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Design of a quencher for gases from pyrolysis of used tyres

Master's Thesis in Sustainable Energy Systems

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Abstract

A quencher with recirculation was designed for cooling of hot gases from pyrolysis of used tyres. This thesis evaluates the heat transfer mechanisms and operational parameters affecting the design of this particular quencher. By deriving two different theoretical models describing the heat transfer between sprayed oil droplets and hot gases entering a quencher, and then applying the calculations in an existing quencher. Correlations between theory and experiments on the existing quencher where evaluated, the correlations functioned as a base for determining a new volume of the exsisitng quencher.

Acknowledgements

I would sincerely like to express my gratitude to Olov Ershag who has been my supervisor at Scandinaian Enviro Systems and helped me with all the practical parts of the thesis, and also given me the material needed for carrying out this thesis. I would also like to thank my supervisor at Chalmers University of Technology, Fredrik Normann who guided me through the theoretical parts.

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Nomenclature

Q	Transferred energy, kJ/s
E	Effect, kW
T	Temperature, K
$\triangle T_{lm}$	Logaritmic mean temperature, K
cp	Heat capacity, kJ/kgK
$\dot{m}$	Mass flow, kg/s
$\dot{V}$	Volumetric flow, m^3/s
U	Overall heat transfer coefficient, W/m^2K
V	Volume, m^3
r	Droplet radius, m
D	Droplet diameter, m
ρ	Density, kg/m^3
h	Heat transfer coefficient, W/m^2K
k	Thermal conductivity, W/mK
Bi	Biots number, Dimensionless
t_r	Residence time, s
LT	Tank level, m^3

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1

Introduction

New methods for handling of waste is an essential question for sustainable development. The waste stream of used tyres is one of the worst waste problems facing developed countries today, and amounts to about 2% of the total solid waste in the world [1, 2]. Tyres have a complex structure and contain several different compounds such as oil, steel, carbon black and gas [4] which make recycling complicated. Today, in Europe, used tyres are retreated, incinerated, landfilled, granulated or shredded [3] which is an inefficient way of handling these valuable compounds. A new technology to recycle tyres has been developed by a small company called Scandinavian Enviro Systems. This technique is based on a new type of pyrolysis called CFC (Carbonized by Forced Convection) which fully separates all the compounds in the tyre. CFC heats nitrogen (N_2) to approximately 600 °C and then distributes the gas evenly inside the direct contact reactor, making the gas and oils liberate from the tyres in an absence of oxygen. The gas which the pyrolysis gives rise to contains oils and volatile compounds that have approximately a temperature of 500 °C, these gases are highly flammable and are presented in the form of hydro carbons C_xH_y with $C_1 - C_{30}$ [4]. The gas is in need of cooling to approximately 100 °C. Since the temperature span is so large, an ordinary heat exchanger would not be suitable for this process, because it would require a large heat transfer area which would contribute to a high material cost. Also an ordinary heat exchanger will not have the same ability to condensate oils which is preferred in this component. The existing cooling technology employed by the plant is a quencher that quenches the gases by spraying recirculated oil inside a cylindrical tank. A quencher enables a large heat transfer area in terms of sprayed oil droplets in a relatively small component which is suitable for higher temperatures [5] and varying quality of the gas in need of cooling [6]. A quencher is a direct-contact cooling component which is typically used to cool down hot gases >500 °C [5]. A direct-contact cooling component means that the cooling media and the hot gases have a direct contact without any separation.

The existing quencher is cylindrical and hot gases from the pyrolysis enter the bottom tangentially, and exit the quencher at the top. Eventually the gases begin to condense on the surrounding walls forming liquid oil which ends up in the bottom of the quencher. The bottom has an outlet which is connected to a tank that accumulates the oil. About 98 % of the accumulated oil is recirculated by being sprayed back into the quencher before passing a plate heat exchanger that lowers the temperature of the oil. The plate heat exchanger can be controlled by increasing the flow on the secondary side which will lower the oil temperature. The spray nozzles determine the size of the oil droplets which is relevant for the amount of heat accumulated by the droplets inside the quencher. The droplets in the existing quencher have a size of approximatley 500 μm with a given pressure and volumetric flow for a specific spray nozzle. In theory, smaller droplets will enhance the heat transfer inside the quencher but too small droplets will be entrained by the flow through the quencher which results in condensed oil in surrounding systems further away after the quencher. The aim is to condense as much gas as possible inside the quencher in order to accumulate it in the buffer tank after the outlet in the bottom of the quencher, this will lower the enthalpy of the gas which enhances the heat transfer [7]. The outside of the quencher is insulated since the volatile compounds from the pyrolysis are highly explosive which makes it a requirement not to have temperatures above 70 °C outside the quencher. The gas which exits the top of the quencher contains mostly nitrogen, methane, hydrogen, carbon dioxide and ethane and is used as fuel to sustain the CFC process, by heating new nitrogen (N_2) to approximately 600 °C which is used in the CFC process, this is further explained in the technical section.

The existing quencher is oversized and malfunctioning and is thus in need of a new design. The knowledge of quencher operation is limited, making it difficult to apply a generalized method for design calculations which is strengthened by literature [6, 8]. Literature suggest that the simplest way of designing a quencher is with an empirical formula with fundamental heat transfer theory [9]. Methods used in literature are usually based on components with water as cooling media and normally includes the heat transfer by condensation in so called quench tanks mostly used in the nuclear industry [6]. Applications have been found where computational fluid dynamics analyses have been applied.

1.1 Objective

The main objective of this thesis was sizing a new quencher that could be applied in the CFC process. The operation of the existing quencher should also be evaluated to find possible malfunctioning. This was done by experiments on the existing quencher, which was used to derive data sets. The data sets were then used to establish clear behaviours of the existing quencher. It was also improtant to derive theoretical models describing the existing quencher and present how they are linked to the volume of a quencher. After the experimental behaviour was determined and theoretical models were derived, they were to be compared to discuss validy of using them as models for sizing of a quencher.

1.2 Scope

The study was based on an existing quencher employed by a plant owned by Scandinavian Enviro Systems. Since this quencher was oversized, it was necessary to find the fundamental mechanisms of heat transfer. The literature study included search for both general design methods for quenchers and fundamental heat transfer theories that could be applied. In the experimental part of this thesis different sets of operational parameters were tested and then evaluated to find correlations between theory and existing quencher. Finally, a new optimized design is purposed.

1.3 Outline

The thesis was clearly divided into five main parts; technical systems, models, experimental section and result & discussion. In the technical system part of this thesis, the pyrolysis plant will be presented to get a basic understanding of how the existing quencher is functioning. In the part named models, a fundamental heat balance and mass conservation of a quencher is presented, two theoretical models were extracted in order to calculate the total heat transfer inside the quencher. One model was based on fundamental heat transfer theory calculating the heat balance for all droplets sprayed inside the quencher, the other model was more detailed with regard to the cooling media, describing the heat transfer of oil spheres with varying surrounding temperatures throughout out the quencher. The experimental part of this thesis was conducted on the existing quencher by varying the mass flow and temperature of the recirculated oil. The result and discussion part compares the theoretical models with extracted results from the experiments. By evaluating trends, it was possible to extract experimental functions for the existing quencher which then was matched and compared with the theoretical models. In addition, this thesis consists of transparent discussion of whether it is reasonable to apply these theoretical models in order to determine a new volume. Further, which uncertainties exist in these models and how they could affect the heat transfer as well as operational errors will be discussed. Finally, two new volumes for a quencher are suggested presenting the results from both theoretical models. Improvements of the existing system is discussed and further analyses are suggested. In the end, a short summary of all conclusions is presented.

2

Technical System

In this part the CFC process is presented and the mechanisms behind the extraction of the compounds in tyres such as oil, steel, carbon black and gas are extracted. The system components are presented in the same order as the gas which the pyrolysis give rise to travels trough the system.

2.1 The CFC process

The CFC process is presented in Figure 2.1. The capacity of one batch is approximately 6 tonnes and takes about four hours to complete. The reactor is filled to the top with shredded tyres. Inert gas in form of N_2, heated to approximately 600 °C is evenly distributed inside the CFC reactor between point 1 and 5 in Figure 2.1, having a direct contact with the tyres. The gas leaving the reactor at point 1 is a mix of volatile compounds and oils in the form of C_xH_y with C_1 - C_{30} [4]. During a batch the mass flow of the entering gas to the quencher varies, since the most volatile compounds inside the tyres are liberated first. This means that the quality of the gas varies during a batch, making the density and heat capacity values also to vary. This gas has a temperature of approximately 500 °C and needs to be cooled down to condense all the oils from the gas, this is done in a quencher, seen in Figure 2.1. The quencher quenches the gas by spraying oil on to it, quenching means rapid temperature change of a material or substance. In this case rapid cooling of a hot gas, hence the name "quencher" of the examined component. This makes the gas condensate and end up in the bottom of the quencher. The condensated oil is then transported to a buffer tank after point 4. About 2 % of the mass flow to the buffer tank is accumulated and the rest, 98 % is recirculated back, by being sprayed into the quencher after point 3. Before being sprayed back, the oil passes a plate heat exchanger to lower the temperature. This makes the enthalpy of the gas leaving the quencher at point 2 lower than at point 1 [7]. The gas leaving the quencher mostly contains of nitrogen, methane, hydrogen, carbon dioxide and ethane,

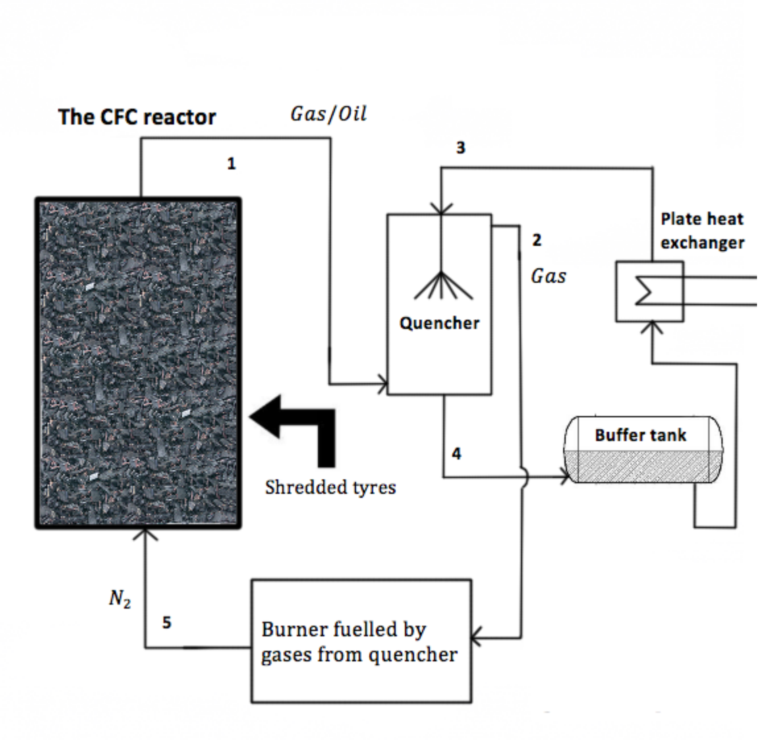

Figure 2.1: The CFC process

the composition is presented in Appendix D. The gas mix from the quencher is used as fuel to sustain the CFC process by using a burner after point 2 in Figure 2.1. The reheated gas is then distributed back to the CFC reactor repeating the process.

Approximately four hours after the process has been initiated the volatile compounds and the oils are fully extracted from the tyres, leaving carbon black and steel left in the CFC reactor, and oil in the buffer tank. Fractions of oil, steel, carbon black and gas from the tyres is presented in Table 2.1, note that more or less all the gas is used as fuel for the CFC process. At the end of the process the carbon black, steel and oils are extracted from the system considered as valuable resources. For more specific composition data of the gas and oils, see Appendix D.

Table 2.1: Distribution of end-products from a batch of used tyres

Oil	**42%**
Carbon black	**32%**
Steel	**14%**
Gas	**12%**

3

Models

This chapter describes the theoretical models used for sizing of a quencher. A simple heat balance is presented and two theoretical models are derived from literature, also quencher volume linked to both models are described. The models are used for calculation of the heat transfer inside the quencher based on oil droplets and surrounding temperature. All the necessary simplifications made in these theoretical models are presented to understand possible errors caused by the calculations. Validation of the two models is briefly discussed.

3.1 Energy balance & Volume of quencher

A heat balance of the sprayed droplets inside the quencher is described by equation 3.1.

$$Q_{droplets} = (\dot{m}_1 - \dot{m}_2 + \dot{m}_3)cp_{oil}T_4 - \dot{m}_3 cp_{oil}T_3 \tag{3.1}$$

Figure 3.1 shows a schematic principle of how the equation is constructed, it should be noted that Q is the energy accumulated by the oil on its path through the quencher. A fraction of the gas/oil-mixture that enters the bottom will be condensed and accumulated in the buffer tank after point 4, the paths for the oil can be seen in Figure 3.1. All heat losses are neglected from surrounding walls.

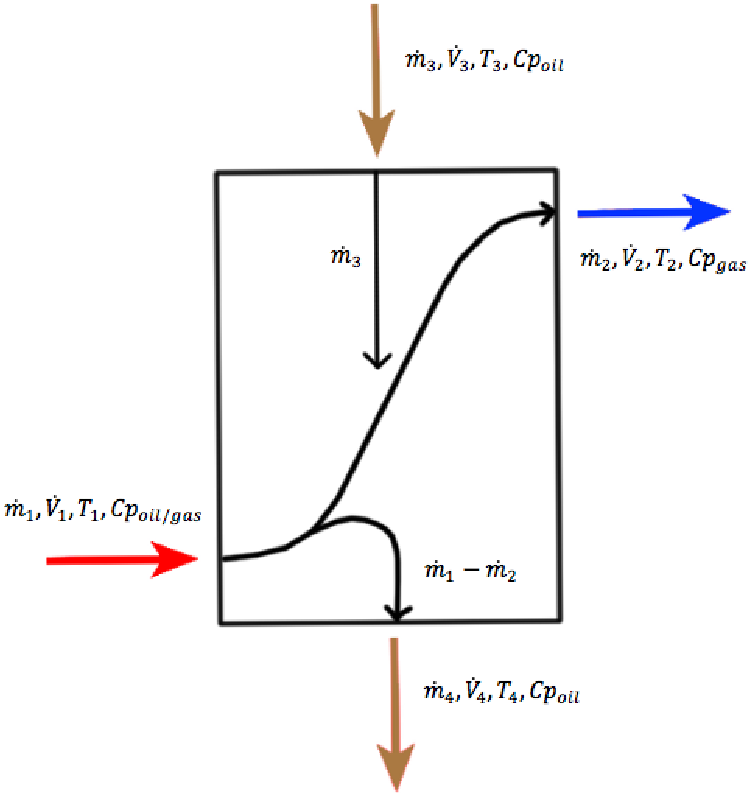

Figure 3.1: The energy path through the quencher

It is important to note that a constant volume of the gas/oil mix throughout the quencher is assumed for $\dot{V}_1$, since the volumetric flow of oil $\dot{V}_3$ is less then 7 % of the total volumetric flow entering the quencher, this flow is neglected in following calculations. The residence time tr is the time needed for the droplets inside the quencher to acquire sufficient heat transfer, the residence time may be decided from heat transfer models located below, the residence time is used in equation 3.2 to determine corresponding volume combined with the volumetric flow occupying the quencher.

$$V_{quencher} = \dot{V}_1 t_r \tag{3.2}$$

3.2 Heat transfer models

From literature two models were derived for calculations on heat transfer inside a quencher. Both models are functions of droplet size and residence time. In theory, a smaller droplet diameter results in enhanced heat transfer and leads to a shorter residence time for the droplets. The residence time is crucial to determine the volume of the quencher as stated in the previous section.

3.2.1 HXT

From basic heat exchanger theory, heat transfer between sprayed oil and entering gas from the CFC process is given by equation 3.3 [11].

$$Q_{droplets} = UA \triangle T_{lm} \tag{3.3}$$

This equation gives an overall heat balance for all droplets inside the quencher, where A is the area of all droplets, U is the overall heat transfer coefficient and $\triangle T_{lm}$ is the logarithmic mean temperature difference for all inlet and outlet temperatures of the quencher.

Since the area of the droplets is determined by the volumetric flow of the sprayed oil, the area can be estimated by equation 3.4.

$$A = \frac{\dot{V}_3}{\frac{r}{3} t_r} \tag{3.4}$$

Where the r is the radius of one oil droplet. Combining equation 3.3 and 3.4 the corresponding residence time can be expressed as equation 3.5.

$$t_r = \frac{Q_{droplets} \frac{r}{3}}{U \triangle T_{lm} \dot{V}_3} \tag{3.5}$$

From now on this model is referred to as HXT (heat exchanger theory).

Simplifications

This model is normally applied to heat exchangers were the logarithmic mean temperature difference is easier to describe. In order to apply the logarithmic mean temperature difference the gas is assumed to have a neglectable phase change throughout the quencher. Condensation is assumed to be neglectable since less than 7 % of the mass flow is condensed. A constant overall heat transfer coefficient is used and all heat losses are assumed to be neglectable. It is also assumed that all droplets are evenly distributed and are spherical when sprayed in to the quencher.

3.2.2 LCM

This model is usually referred to in literature as LCM (Lumped Capacitance Method) and is a way of estimating the energy entering a sphere specimen with constant surrounding temperature [10], This model is from now on referred to as LCM. The theory behind the model is shown in Figure 3.2. The time it takes for an oil sphere to reach the required temperature is calculated from equation 3.6.

$$t_r = \frac{\rho c_p V_{oil}}{h_{oil} A_{oil}} \ln \frac{T_{gas} - T_{oil}}{T_{gas} - T_{out}} \tag{3.6}$$

In this case the spheres are oil droplets and the surrounding gas temperature varies inside the quencher. In order to achieve a more accurate temperature profile the quencher was divided into 10 slice elements with temperatures ranging from the entering temperature to the preferred exit temperature. In each of these slice elements, LCM could

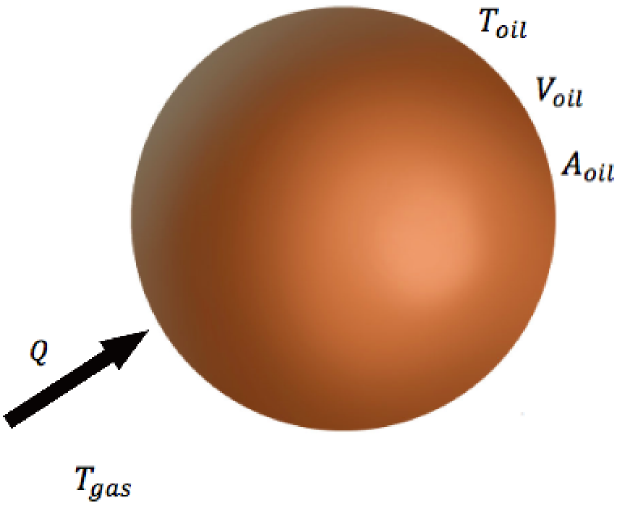

Figure 3.2: Energy transport between gas and oil droplet

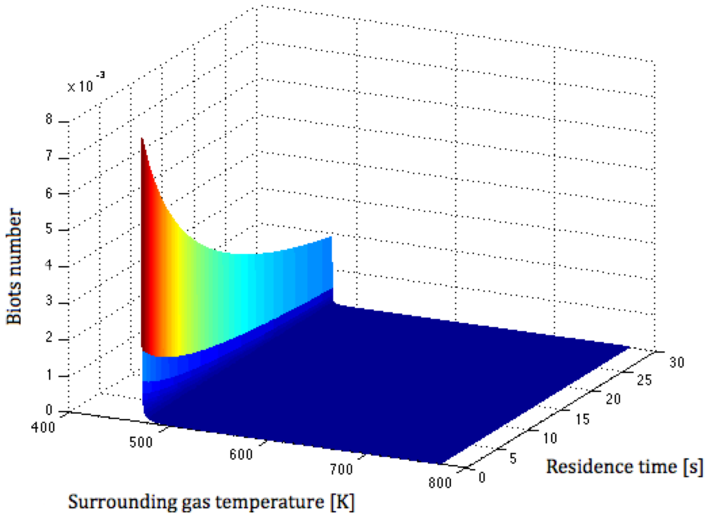

Figure 3.3: Biots number for all points inside the quencher with varying temperatures and residence time

be applied and then summed up to obtain a better approximation of the total energy transfer between the oil droplets and the entering gas/oil-mixture[8]. To test the validity of LCM, Biots-number was derived for all possible temperatures and droplet diameters illustrated in Figure 3.3.

Biots number is a straightforward way to validate LCM. It is stated in the literature that if Biots number <0.1 the error of using this model will be small but the model is still valid for Biots number <1, calculating biots number for all points inside the quencher with varying temperatures and residence times a maximum value of 0.0078 is found. Accordingly, LCM is valid for this application [11]. Calculations for biots number are presented in Appendix A.

Simplifications

This model is normally applied on a specimen of a solid material, for example a metal sphere. It is assumed that the oil droplets are spherical and have a constant diameter throughout the quencher. In other words, no phase change will occur. This is consistent with the previous model where less than 7 % is condensed. It is also assumed that the gas temperature which surrounds the droplets varies from the bottom to the exit temperature. This provides a more correct gas temperature profile around the droplets, calculations of the temperature profile is presented in Appendix C, with temperature profile presented in Figure C.1.

Table 3.1: Input values for models

Parameter	**Value**
ρ_{oil}	945 kg/m^3
Cp_{oil}	1425 kJ/kgK
h_{oil}	100 W/m^{2}K
$V_{droplet}$	8.18 $^{-12}$m
$A_{droplet}$	1.96 10^{-7} m
$A_{droplets}$	1567.2 m^3 m
T_1	380 C
T_2	100 C (Set value)
T_3	32 C
T_4	100 C
Q	300 kJ/s
r	2.5 10^{-4} m
V_3	6.67 m^3/s
U	0.3 W/m^{2}K (Calculated from equation 3.3)
t_r	9.7904 (Calculated from equation 3.2)

3.3 Modelling

To simulate heat transfer inside the quencher both models where simulated with theoretical values, these values are presented in Table 3.1. Note that the residence time t_r and overall heat transfer coefficient U are calculated from the existing quencher with equation 3.2 and 3.3 respectively. The residence time and overall heat transfer coefficient are used as design parameters in LCM and HXT respectively to adjust the heat transfer inside the quencher. Plots simulated for HXT and LCM are presented in Figure 3.4, 3.5 respectively. The plots are a function of outlet temperature from the quencher and sprayed oil temperature which is further discussed in the Results & Discussion section. Note that when decreasing U and t_r both curves are pushed upwards, the opposite behaviour goes for increased values resulting in the curves being pushed down. This behaviour is graphically presented in Figure 3.4 and 3.5.

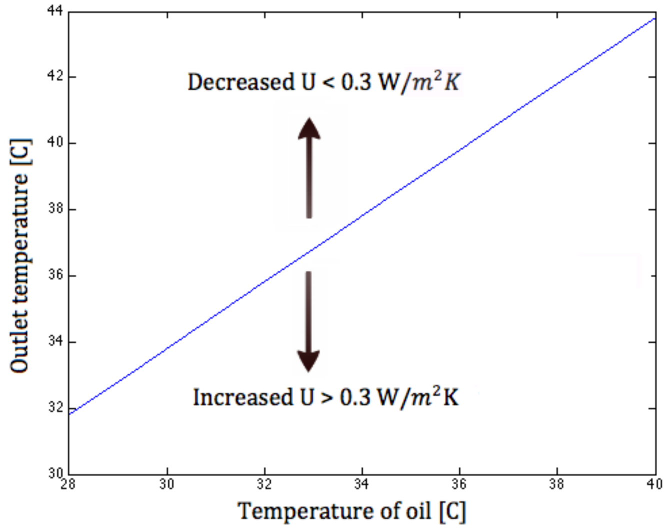

Figure 3.4: Simulation for HXT

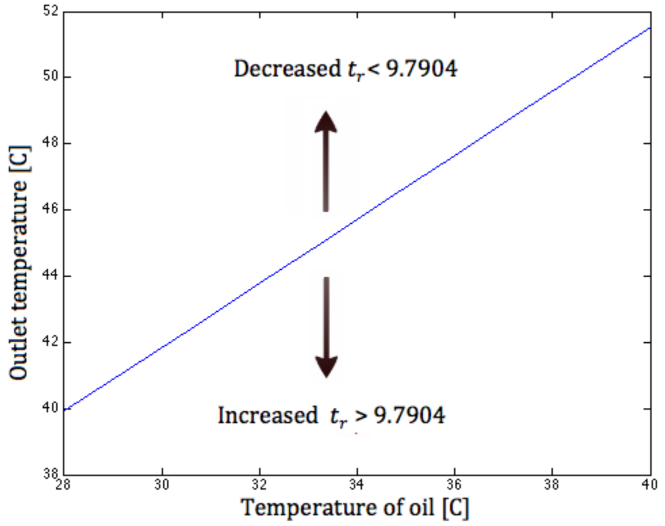

Figure 3.5: Simulation for LCM

4

Experimental Section

The experimental section of this thesis is used to validate the theoretical calculations with an actual operating quencher. The first part of this chapter presents technical specifications of the existing quencher. Also, equipment used to measure flows, temperatures and oil levels in the buffer tank.

4.1 Experimental setup

A 3D-drawing of the existing quencher is presented in Figure 4.1. In Figure 4.2 a schematic principle of the quencher is presented. During experiments, seven measuring points in the quencher were used to measure temperature, volumetric flow and tank level, shown in Figure 4.2. All points and specification of measuring equipment are presented in Table 4.1. Note that LT_{buffer} is the oil level inside the buffer tank, the mass flow out $\dot{m}_{out}$ of the quencher is calculated by the frequency of the blower described in Table 4.1. The existing quencher is cylindrical and has approximately a diameter of 1.5 m and a height of 5 m. A full scale drawing of the existing quencher is presented in Appendix E.

4.2 Experimental procedures

The existing quencher is nearly managing the task for cooling at the moment which complicated the realization of experimental conditions, making it difficult to perform the intended experiments, because this would cause too large peaks in the outlet temperature of the quencher.

Figure 4.1: A 3D representation of the exisitng quencher

To establish a relationship between the derived models and the existing quencher, experiments were performed. Parameters that could be varied were the mass flow of recirculated oil $\dot{m}_{recirculated}$ and the energy extracted from the oil, E_{hx} seen in Figure 4.2, resulting in a lower temperature of the sprayed oil, T_{oil}. Three arbitrary pyrolysis batches were examined, where the oil temperature, T_{oil} and mass flow, $\dot{m}_{recirculated}$ were varied. As mentioned before, the quencher is nearly managing the task of cooling,

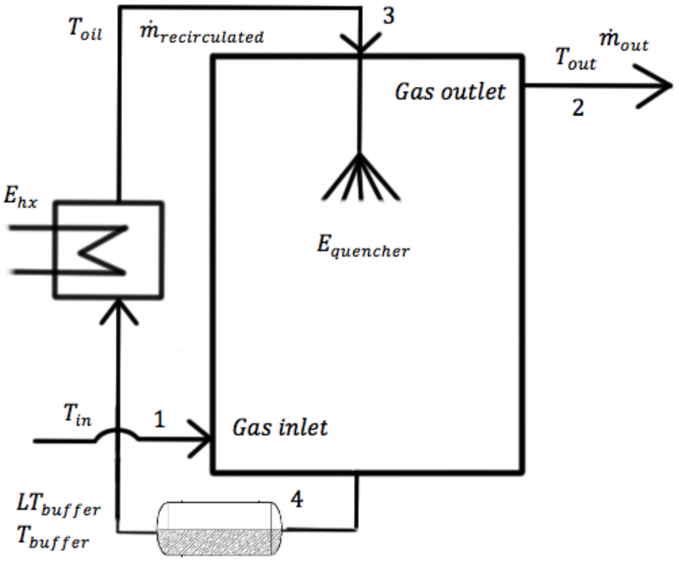

Figure 4.2: Experiments on quencher

Table 4.1: Manufacturer information for different objects

Point	Quantity	Value intervall	Messuring equipment
1	T_{in}	20 - 400 °C	SIEMENS, SITRANS TH100,7MC1006-3DE14-Z
2	T_{out}	50-100 °C	SIEMENS, SITRANS TH100,7MC1006-3DE14-Z
2	$\dot{m}_{out}$	0.0255-0.0349 kg/s	Tuthill PD Plus 5511-67L2VP
3	$\dot{m}_{recirculated}$	5.25-7.88 kg/s	SIEMENS ,SITRANS F US SONOFLO SONO 3300, 7ME3300-1HH30-1QC7-Z, FUS060
3	T_{oil}	28-35 °C	SIEMENS, SITRANS TH100,7MC1006-3DE14-Z
4	LT_{buffer}	1.4-3.9 m^3	Exac, NIVOTRAC, MTA-617-6
4	T_{buffer}	20-100 °C	SIEMENS, SITRANS, TH100, 7MC1006-3DE14-Z

this made it difficult to have a strict agenda of experimental data sets to vary the parameters $\dot{m}_{recirculated}$ and T_{oil}. The approach was instead to stress the systems by varying the parameters in reasonable intervals without creating to large peaks in the outlet temperatures.

One clear relationship could be established between the sprayed oil and outlet temperature, the plots of outlet temperature T_{out} and sprayed oil temperature T_{oil} are presented in Appendix B. Several trends indicated that the mass flow $\dot{m}_{recirculated}$ affected the heat transfer but could not be confirmed by the experiments. Since the system had too narrow marginals this would result in too large temperature peaks of the outlet gas. All typical values during a batch for each point in Figure 4.2 are presented in Table 4.1.

4.3 Experimental function

Figure 4.3 shows both temperatures plotted over a time period of 75 minutes for a typical batch. There is a clear relationship between the sprayed oil and the outlet temperature, it is established that the outlet and sprayed oil temperatures have the same behaviour over all periods of time. In this batch, the energy extracted by the plate heat exchanger was increased compared to normal operation which resulted in a lower temperature of the recirculated oil, enhancing the heat transfer inside the quencher. Since a clear relationship was established it was of interest to find a experimental function, $T_{out}(T_{oil})$, describing the relationship between the oil and outlet temperature from the quencher. Three functions were constructed to verify the behaviour of the temperature relation between the sprayed oil and outlet temperature. These three functions were constructed by calculating the slope between the average change in both temperatures with the same time interval, shown by the green lines in Figure 4.3. It was important to carefully choose the interval where a distinct change in temperature was proven, this was done for three intervals where the system was stressed. The intervals are shown in Figure B.2, B.3 and B.4 in Appendix B and the intervals were chosen to 5, 3 and 13 minutes respectively and the mean slope was calculated which gave the experimental function presented in Figure 4.4. For a detailed calculation of the experimental function, see Appendix B. The experimental function is presented by equation 4.1.

$$T_{out} = 3.3845 T_{oil} - 51.2253 \tag{4.1}$$

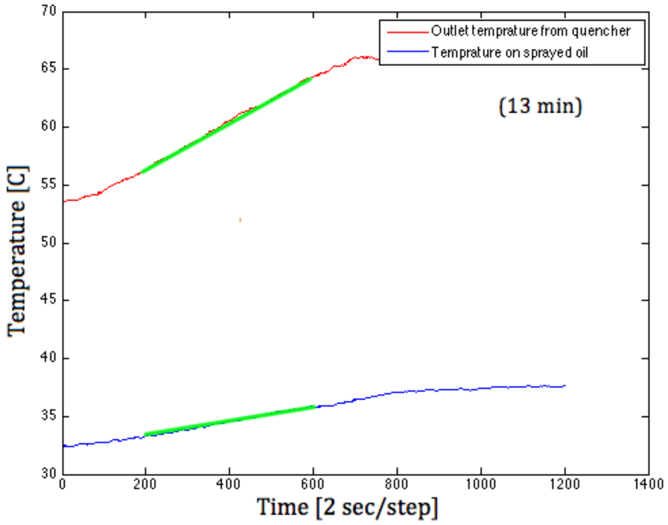

Figure 4.3: Links between sprayed oil and outlet temperature

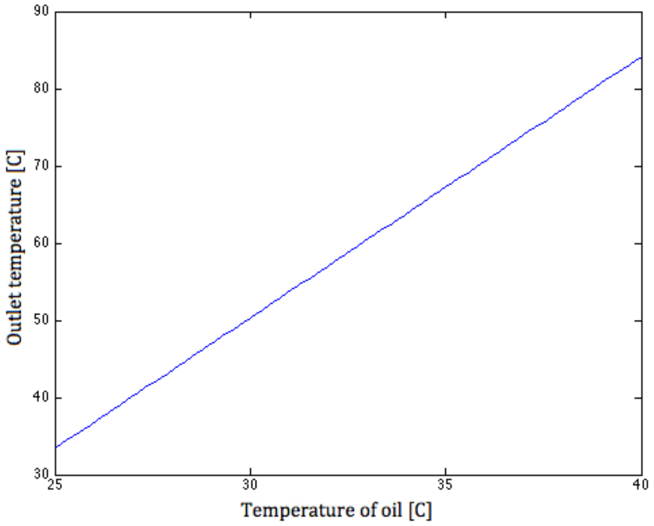

Figure 4.4: Experimental function between sprayed oil and outlet temperature

5

Results & Discussion

The chapter of results and discussion compares the theoretical models with the experimental function. Models are presented where they are matched to correlate to the experiments, they are also presented with the theoretical values of these parameters mentioned in the modelling section. A detailed and transparent discussion of the errors and uncertainties is presented. Other results from the theoretical models will also be discussed such as varying the mass flow of the recirculated oil. Also improvements of the existing quencher are suggested to imitate the models. Geometry and further studies of the quencher is briefly mentioned. Finally, new volumes of the quencher for both theoretical models will be presented.

5.1 Models versus experiments

Following section compares the experimental results with the models, other theoretical results are also presented.

5.1.1 Theoretical models

By using theoretical values shown in Table 3.1 for residence time and overall heat transfer coefficient as presented in the modelling section, both models where plotted in the same interval as the experimental function. The models had a large mismatch seen in Figure 5.1. As mentioned before the overall heat transfer coefficient U was calculated to 0.3 W/m^{2}K which is rather low and would most probably be larger for this application [11]. The area of all droplets is calculated to 1567.2 m^2 for the given volumetric flow and size of droplets which contributes to a low overall heat transfer coefficient. LCM did not match the experiments either, which can be seen in Figure 5.1, even though the same residence time (t_r = 9,7904 s) as the existing quencher was used. The model is very much depending on the residence time of the heat entering the oil droplets. It can be seen that both models have almost the same appearance and are in theory more effective than the existing quencher given that the aim is to lower the outlet temperature. The most reasonable explanation of the gap between the models might be the overall heat transfer coefficient used in HXT, this value is difficult to estimate beside the experimental calculations.

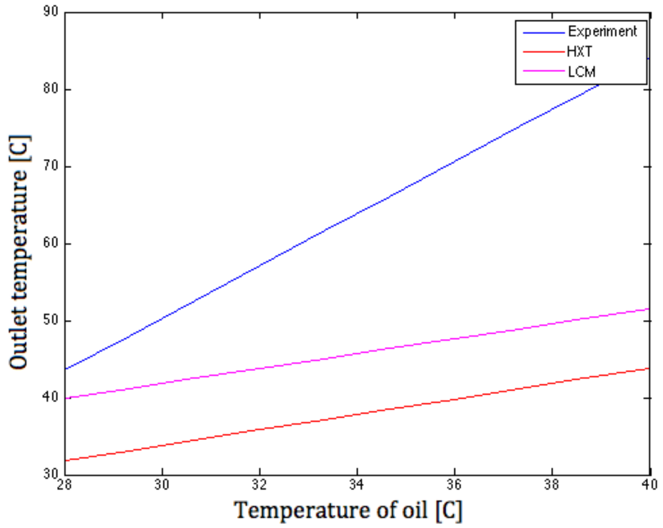

Figure 5.1: HXT and LCM compared to the experimental function

5.1.2 Flow of recirculated oil

As seen in Figure 5.2 the recirculated oil affects the energy transfer inside the quencher when the volumetric flow increases for LCM. The heat transfer is nearly constant for HXT. One simple explanation of the gap between the models is the overall heat transfer coefficient which is set to 0.3 W/m^{2}K, this value is assumed to be constant throughout

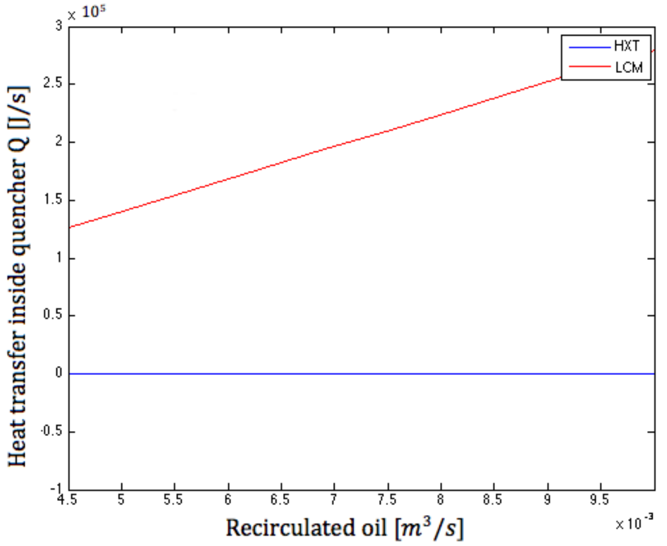

Figure 5.2: Energy transferred with varying recirculation of cooling oil

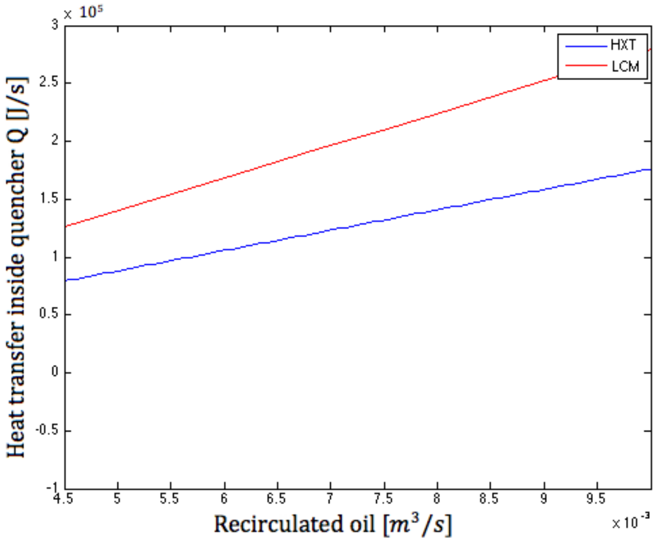

Figure 5.3: Energy transferred with varying recirculation of cooling oil

the whole quencher, which it will most probably not be. The value of 0.3 W/m^{2}K is calculated from equation 3.1 and 3.3 applied on the existing quencher and the residence time t_r is set to 9.79 s which is the same as in the existing quencher. The interval of the recirculated oil $\dot{V}_3$ lies between 15 m^3/h to 36 m^3/h. For a higher value of the overall heat transfer coefficient, HXT will also present a higher heat transfer when increasing the volumetric flow of recirculated oil seen in Figure 5.3, where a value of 20 W/m^{2}K is used for U. Varying the flow might be difficult to realize since the existing quencher is by now nearly managing the task of cooling. Another important matter is the spray nozzles which are designed for a specific flow and pressure which the models do not take into account. It was not possible to find any clear relationships in the experiments between volumetric flow and heat transfer, even though the models suggest such a relationship and some of the experimental trends indicated it.

5.1.3 Droplets size

The size of sprayed oil droplets inside the quencher were found to have an strong impact on the heat transfer for both HXT and LCM, the results are plotted in Figure 5.4 and 5.5 for theoretical values of U and t_r presented in Table 3.1. Both models suggest that a smaller droplet size will enhance the heat transfer, LCM approaches a constant heat transfer value for droplets below 500 μm and HXT approaches infinity. When increasing the droplet size the opposite behaviour is obtained. Knowing this the models together suggest that an optimal droplet size would be around 500 μm wich is determined by the spray nozzles inside the quencher. Also its impossible for the heat transfer to approach infinity for smaller droplets as in HXT. LCM suggest that an increased droplet diameter will have a strong impact on the heat transfer since it approaches a smaller heat transfer value rapidly.

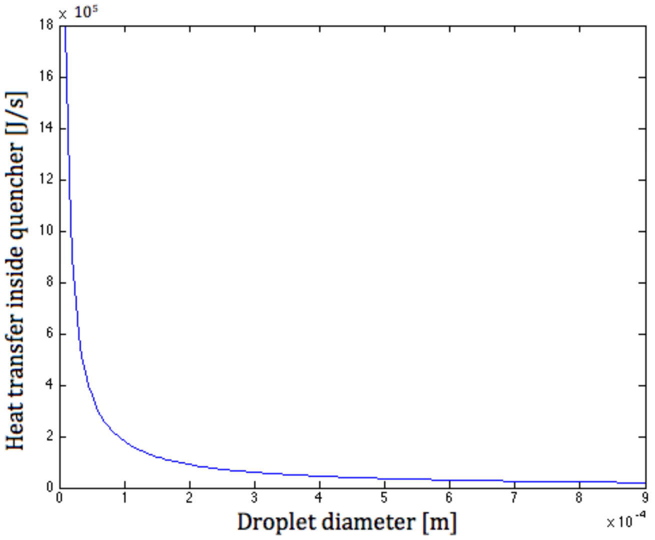

Figure 5.4: Diameter of sprayed oil droplets and heat transfer for HXT

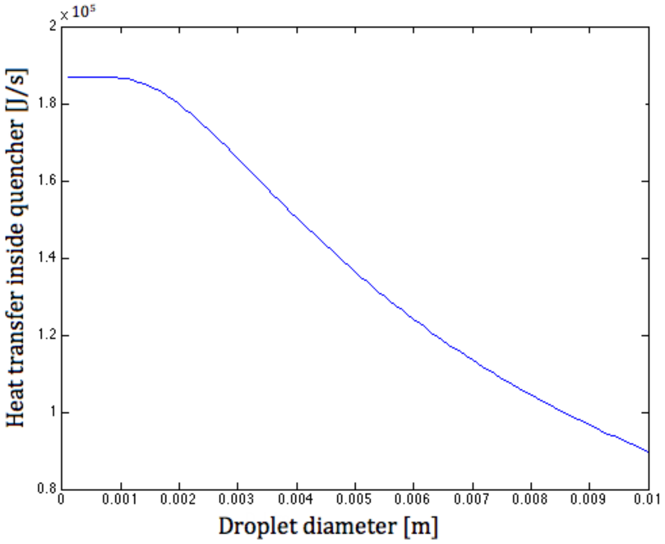

Figure 5.5: Diameter of sprayed oil droplets and heat transfer for LCM

5.1.4 Models fitted to experimental results

All input values for the models are presented in Table 5.1, note that the residence time t_r and overall heat transfer coefficient U have adopted values to fit the experimental function.

In order to correlate the models to the experiments, parameters in both models needed to be fitted to the experiments. Parameters that were varied were the residence time for LCM and the overall heat transfer coefficient for HXT. The models were matched to fit the experimental linear function seen in Figure 5.6. The overall heat transfer coefficient U was set to 0.0370 W/m^{2}K and the residence time t_r to 8.3501 s. The rest of the input values can be seen in Table 5.1. Looking at Figure 5.6, the models did still not match the experimental function perfectly which might be explained by the malfunctioning of the existing quencher which is discussed later on in this chapter. It can be seen that the slope in both models have similar appearance which strengthens the models validity. One might think that changing the slope of the models would be trivial but it was proven to be unexpectedly difficult.

Table 5.1: Input values for both models

Parameter	**Value**
ρ_{oil}	945 kg/m^3
Cp_{oil}	1425 kJ/kgK
h_{oil}	100 W/m^{2}K
$V_{droplet}$	8.18 $^{-12}$m
$A_{droplet}$	1.96 10^{-7} m
$A_{droplets}$	1567.2 m^3 m
T_1	380 C
T_2	100 C (Set value)
T_3	32 C
T_4	100 C
Q	300 kJ/s
r	2.5 10^{-4} m
V_3	6.67 m^3/s
Matched value: U	0.0370 W/m^{2}K
Matched value: t_r	8.3501 s

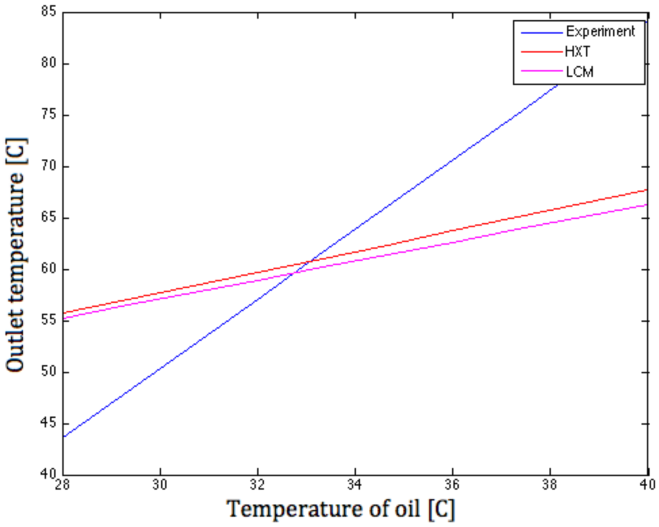

Figure 5.6: Models matched with experimental function

5.1.5 Uncertainties & Mismatch

None of the models matched the experiments. The mismatch of the models can be explained by several operational errors and uncertainties. In both models the spray nozzles are assumed to make an even distribution of spherical oil droplets, this is most probably not the case in the existing quencher since the pressure before the spray nozzles are about 1.7 bars, needed pressure for these nozzles is 5 bars. This will not ensure fine spherical droplets, which is assumed in both models. It has been noticed that foam has been accumulated in the buffer tank of the recirculated oil, most probably due to volatile compounds in the oil. The foam is mixed with the recirculated oil and can therefore affect the formation of sprayed oil droplets. A typical batch, which is 6 tonnes of tyres, takes about 4 hours to complete and during this time the volumetric flow of the entering gas increases, most likely because the most volatile compounds inside the tyres liberates first and the less volatile later on. this creates an uncertainty of oil and gas data which made it difficult to establish a correct density and heat capacity, which as a result could provide a misleading model. The walls inside the quencher will enhance the condensation and heat transfer which is not included in the models, and might result in less correct models. As stated the experimental function might be failing to describe the existing quencher. However since both theoretical models have similar appearance, the conclusion can be drawn that they are correct for specified conditions in terms of volumetric flow and droplets size and might be used for determination of a quencher volume.

5.2 Design & Improvments

With predetermined data required for the oil- and gas flows as well as for all the temperatures except the outlet temperature, the residence time could be calculated for a new quencher with the preferred outlet temperature. Knowing the residence time for both models, equation 3.2 was applied to obtain the corresponding volume. All input data is presented in Table 5.1 except for the overall heat transfer coefficient. The energy, Q, and temperatures, T, are taken at operation during a typical batch and are the maximum values that the quencher is exposed to. Note that the input values in Table 5.1 have the same nomenclature as in Figure 3.1.

5.2.1 HXT

The major uncertainty in HXT was the overall heat transfer coefficient U which was calculated to 0.3 W/m^{2}K, as mentioned in the previous chapter this value is most probably too low. Different volumes for various overall heat transfer coefficients which are presented in Figure 5.7 have been calculated from HXT. One important notation is that for overall heat transfer values above 7 W/m^{2}K have almost no impact on the corresponding volume, making values below this point critical. From the literature it can be interpreted that similar applications would have at least a value of 20 W/m^{2}K [11]. Assuming a value for the overall heat transfer coefficient of 20 W/m^{2}K results in a residence time of about 3.8977 s, the final volume could then be calculated to 3.5570 m^3 by using equation 3.2.

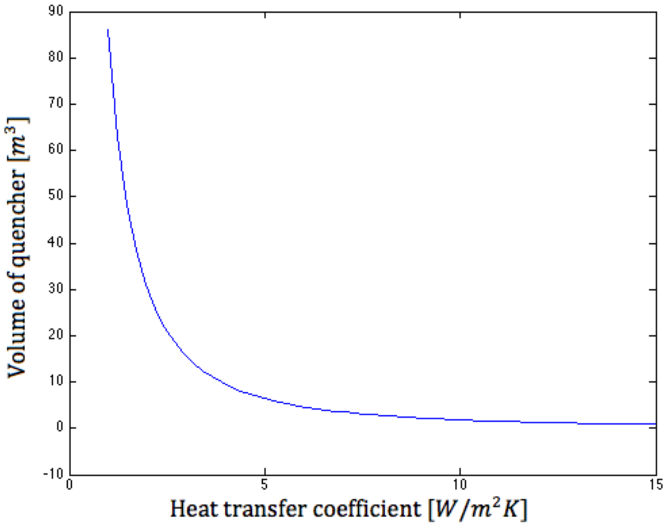

Figure 5.7: Calculated volume for various overall heat transfer coefficients

5.2.2 LCM

In this model the quencher was divided into ten slice elements, which can be seen in Appendix C. The gas surrounding the droplets was assumed to vary between these slices, meaning that each slice would theoretically have different residence times in order to achieve sufficient cooling of the gas. Figure 5.8 presents different residence times for various gas temperatures. The longest residence time is for the slice elements in the top of the quencher since the gas temperature will be lowest there. For this slice element the residence time is about 2.4661 s which results in a final volume of 2.2506 m^3 using equation 3.2.

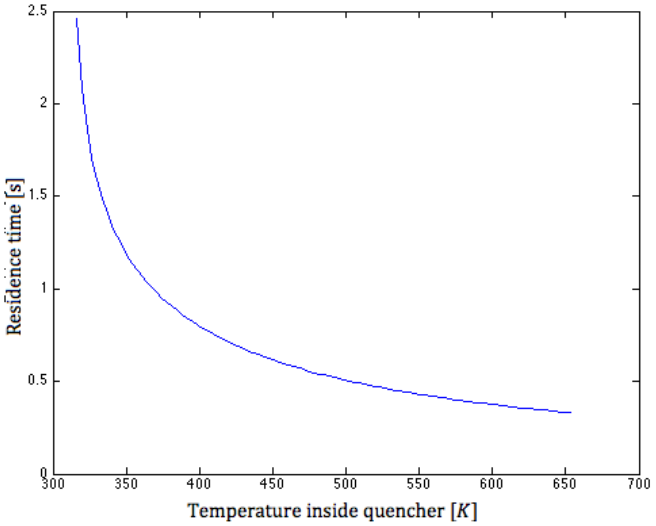

Figure 5.8: Residence time for various gas temperatures surrounding the droplets

5.2.3 Errors

For the quencher to function as intended, the spray nozzles must produce fine spherical droplets at all times. Suspected malfunctioning of the spray nozzles for this application might be that foam has accumulated in the buffer tank, which later is sprayed back into the quencher causing problems producing oil droplets. The pressure before the spray nozzles are at present time about 1.7 bars and the spray nozzles are designed for 5 bars, this means that oil droplets can not be produced properly while being sprayed back into the quencher.

5.2.4 Improvements according to models

The models have a strong relationship to the size of the sprayed oil droplets, meaning that the nozzles must produce fine spherical droplets at all time. If the pressure before the nozzles is increased to about 5 bars, the nozzles might be able to function as intended. Also the foam that has been noticed inside the oil tank might have an impact on the droplets as well. To avoid this type of problem, the temperature interval at which the quencher is working, might need to be changed. At present time the quencher is cooling gases from approximately 380 °C to 100 °C. If the temperature span is increased, the volatile compounds in the oil that accounts for the foam will pass the quencher, without condensing and leaving the heavier oil in the buffer tank, from Appendix D it can be interpreted that 190 °C is a threshold for volatile compounds. But this would result in another component is needed after the quencher to condensate these volatile compounds. To increase the temperature span the temperature of the sprayed oil can easily be increased. To determine a more specific temperature span further analysis of oil and gas composition is needed. Since both models clearly suggest that a lower temperature of the sprayed oil will increase the heat transfer, the energy extracted by the plate heat exchanger from the recirculated oil should be increased as much as possible. Both models also suggest that an increased volumetric flow of the recirculated oil will enhance the heat transfer inside the quencher, but if the volumetric flow is changed the spray nozzles also need to be evaluated for a new pressure and volumetric flow.

5.2.5 Further analysis

Since there is a big uncertainty of the oil and gas data it might be of interest to examine the composition over time to determine heat capacity values and densities. As explained in previous chapters, the most volatile compounds in the tyres liberates first making it difficult to have constant values of densities and heat capacities over an entire batch. To get a more correct model, these need to be varied over a batch. To get a more detailed model it would be of interest to perform a computational fluid dynamics model in which a simulation of the quencher can be done. Also the height to diameter ratio H/D is not determined, in this thesis the exisitng value is ≈ 3.5. Even though literature suggest a ratio of H/D=2-3 [6, 8] this might be interesting to examine in order to find the optimal geometry of the quencher.

6

Conclusions

Two models, HXT and LCM were derived from basic heat transfer theory. HXT is based on heat exchanger theory and calculates the overall heat balance for sprayed oil droplets inside a quencher. LCM gives a more detailed heat balance of multiple oil droplets sprayed inside the quencher. Both models are used to determine a new volume of the quencher and examine the existing quencher.

- A clear relationship between heat transfer and volume was established for both HXT and LCM.
- Both LCM and HXT indicated the same behaviour in heat transfer which validates the models for being used when determining the volume of a quencher.
- Both models clearly suggest a lower outlet temperature from the quencher when lowering the sprayed oil temperature inside the quencher.
- Two new volumes for the quencher are determined, 3.5570 m^3 for HXT and 2.2506 m^3 for LCM. The later one mentioned is the most promising, since the overall heat transfer coefficient U for HXT is difficult to estimate.
- For the design of this quencher the residence time and overall heat transfer coefficient were crucial design parameters.
- Both HXT and LCM suggest that a droplet size around 500 μm is optimal for heat transfer in this application.
- Increased flow of the sprayed oil enhances the heat transfer inside the quencher for both HXT and LCM.

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A

Biots number

The biots number is defined by equation A.1 [10]

$$Bi = \frac{hV_d}{kA_d} \tag{A.1}$$

Where h is calculated by equation A.2 below.

$$h = \frac{\rho c_p V}{t_r A} \ln \frac{T_{oil} - T_{gas}}{T_{out} - T_{gas}} \tag{A.2}$$

Biots number was calculated for one spherical droplet with an assumed starting temperature *Toil* and surrounding temperature *Tgas*, *Tout* is the temperature after the time *tr*. It was interesting to calculate all possible biots number for various temperature changes and residence times inside the quencher. The residence time was varied between 0.01 second to 30 seconds and the inlet temperature *Tgas* was varied between 200°C to 500 °C. The thermal conductivity constant k is assumed to have the same value as engine oil [11].

Table A.1: Assumed values to calculate biots number

Parameter	Value
k	145 W/mK
ρ_{oil}	945 kg/m^3
T_{gas}	200-500 °C
T_{oil}	32 C
T_{out}	150 C
t_r	0.1-30 sec
D	500 10^{-7}
V	6.5450 10^{-11} m^3
A	7.8540 10^{-7}m^2

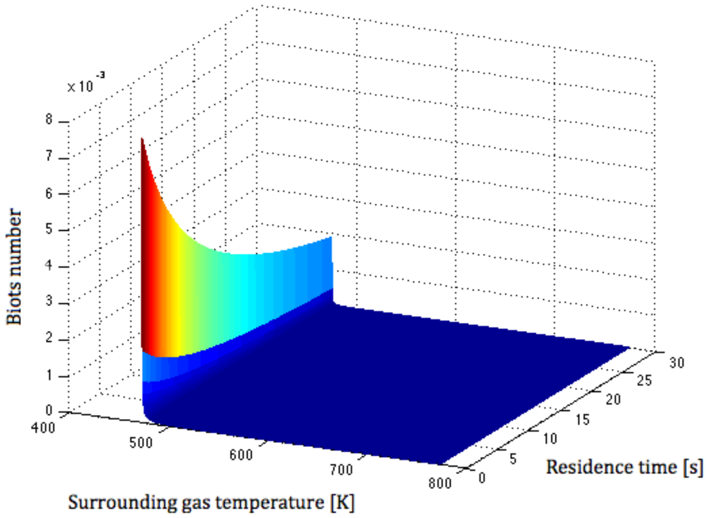


Figure A.1: Biots number for all points inside the quencher with varying temperatures and residence time

Table A.1 present all input values for the calculations.

All biots numbers where calculated for 1000,000 points and resulted in a matrix plotted in Figure A.1.

It is clearly stated in literature that biots number below 0.1 contributes to small errors when using LCM, and as seen in the Figure the highest values of biots number is 0.0078, which is much smaller then 0.1.

B

The final linear function of temperatures

The experimental linear function was defined as the ratio between each temperature change for an arbitrary interval. This was done for three carefully selected intervals, the main criteria was that a distinct rise in both the gas outlet and sprayed oil temperature could be proved. One clear example can be seen in Figure B.1. The ratio between each temperature change can be expressed as equation B.1.

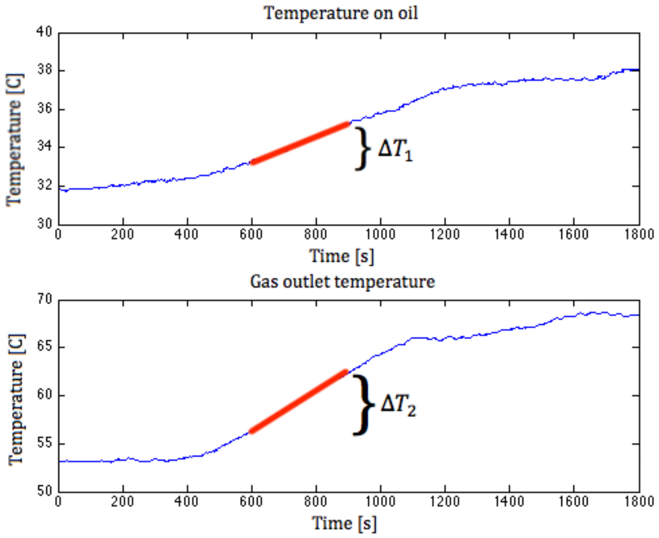


Figure B.1: Temperature of outlet gas and sprayed oil over 30 minutes

$$K = \frac{\triangle T_2}{\triangle T_1} \tag{B.1}$$

The value where the line intersects the y-axis is calculated by equation B.2.

$$m = y - kx \tag{B.2}$$

Where x is set to zero and y is chosen by the corresponding y-value. Equation B.1 and B.2 was applied for three arbitrary intervals of 5, 3 and 13 min shown in Figure B.2, B.3, B.4 respectivley, where a distinct rise in temperature was established. This resulted in three linear functions which are presented in Figure B.5. A final linear function was determined by taking the mean of these three functions, which is also presented in Figure B.5. The final linear function was presented numerically in equation B.3

$$Y = 3.3845X - 51.2253 \tag{B.3}$$

or even more specific by equation B.4

$$T_{out} = 3.3845T_{oil} - 51.2253 \tag{B.4}$$

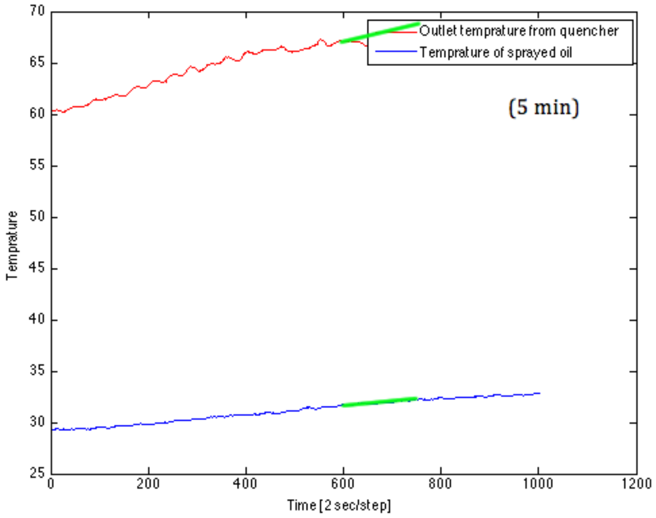


Figure B.2: Experiments on quencher

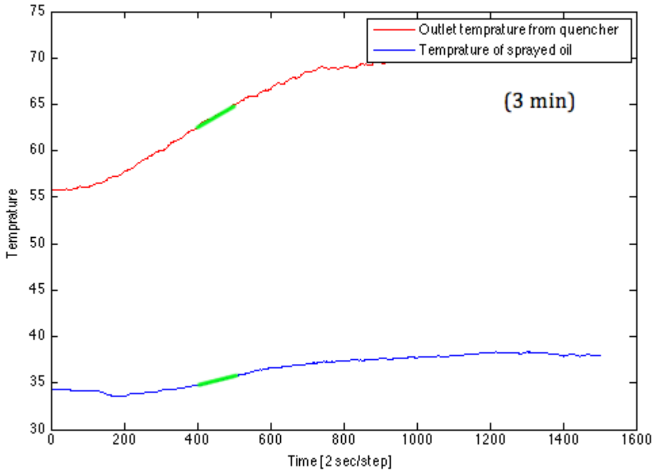


Figure B.3: Experiments on quencher

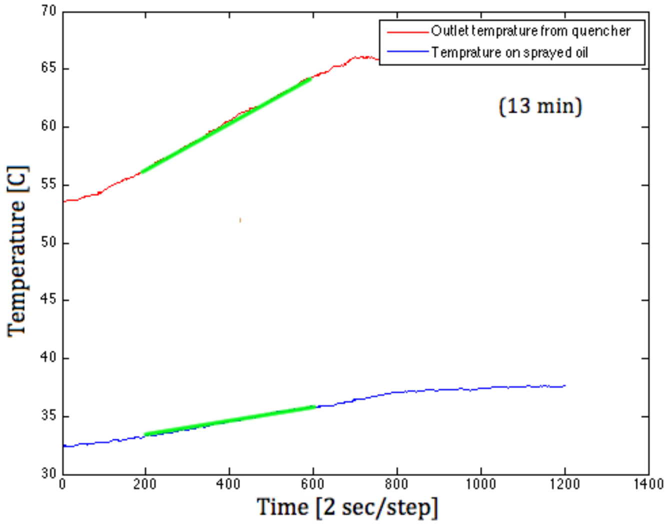


Figure B.4: Experiments on quencher

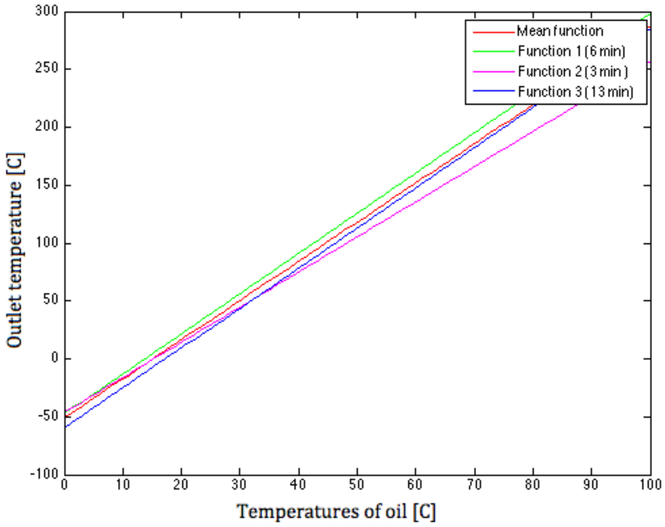


Figure B.5: Three linear functions from three arbitrary intervalls and corresponding mean function

C

Calculation of outlet temperature for LCM

The quencher was divided into ten slice elements which each had an individual gas temperature surrounding the droplets, starting from the bottom with a given inlet temperature. The inlet temperature was assumed to be the gas temperature that surrounds the droplets for the first slice. An outlet temperature for the first slice was calculated by equation C.1 [11].

$$T_{out} = T_{gas} + (T_{oil} - T_{gas}) \exp(\frac{-h_{oil} A_{oil} t_r}{\rho_{oil} c_p V_{oil}}) \tag{C.1}$$

This was done stepwise, so that the outlet temperature for the first slice element was assumed to be the gas temperature for the second slice element and so on. This resulted in a outlet temperature at the top of the quencher. A schematic of the temperatures are shown in Figure C.1. Each slice element had a residence time of 1/10:th of given residence time.

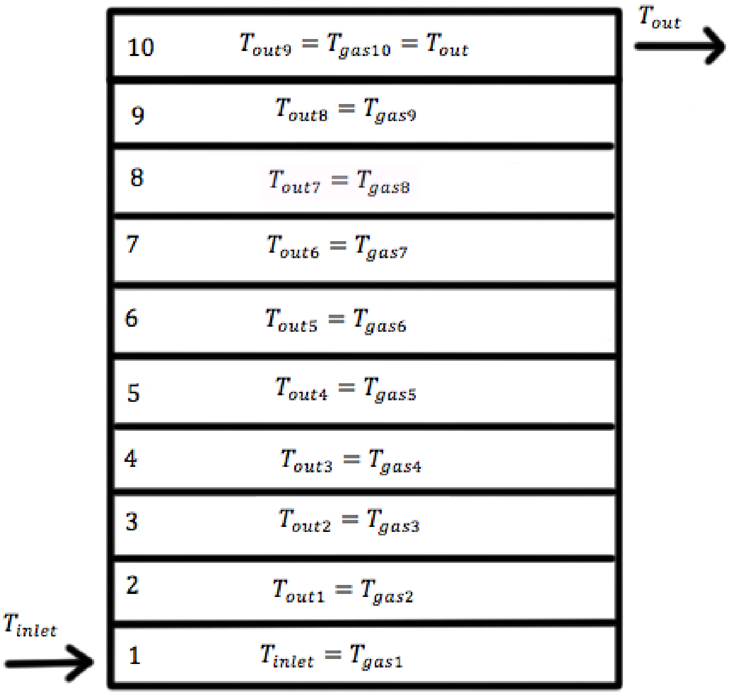
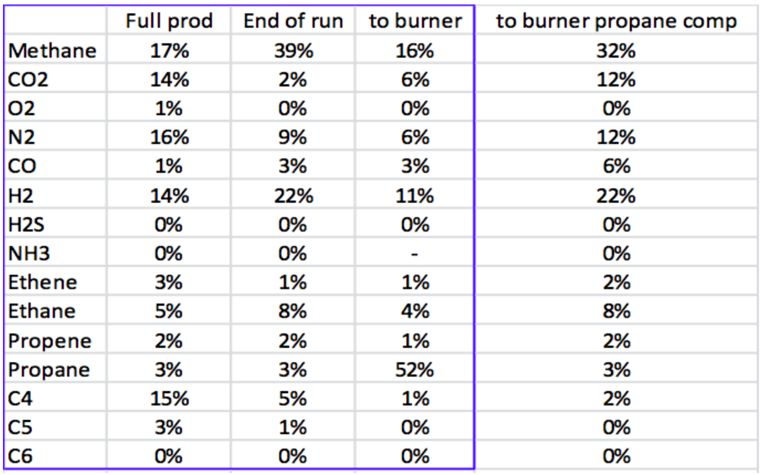


Figure C.1: Quencher divided in 10 slice elements with corresponding gas and outlet temperatures

D

Composition of gas and oils

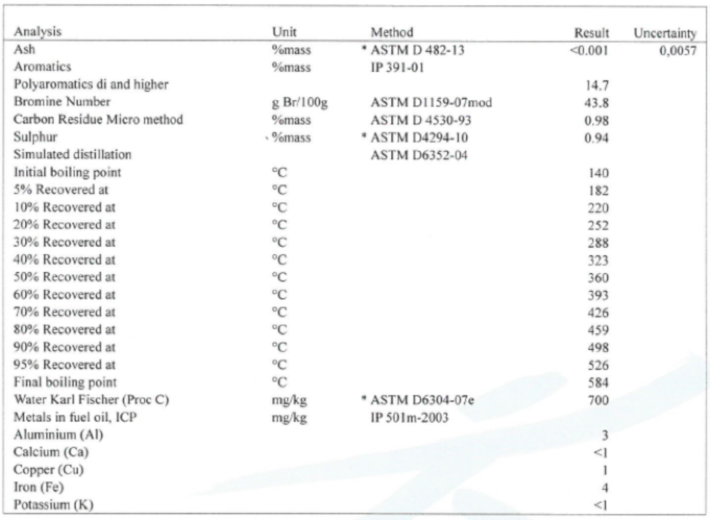
The gas and oil composition are presented at different times and points in the process in the Figures below.



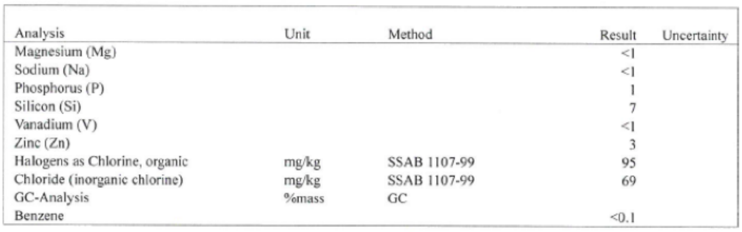
	Full prod	End of run	to burner	to burner propane comp
Methane	17%	39%	16%	32%
CO2	14%	2%	6%	12%
O2	1%	0%	0%	0%
N2	16%	9%	6%	12%
CO	1%	3%	3%	6%
H2	14%	22%	11%	22%
H2S	0%	0%	0%	0%
NH3	0%	0%	-	0%
Ethene	3%	1%	1%	2%
Ethane	5%	8%	4%	8%
Propene	2%	2%	1%	2%
Propane	3%	3%	52%	3%
C4	15%	5%	1%	2%
C5	3%	1%	0%	0%
C6	0%	0%	0%	0%

Figure D.1: All gas compositions

Boiling point over 190°C (Mass fraction 90%)

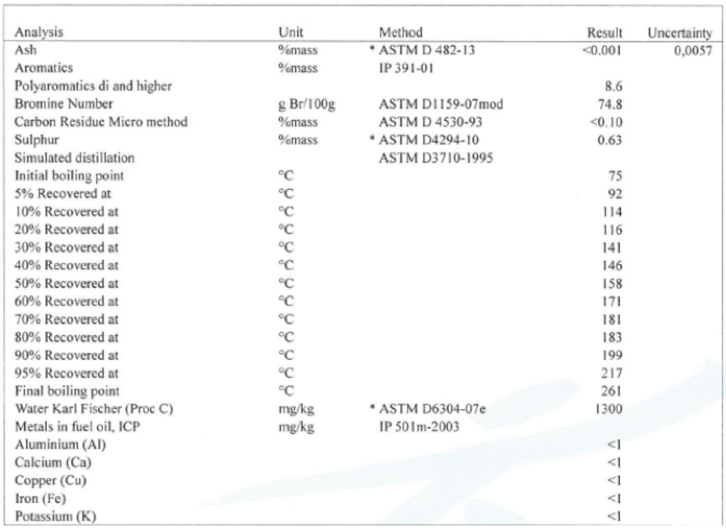


Analysis	Unit	Method	Result	Uncertainty
Ash	%mass	* ASTM D 482-13	<0.001	0,0057
Aromatics	%mass	IP 391-01		
Polyaromatics di and higher			14.7	
Bromine Number	g Br/100g	ASTM D1159-07mod	43.8	
Carbon Residue Micro method	%mass	ASTM D 4530-93	0.98	
Sulphur	%mass	* ASTM D4294-10	0.94	
Simulated distillation		ASTM D6352-04		
Initial boiling point	°C		140	
5% Recovered at	°C		182	
10% Recovered at	°C		220	
20% Recovered at	°C		252	
30% Recovered at	°C		288	
40% Recovered at	°C		323	
50% Recovered at	°C		360	
60% Recovered at	°C		393	
70% Recovered at	°C		426	
80% Recovered at	°C		459	
90% Recovered at	°C		498	
95% Recovered at	°C		526	
Final boiling point	°C		584	
Water Karl Fischer (Proc C)	mg/kg	* ASTM D6304-07e	700	
Metals in fuel oil, ICP	mg/kg	IP 501m-2003		
Aluminium (Al)			3	
Calcium (Ca)			<1	
Copper (Cu)			1	
Iron (Fe)			4	
Potassium (K)			<1	

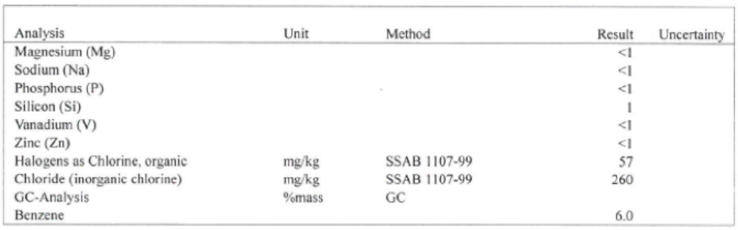


Analysis	Unit	Method	Result	Uncertainty
Magnesium (Mg)			<1	
Sodium (Na)			<1	
Phosphorus (P)			1	
Silicon (Si)			7	
Vanadium (V)			<1	
Zinc (Zn)			3	
Halogens as Chlorine, organic	mg/kg	SSAB 1107-99	95	
Chloride (inorganic chlorine)	mg/kg	SSAB 1107-99	69	
GC-Analysis	%mass	GC		
Benzene			<0.1	

Under 190°C (Mass fraction 5%)



Analysis	Unit	Method	Result	Uncertainty
Ash	%mass	* ASTM D 482-13	<0.001	0,0057
Aromatics	%mass	IP 391-01		
Polyaromatics di and higher			8.6	
Bromine Number	g Br/100g	ASTM D1159-07mod	74.8	
Carbon Residue Micro method	%mass	ASTM D 4530-93	<0.10	
Sulphur	%mass	* ASTM D4294-10	0.63	
Simulated distillation		ASTM D3710-1995		
Initial boiling point	°C		75	
5% Recovered at	°C		92	
10% Recovered at	°C		114	
20% Recovered at	°C		116	
30% Recovered at	°C		141	
40% Recovered at	°C		146	
50% Recovered at	°C		158	
60% Recovered at	°C		171	
70% Recovered at	°C		181	
80% Recovered at	°C		183	
90% Recovered at	°C		199	
95% Recovered at	°C		217	
Final boiling point	°C		261	
Water Karl Fischer (Proc C)	mg/kg	* ASTM D6304-07e	1300	
Metals in fuel oil, ICP	mg/kg	IP 501m-2003		
Aluminium (Al)			<1	
Calcium (Ca)			<1	
Copper (Cu)			<1	
Iron (Fe)			<1	
Potassium (K)			<1	



Analysis	Unit	Method	Result	Uncertainty
Magnesium (Mg)			<1	
Sodium (Na)			<1	
Phosphorus (P)			<1	
Silicon (Si)			1	
Vanadium (V)			<1	
Zinc (Zn)			<1	
Halogens as Chlorine, organic	mg/kg	SSAB 1107-99	57	
Chloride (inorganic chlorine)	mg/kg	SSAB 1107-99	260	
GC-Analysis	%mass	GC		
Benzene			6.0	

Figure D.2: All oils liberated below and above 190 °C

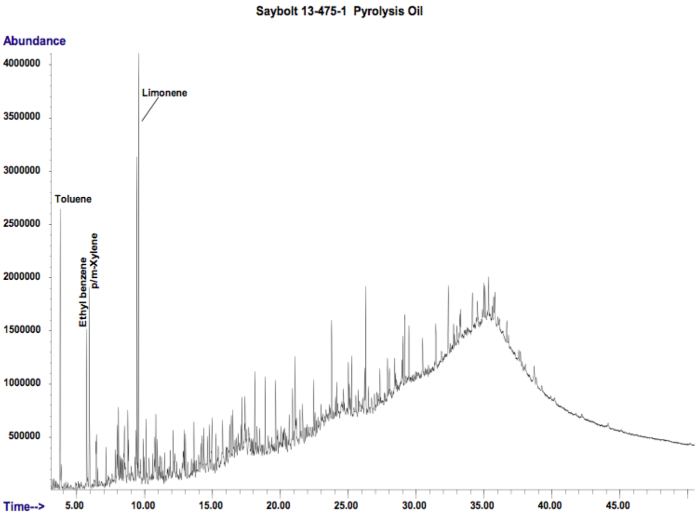


Figure D.3: All oils over a batch

E

Full scale drawing of the existing quencher

The drawing is confidential material.