system is estimated. For the feedback control, it is assumed that the AdBlue temperature in the hose is measured with high resolution and no signal noise.



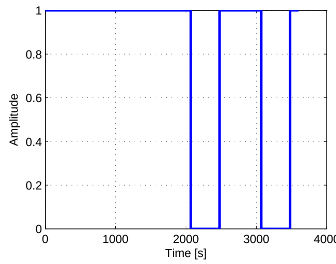
(a) Temperature on/off open-loop control



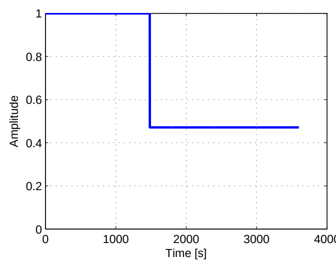
(b) Temperature proportional open-loop control



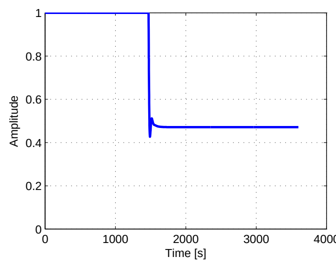
(c) Temperature feedback control



(d) Control signal on/off open-loop control



(e) Control signal proportional open-loop control



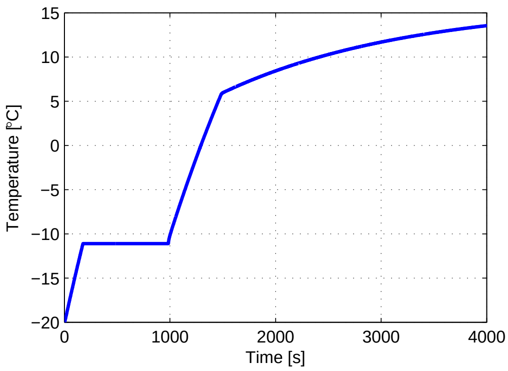
(f) Control signal feedback control

Figure 5.5. Temperature and control signal for each of the three controllers.

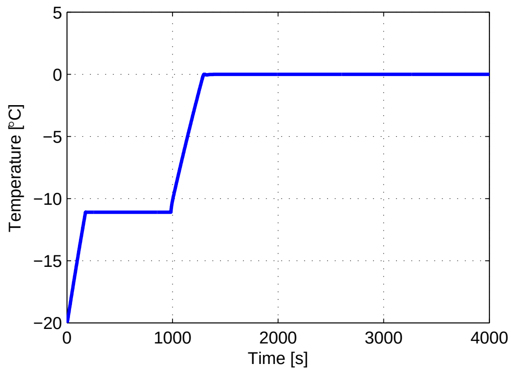
The resulting temperatures and control signals for each controller are shown in Figure 5.5. The energy consumption and time to reach the setpoint for each controller

Control method	t_{set} $[s]$	W $[kJ]$
On/Off	1485	100.1
Open-loop	1485	89.32
PI	1600	89.21

Table 5.3. Time to reach the setpoint 0 °C and energy consumption the first hour.



(a) Proportional open-loop control



(b) Feedback control

Figure 5.6. Temperature using the Prototype hose using the same controller parameters.

are shown in Table 5.3. The energy consumption W is calculated from the control signal as

$$W = \int_0^t P(s)ds \tag{5.23}$$

where P is the power into the hose.

In Table 5.3 the time to reach the setpoint is longer for the PI-controller than for the other controllers. However, the temperature for the PI-controller is very close to the setpoint at $t = 1485$ s which can be seen in Figure 5.5.

To see how well the controllers can handle model errors the hose is changed to the one called *Prototype* and everything else is left unchanged, including the controller parameters. The results are shown in Figure 5.6. It is clearly seen that the proportional open-loop controller fails to reach the setpoint when the hose is changed.

6 DISCUSSION

In this chapter the results are discussed and suggestions of future work are given. A description of what the Simulink model can be used for is also presented.

6.1 Temperature Estimation

As has been obvious in this report, many parameters are not possible to find in tables and are therefore adjusted to measurement data. The majority of the data for these parameter adjustments were given from only one measurement occasion, i.e. the data from Chapter 3, and most of the measurements were made using external thermocouple sensors. As a result from this it can be hard to tell if it is always the right thing that has been measured and adjusted to. Therefore, to get a reliable model more measurements in different setups are needed. Here follows some comments of the results from the different components.

The AdBlue temperature in the coolant heated hoses was possible to measure at both measurement occasions. The amount of available data for these hoses was therefore considered satisfying. However, even though the measurements were made in similar parts of the same type of hoses, the measurement data had significant temperature variations. To deal with this the ”worst case” temperature was regarded as the parameter tuning value. By more measurements in similar setups, one could possibly get a better idea of which temperature that actually is representative in the general case.

Concerning the electrically heated hoses the major problem was the fact that it was not possible during the project to measure the AdBlue temperature on the truck without leakage. The temperature was therefore not possible to measure in any of the two measurement occasions. The problem here is then not just lack of validation data but also the fact that the measured temperatures in the isolated tests may differ from what the results had been if the measurements would be done on the real system.

For the AdBlue tank all measurements have been made with a frozen tank and it has been heated for a relatively short amount of time. The model can predict the temperature in this time rather well, however there has been no opportunity to test the model accuracy over longer periods i.e. when the temperature has reached the stationary point. Further measurements are needed to test this but it was unfortunately not possible during the time of this project. Also in all tests the tank has been totally filled and it would be of interest the see how and if the behaviour changes with other volumes in the tank.

Regarding the pump unit the main problem was the high complexity of its shape and mix of material which made the measurements important in the parameter tuning of the model. The measurements however was a problem themselves since it is hard to tell where the measurement point should be to give the true AdBlue temperature. Therefore the assumption was made that the measurement with a drilled hole into the Adblue filter gave the most reliable data. This data was given first at the second measurement occasion that was made at the end of the project and therefore no dedicated validation data was avaliable.

To further improve the results in this project more testing is definitely needed. With more measurements from different test runs it could be possible to get a better idea of the model performance. Highest priority has measurements on the pump unit and the electrical heated hoses since this is needed for validation. Further tuning of the model parameters or augmenting some parts can also turn out to be necessary with more reference data.

6.2 Control Methods

From the results in Table 5.3 it is seen that there are rather small differences between the controllers. This is mainly caused by the saturation of the control signal which limits the effect on the output from changes on the control signal. However, more properties than thawing time and energy consumption can be regarded when evaluating the controllers. The following can be said about the different methods:

- *On/off open-loop control* is simple and easy to implement. The method does not require much calculations, but knowledge about the system is needed to get a good estimation of the temperature in the hose. Since this estimation is hard to make and the limits must be put on the "safe side" the method easily gets energy consuming.

- *Proportional open-loop control* is possible to implement without investments in an extra temperature sensor and gives an energy efficient way of heating. In a final setup of hardware this may be seen as an alternative setup to the current since it is easy to implement without additional hardware but still energy saving in comparison with today's solution. The controller however is very sensitive to the hose properties and not robust to changes, see Figure 5.6a. To get a reliable controller good measurement data is also needed and small changes may require new measurements and design.

- *Feedback control* demands a sensor in the hose, and today that investment is not profitable. If a specific temperature in the hose is necessary or a demand would be that one must be able to change arbitrarily between hoses, the investment in a sensor could be considered. An example of the controller robustness was seen in Figure 5.6b.

As mentioned the controllers have been evaluated based on simulations and there were no time or possibilities to try them on the real system. To verify if the conclusions from the simulations are valid the controllers must be implemented on the real SCR-system and tried under different circumstances.

6.3 Simulink Model Applications

Except for temperature estimation in the SCR-system the Simulink model can be used for a variety of tasks both concerning software and hardware design. One hardware application that the model can be used for is when designing the AdBlue tank and its heating configuration. Arbitrary values of tank volume and length, diameter and thickness of the coolant pipes can be chosen and evaluated. This way there is a possibility to get a primary idea of these parameters before ordering a prototype tank. Each prototype that can be avoided means saving a significant amount of money. The same thing goes for the number of measurements; Each measurement requires several hours of preparations from engineers and mechanics and the actual measurement takes costly time in the testing cells. Every saved hour means money that can be used for other things. Another hardware application is testing of electrically heated hoses. With knowledge of its physical properties it is possible to get an estimation of the performance before actual testing on the hose itself.

The main software application is testing of different control concepts, mainly for the electrically heated hoses. Apart from the methods mentioned in this report it is relatively easy to implement and evaluate other methods.

6.4 Implementation in the Truck Control Unit

There are a number of applications of the model that could be useful if implemented on a truck. The main application is of course to get an estimate of the temperature in the unmeasurable parts of the system. This together with the estimation of the initial states would be very useful when a fast and energy efficient heating is wanted. The model can also as mentioned be of use when designing diagnosis functions to detect sensor failures or system malfunctions.

7 CONCLUSIONS

Models describing the temperatures in the different parts of the two SCR-systems used at Scania have been developed. The parts that have been modeled are the Adblue tank, the pump unit and the suction, backflow and pressure hoses. The models are based on physical relations but some tuning parameters exist to enable model adjustments to measurement data. To collect measurement data, tests were done both on complete SCR-systems in a test cell and by separate tests on individual components.

The two models were built up using Matlab/Simulink. A logical structure and masking of the Simulink blocks make the models easy to understand and usable even for those with only little experience in Matlab/Simulink. There are a number of parameters that can be adjusted and tested using the model such as different environmental temperatures, tank volumes and length of the hoses. From this the model can be a helpful tool for hardware design and controller design for electrically heated hoses.

With the unknown parameters adjusted to reference data the temperature estimation in the different parts of the SCR-system can be done with good results. There is some uncertainty concerning the temperatures in the pump units on both systems because of the large temperature variations in different parts of the pumps. For the pump unit in particular, but also for the other components, the main problem is the lack of measurement data. More data needs to be collected to validate the model further.

Based on knowledge from the model, new algorithms for controlling the electrically heated hoses have been developed and compared to the current on/off-controller, one open-loop and one feedback controller. During the thesis work there have been no possibilities to test these control concepts on the actual system but from simulations it can be concluded that the feedback controller would not be profitable to realize. The small energy saving in comparison with open-loop solutions does not justify the additional cost related to the introduction of a new sensor. An alternative is the proportional open-loop controller which, based on simulations, can give an equally fast thawing but with less energy consumption than today's method.

Bibliography

aus der Wiesche, Stefan (2007). Numerical heat transfer and thermal engineering of AdBlue (SCR) tanks for combustion engine emission reduction. *Applied Thermal Engineering*, **27**, 1790–1798.

BASF Aktiengesellschaft (2005). *AdBlue technical leaflet*. Ludwigshafen, Germany. `www.resnova-m.com/AdBlue__Dati_Tecnici_GB.pdf`.

Engman, Daniel (2006). Optimering av ureainsprutning för SCR katalysator.

Ericson, Claes (2007). NO_x modelling of a complete diesel engine/SCR system.

Glad, Torkel and Ljung, Lennart (Eds.) (2000). *Control Theory Multivariable and Nonlinear Methods*. Taylor & Francis. London, Great Britain.

Lennartsson, Bengt (Ed.) (2006). *Reglerteknikens grunder*. 4th edn. Studentlitteratur. Lund, Sweden.

Lienhard IV, John and Lienhard V, John (Eds.) (2008). *A Heat Transfer Textbook*. 3rd edn. Phlogiston Press. Cambridge Massachusetts, USA.

Ljung, Lennart and Glad, Torkel (Eds.) (1994). *Modeling of Dynamic Systems*. Prentice Hall Information And System Sciences Series. 1st edn. P T R Prentice Hall. Upper Saddle River, NJ.

Nilsson, Magnus (2006). Low temperature benchmark of SCR catalysts.

Nordling, Carl and Österman, Jonny (Eds.) (2004). *Physics Handbook*. 7th edn. Studentlitteratur. Lund, Sweden.

Sandler, Stanley I. (2006). Thermodynamics. *Kirk-Othmer Encyclopedia of Chemical Technology*, **24**, 641–695.

Appendix A

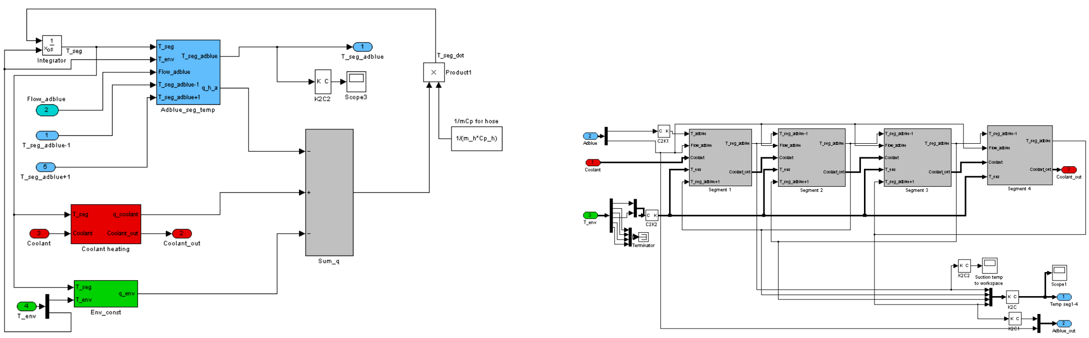
Simulink Implementation

To be able to get a good overview of the whole system, it is implemented in Simulink which is a graphical modeling program widely used at both Scania and in the academic world. The main advantage with Simulink is that it is easy to construct models based on formulas and equations, but still make it easy to understand.

In this chapter it is shown how the SCR-models are implemented and how the user interface is formed to make it easy to change variable parameters.

A.1 Hose Model

The hose model is as previously mentioned divided into segments. In each of these segments the temperature is calculated using the equations given in Section 2.2.2 and each segment is constructed as a subsystem (see Figure A.1a). The subsystems



(a) One hose segment implemented in Simulink

(b) One hose that consists of a number of segments

Figure A.1. A hose implemented in Simulink, the concept is the same for the electrically heated hoses except that the coolant is replaced by electrical heating.

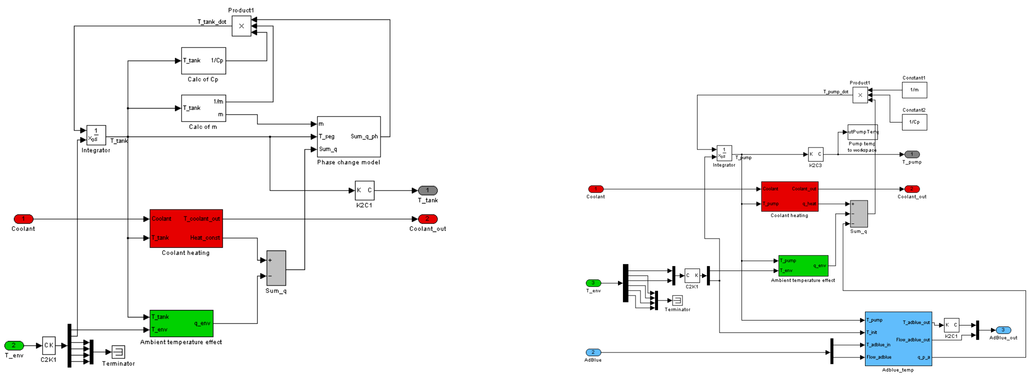
are connected to form the whole hose (see Figure A.1b) which is then used as a subsystem itself with the inputs; coolant, AdBlue and ambient temperature. The coolant and AdBlue inputs both contain signals concerning the temperature and flow. The output of the hose subsystem is the temperature in each segment.

A.2 Tank Model

Based on the equations in Section 2.2.3, the AdBlue tank is implemented as in Figure A.2a. The inputs are the ambient and coolant temperature and output is the tank temperature.

A.3 Pump Model

Similarly to the tank model the pump unit is implemented using the equations given in Section 2.2.4 (see Figure A.2b). Input is the ambient temperature, and the temperature and flow of AdBlue and coolant respectively. Output is the temperature in the pump.



(a) Tank model (b) Pump model

Figure A.2. The AdBlue tank and pump unit models implemented as subsystems in Simulink.

A.4 Complete SCR-model

The complete model is formed by connecting the subsystems for the three hoses, the tank and the pump. An input data block is also added to define the simulation conditions regarding for example environmental temperature and heating.

A.5 User-Friendly Simulation Environment

To make the model useful even for those with just basic Matlab skills, a simple interface is developed. This is done by masking the subsystems and show only those parameters the user must be able to change. By double clicking the blocks representing the different components of the SCR-system (seen in Figure A.3) a dialog box appear where the properties for each part can be input, see examples in

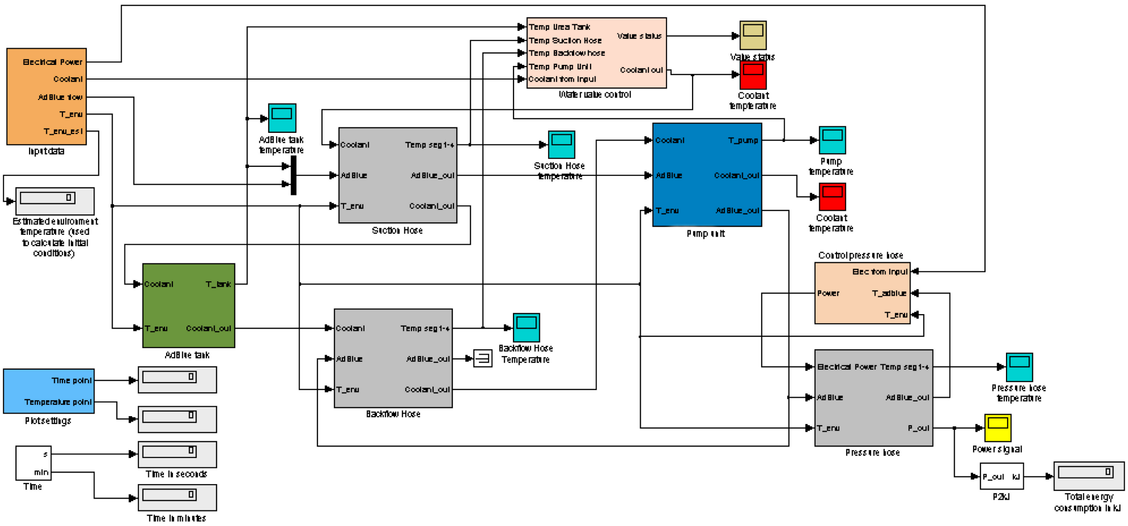
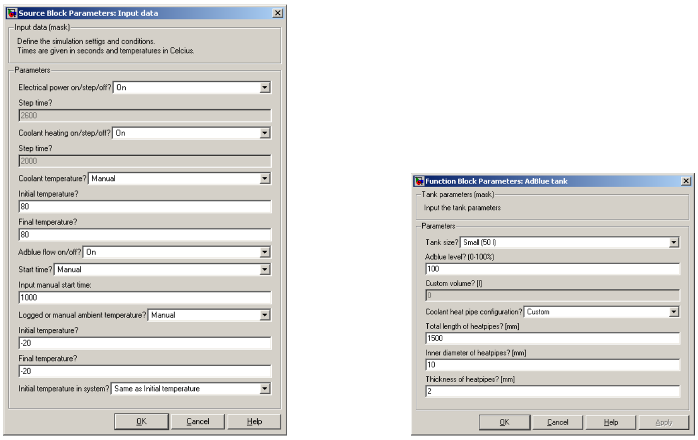


Figure A.3. The complete model of System 1.

Figure A.4.



(a) Properties for the simulation environment

(b) Inputs for the AdBlue tank

Figure A.4. Dialog boxes for initialization of the simulation.

As well as for the initialization it is of importance that the presentation of the simulation results is simple. Therefore a summary of the temperature in the different components, as in Figure A.5, is shown when the simulation is stopped. A cross, that can be put at a specific temperature and time, makes it easy to compare different simulations or see which presumptions that fulfilled a desired criteria.

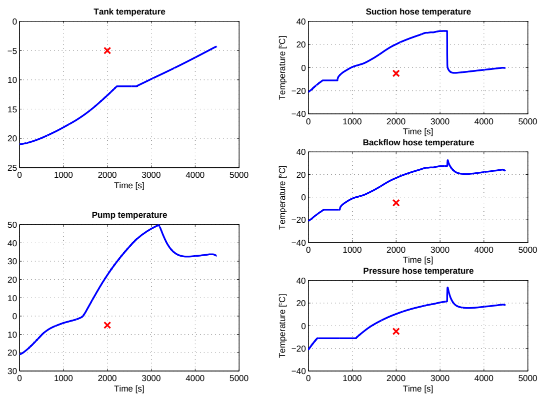


Figure A.5. Simulation summary that appears when the simulation is stopped.