Waste heat recovery from quenching towers

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by

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Abstract

Steel plants are one of the largest sources of waste heat. Waste heat recovery throughout the steelmaking process is not a new phenomenon. One of the sources of waste heat is found in the coke plant. Cokes are an essential part of steel production. During the coking process hot cokes are cooled down. Most coke plants in the world traditionally use water, so called wet quenching. In this process, all the heat put into the cokes is dispersed to the environment as steam. This waste heat source has huge potential. The goal of this study is to find a method to utilise this waste heat and to evaluate this method's technical and economic feasibilities.

The chief issue that must be tackled in a design is the fact that the steam generated during a quench is close to atmospheric pressure. Another issue to be solved is that of the solid particles suspended in the steam. Several potential designs were produced to use the steam from a quench to recover the waste heat. Based on several criteria, the design using the Synext engine was found to be the superior one and was developed further.

This design is divided into three sections, capture, cleaning and storage. A water wall and capture valve are used to capture the steam. An impaction and a cyclone separator are used to rid the steam of the solid particles to the extent that their detrimental effect to the Synext engine is minimised. The separators' dimensions are derived based on the steam input and Synext engine requirements. The steam is then stored in a storage vessel.

A Simulink model of the design is composed to simulate the process and evaluate its efficiency and technical feasibility. The model's findings show that the outputs for certain cases require unreasonable dimensions for the design. The economic analysis showed the designs costs make it an unlucrative investment.

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LIST OF SYMBOLS

This is a list of symbols used in this study. Each symbol has been explained or defined in the equations. The commonly used unit is mentioned, but alternative units occur in this report. Some symbols are presented here in their general form; they are made more specific in the tables and equations by adding superscripts and subscripts.

Symbol	Unit	Description
Abbreviations		
CDQ	-	Coke dry quenching
CSQ	-	Coke stabilization quenching
CWQ	-	Coke wet quenching
DAES	-	Differential algebraic equation systems
PSD	-	Particle size distribution
Symbol		
a	$[kg/kg]$	Moisture content
A	$[m^2]$	Area
b	$[kg/kg]$	Dry yield cokes/coal
Bi	$[-]$	Biot number
c	$[m^2]$	Flow conductance
c_p	$[kJ/kgK]$	Specific heat capacity
C	[€]	Costs
C_B	[€]	Base costs
C_E	[€]	Equipment costs
C_F	[€]	Capital costs
CDF	$[-]$	Cyclone dimension factor
D	*[m]*	Diameter
f	$[-]$	Friction factor
f_M	$[-]$	Correction factor for material
f_P	$[-]$	Correction factor for pressure
f_T	$[-]$	Correction factor for temperature
f_I	$[-]$	Overall installation factor for the system
F	$[N]$	Force
g	$[m^2/s]$	Gravity constant
G	$[kgm/s]$	Momentum
H	$[kJ]$	Enthalpy
h	$[kJ/kg]$	Specific enthalpy
K	$[-]$	Friction coefficient
K_{cycl}	$[-]$	Cyclone volume constant
l	$[m]$	Length
L_n	$[m]$	Natural length
m	$[kg]$	Mass
$\dot{m}$	$[kg/s]$	Mass flow rate
M	$[-]$	Constant dependant on equipment type
n_i	$[-]$	Efficiency for particle diameter

p	$[bar]$	Pressure
P	$[W]$	Power
Pen	$[-]$	Penetration
q	$[J/m^2 s]$	heat flux
Q	$[J]$	Heat
Q_B	[-]	Volumetric base capacity
$\dot{Q}$	$[J/s]$	Heat transfer rate
R	$[-]$	Resistive module
r	$[m]$	Radius
r^*	$[-]$	Dimensionless radius
s	$[kJ/kgK]$	entropy
S	$[-]$	Storage module
t	$[s]$	Time
T	$[°\,C]$	Temperature
u	$[J]$	Internal energy
U	$[W/m^2 K]$	Overall heat transfer coeffi-cient
v	$[m/s]$	velocity
V	$[m^3]$	Volume
$\dot{V}$	$[m^3/s]$	Volume rate
V_s	$[m^3]$	Entrance duct volume
w	$[m]$	Width
z	$[m]$	Height
Subscript		
air	-	Air
c	-	Cokes
Cap	-	Capture
$chimney$	-	Chimney
$coal$	-	Coal
Cle	-	Cleaning
$cond$	-	Condensing
$cycl$	-	Cyclone
d	-	Diffiusophoretic
$draft$	-	Draft
e	-	Electrostatic
E	-	Entering
Eq	-	Equipment costs
f	-	Pressure gradient
f	-	Friction
fan	-	Fan
$fluid$		Fluid
g	-	Gravity
gas	-	Gas
i	-	Index number
L	-	Leaving
Lg	-	Vapor to liquid
$losses$	-	Losses
$mixture$	-	Mixture
$motor$	-	Motor

p	-	Particle
r	-	Viscous resistance
ral	-	Rotary air lock
s	-	Shaft
sat	-	Saturated
$steam$	-	Steam
Sto	-	Storage
Syn	-	Synext
tan	-	Tangential
Th	-	Thermophoretic
W	-	Water
$wall$	-	Wall
Superscripts		
v	-	Vapor
l	-	Liquid
Greek		
λ	$[m^2/s]$	Thermal diffusivity
κ	$[W/mK]$	Thermal conductivity
Δ	$[-]$	Difference
ρ	$[kg/m^3]$	Density
ζ	$[-]$	Root
Φ	$[-]$	Dimensionless temperature
α	$[kJ/kgK]$	Heat transfer coefficient
τ	$[-]$	Dimensionless time
η	$[-]$	Efficiency
Ψ	$[-]$	Impaction parameter
μ	$[Pas]$	Dynamic viscosity

1. INTRODUCTION

The Netherlands has a yearly energy consumption of around 3200 PJ. This energy can be found in the form of electricity, raw materials and fuels, but the biggest share by far is heat (40%). The industry uses half of all this heat. Only 60% of the produced heat is used, the remainder is vented to the environment. This waste heat is equivalent to 15 billion cubic meters of natural gas. For comparison, in 2009 the Dutch households used less than 10 billion cubic meters according to the study of Schepers and Van Lieshout.

Another study by the U.S. Department of Energy, states that 20 to 50% of the industrial energy input is wasted as heat. Industrial waste heat is the energy generated in industrial processes without being utilized. The source contains among others high temperature combustion gases, heat losses from equipment and hot products leaving industrial processes.

It seems that this massive resource can contribute as a large player in the renewable energy world, although some heat losses are inevitable. Waste heat recovery entails capturing and reusing industrial waste. This can then be used for heating purposes or to generate mechanical or electrical work. Most of the waste heat is low grade. Low grade heat is low temperature heat (<150°C) and according to Carnot's theorem, only a fraction of this heat can be converted into work. The low quality of the waste heat therefore heavily affects the feasibility of waste heat recovery.

Steel plants are one of the largest sources of waste heat as a result of the high temperatures used in the energy intensive production of steel. Waste heat recovery throughout the steelmaking process is not a new phenomenon. As can be seen in Figure 1.1, from 1960 to 2014 a reduction of energy consumption of 60% is realized in the production of a ton of crude steel, because of improvements in energy efficiency (Worldsteel Association, 2018).

Cokes are an essential part of steel production. They are used as a fuel and reductant. Coke is made from coal in a coke and gas plant. Coal will be transported to the coke plant, where it is heated to about 1000°C. After heating, hot coke is pushed out of the coke ovens and cooled down. Most coke plants in the world cool down traditionally using water, so called wet quenching. In this process, all the heat put into the cokes is dispersed to the environment as steam. This waste heat source has huge potential.

There are different stakeholders in this research, so it is important to name them and state their aim of the research. Tata Steel IJmuiden B.V. is an integrated steel company, where more than 9000 people work to produce and supply more than 7 million tons of high-quality and coated steel, including design, technology and consulting services. The produced steel is mainly processed in the automotive industry, construction and packaging industry.

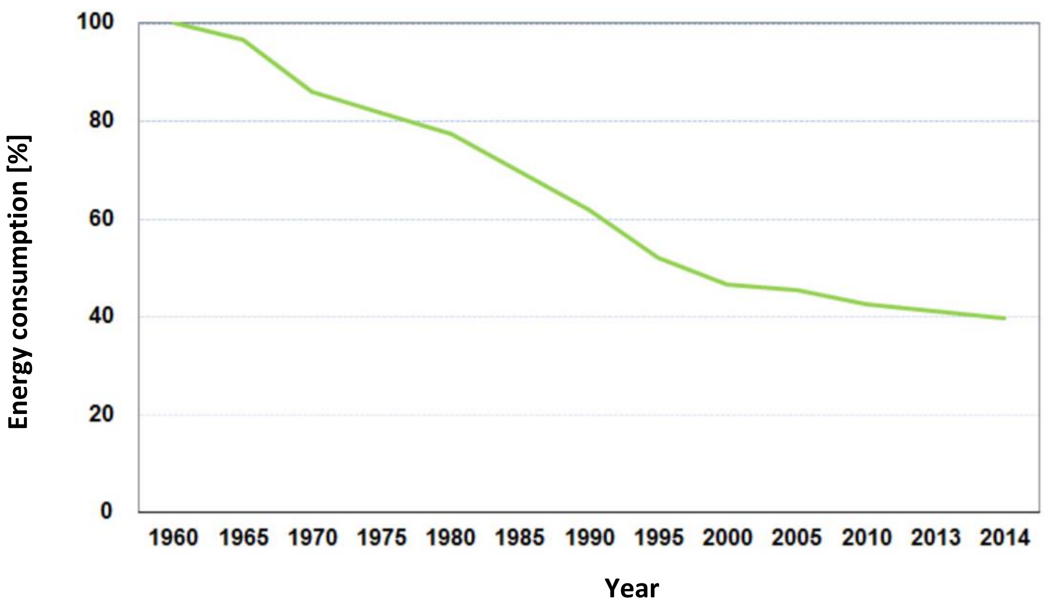


FIGURE 1.1 - PERCENTAL ENERGY CONSUMPTION REDUCTION 1960 – 2014. INDEXED GLOBAL ENERGY CONSUMPTION / TONNE OF CRUDE STEEL PRODUCTION (WORLDSTEEL ASSOCIATION, 2018)

The material is further used in batteries, tubes, industrial vehicles and in domestic appliances (Tata Steel, 2018). Tata Steel is willing to reduce its carbon footprint and investigates possible applications of the available waste heat streams.

Synext B.V. has a mission to fight global warming with waste heat. One of their products is an engine which converts low pressure saturated steam into electricity and liquid water. Synext is interested in investigating the capabilities of their concept to recover the waste flow of the coke quenching towers of Tata Steel Ijmuiden.

1.1. RESEARCH QUESTION

Tata Steel IJmuiden, as all European steel plants, uses coke wet quenching to cool down the cokes. There is a potential for using waste heat from the quenching towers. Tata Steel also wants to dispose of this steam for safety, environmental and image reasons. As the Synext engine needs steam as an input, this brings us to the main research question:

'Is it technically and economically possible to use the coke quenching steam of Tata Steel IJmuiden to generate electricity in the Synext engine?'

An answer to this question is found by answering the following sub-questions:

- *Which different waste heat recovery options are possible for the coke quenching towers?*
- *What is the optimal waste heat recovery solution for the coke quenching towers?*
- *For this optimal solution; what is the expected steam output and process needed?*
- *Is this option financially viable?*

The scope is defined as all the processes between the quenching towers and the Synext engine.

1.2. RESEARCH METHODOLOGY AND APPROACH

The types of research that will be used to approach this problem are both qualitative and quantitative researches. At first, a qualitative analysis will be made to gather in-depth understanding of steel plants, the coke quenching process, the steam it generates and the different concepts for waste heat recovery of the quenching process.

As part of the qualitative study, several waste heat recovery concepts are generated. The concepts are created by combining knowledge from literature studies, desk studies and interviews conducted with experienced steel plant engineers. The most technically and economically feasible concept is chosen and described in more detail: the Synext engine in a continuous process.

Next, a more quantitative approach is applied by modelling the steam output (capturing, cleaning and storing the steam). The modelled results are validated using the existing processes in the coke plant. Finally, an economic study is performed to demonstrate the potential and feasibility of the concept.

In Chapter 2 background information can be found on the steelmaking process, the current technologies used for quenching coke and on steam engines. Chapter 3 elaborates on different waste heat recovery options for the quenching towers and from these options the best concepts will be chosen. Chapter 4 offers the theory and modelling used to calculate the expected steam output and process needed. In chapter 5 the results are analyzed and discussed. An economic analysis will be made in Chapter 6.

2. BACKGROUND

Knowledge of the steel making process is necessary to understand this research. Therefore, this chapter will explain the basic working principle of a steel plant and specifically the coke plant and its quenching tower. As steam is an output of the quenching tower, steam engines and its history will also be discussed.

2.1.STEEL PLANT

Steel and iron have been one of the main drivers of the development of human civilisation for thousands of years and can be found in every aspect of our lives. It has been utilized in every industry, from agriculture to medicine. The industrial revolution was not possible without iron and steel, as these were one of the principal materials together with coal and cotton. The technical developments resulted in dramatic surge in the world steel production and this growth continued and has even exceeded 1000 million tonnes for the first time in 2004 as can be seen in Figure 2.1.

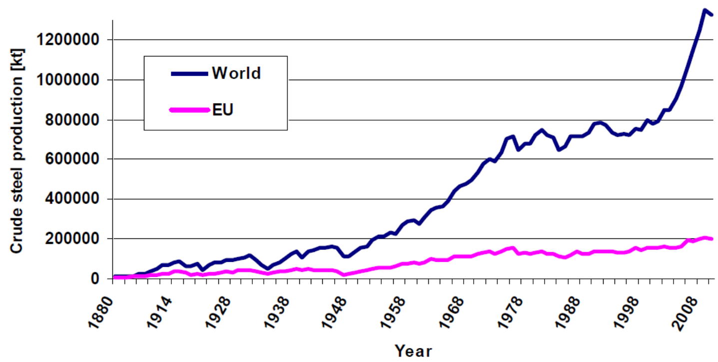


FIGURE 2.1 - CRUDE WORLD STEEL AND EUROPEAN PRODUCTION (WIRTSCHAFTSVEREINIGUNG STAHL & STAHLINSTITUT VDEH, 2009)

2.1.1. INTEGRATED STEEL PLANT

There are four methods of steel making. The first and most used is the classic blast furnace followed by the basic oxygen furnace route. The second technique is direct melting of scrap using an electric arc furnace. Thirdly comes smelting reduction and the last way of producing steel is direct reduction. These production methods are summarized in Figure 2.2.

The route of blast furnace and basic oxygen furnace is clearly the most complex. This production method is realized in large industrial sites called integrated steelworks. An integrated steel plant consists of interconnecting production plants with interdependent energy and material flows. These production plants are sinter plants, pellet plants, coke oven plants, blast furnaces, basic oxygen steelmaking plants and different casting plants. The steel making process is discussed in 2.1.2 using the Tata Steel plant in Ijmuiden.

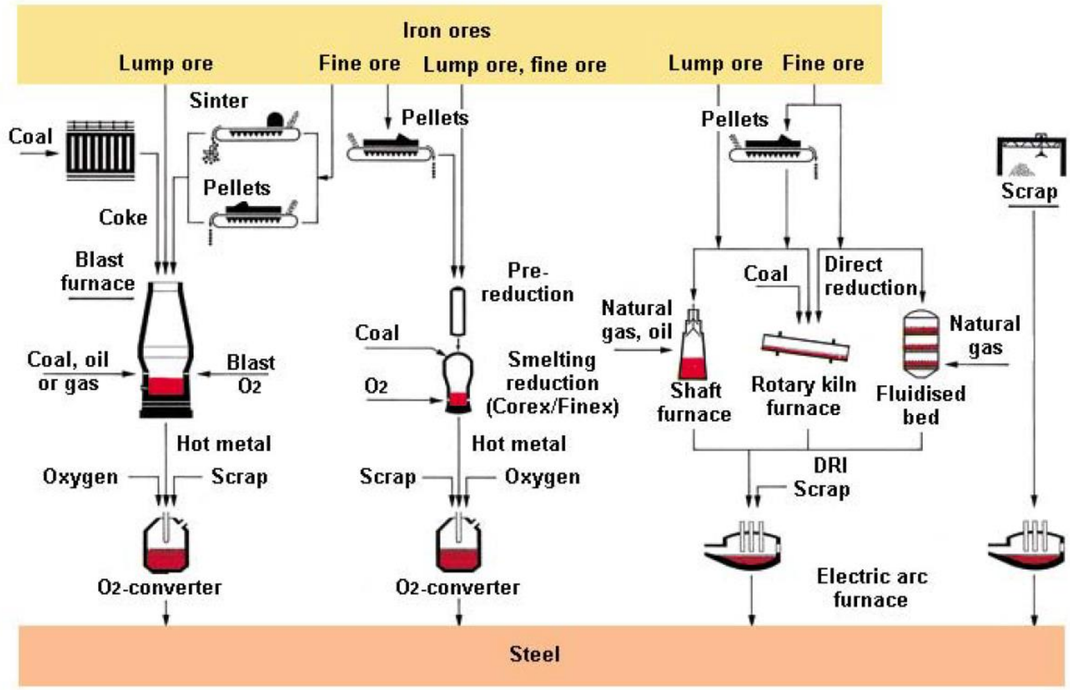


FIGURE 2.2 – METHODS FOR STEEL PRODUCTION (DEGNER, 2008)

2.1.2. TATA STEEL IJMUIDEN PLANT

HISTORY

In 1914, the entrepreneur H.J.E. Wenkebach and engineer Jan C. Ankersmit developed the first concepts of a steelmaking industry in the Netherlands. The incentive was to make the country less dependent of steel imports. As a result of the First World War, these plans were accelerated. On September 20, 1918, the *Koninklijke Nederlandsche Hoogovens en Staalfabrieken NV* was established and in 1920 the work began. On the 6th of October 1999, the *Koninklijke Hoogovens* merged with British Steel to form Corus and was later taken over by Tata Steel on the 3th of April 2007 (Wikipedia, 2018).

Over the years, many different products were manufactured including aluminium parts and cast-iron pipes, but now Tata Steel IJmuiden mainly produces steel rolls for the automotive industry, construction and packaging industry. The material is further used in batteries, tubes, industrial vehicles and in domestic appliances.

STEEL PROCESS

The integrated steelworks of Tata Steel IJmuiden will be used as an example to examine the steel process. Steel in IJmuiden is made using the most common way, which is the route of blast furnace and basic oxygen furnace. The different plants can be seen below in Figure 2.3.

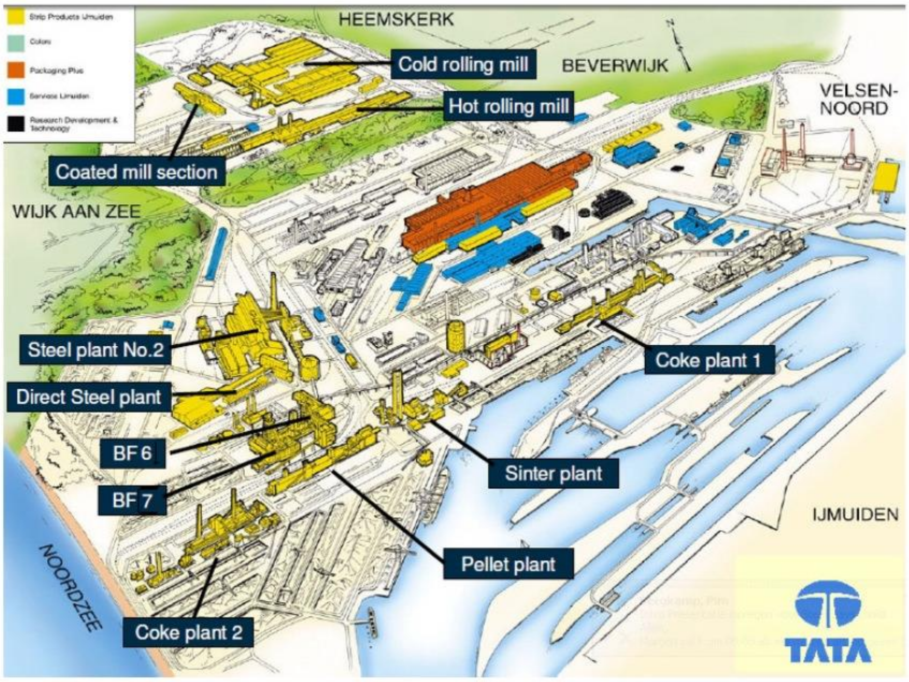


FIGURE 2.3 - MAP OF TATA STEEL IJMUIDEN (TATA STEEL, 2016)

ORE TREATMENT

Like most heavy industries, the making of steel starts deep in the mines. There are different rocks and minerals, where iron can be extracted from. The iron can be found as hematite (Fe_2O_3) or magnetite (Fe_3O_4) and between 25% to 65% is actually iron (Worrel et al., 2010). Firstly, earth is removed from the ore and then the iron ore is sorted on size. Ore rich in iron can be used directly into the blast furnace without any treatment. The blast furnace will be discussed later on in more detail. Iron poor ore needs further processing to raise the iron content. This is done in the pellet plant or in the sinter plant.

Tata Steel IJmuiden has its own harbour, where almost every day a ship docks with a up to 150 kilotons of material (Tata Steel, 2016). After the raw materials are unloaded, they are transported to the two stockyards of GSL (Grondstoffenlogistiek). The road of the raw material afterwards can be followed in Figure 2.4.

PELLET PLANT

Palletisation is the main way of agglomerating ore to small spheres, called pellets, that can be charged into the blast furnace. This is usually done near the mine. Tata steel IJmuiden however, is the only integrated steelworks in the EU with its own pellet plant. The principal process steps in this pellet plant are as follows. The ores are dried in the drying chamber of the ball mill so that they can be grinded to a finer particle size. This is done in the three ball mills, where fluxes and coke breeze are added. Fluxes are included to control the basicity of the slag of the pellets. Coke is needed to supply additional energy for the induration, which means thermal treatment. The mixture is then moisturized and homogenized. Now, the real pelletising starts.

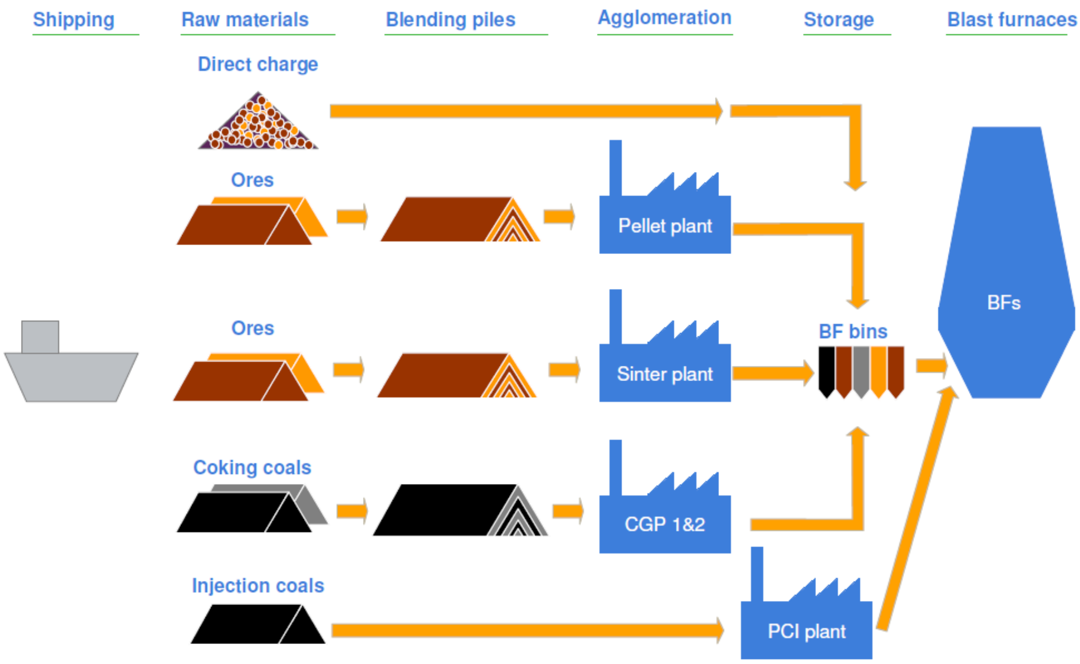


FIGURE 2.4 – PROCESS FLOW RAW MATERIALS TATA STEEL IJMUIDEN (TATA STEEL, 2016)

In 7 pelletising circuits, containing big drums, only pellets of a similar size are let through. These green pellets can later be stacked optimally in the blast furnace due to their size. But before that happens, the green pallets are dried and indurated in the induration machine to produce fired pellets. Typically in IJmuiden, 550 - 600 tons/hour (Tata Steel, 2016) is produced with an iron content of 60% to 65% (Worrel et al., 2010).

SINTER PLANT

The main purpose of a sinter plant is to sinter fine ore and other iron containing materials together into a porous agglomerate. Sintering is the process of compressing and forming a solid mass by pressure or heat. These formed agglomerates are necessary to increase the permeability inside the blast furnace. In the sinter plant of Tata Steel IJmuiden, the following materials are blended together. Sintering ores in the size range of 1-2 mm are used. Finer concentrates are also added, because they have a low SiO_2 level. Fluxes are needed to tune the slag chemistry at the furnaces. An important job of the sinter plant is to process internal recycling streams by accepting plant reverts, such as flue dust. Lastly, coke breeze is added as a reductant, to control FeO and as fuel. The sinter strand is a large travelling grate carrying the sinter feed. Gas burner, burning coke oven gas, ignite the coke, found in the upper layer. The flame front, fuelled by the coke oven gas and coke, moves down through the sinter directed by the fans. Afterwards, the sinter is cooled by air.

COKE & IRON PRODUCTION

Coke is an essential part of steel making in Tata Steel IJmuiden. Iron, in the form of hot liquid metal, is the main product of the blast furnace. It is produced by chemically reducing and physically converting iron oxides. Tata Steel IJmuiden has two blast furnaces on site. They are numbered as number 6 and 7. Blast furnace 1 to 5 have been demolished in the past. A blast furnace is a counter-current reactor lined with refractory bricks where there is a stream of solid iron ore going down exposed to hot reducing gas flow going up, as can be seen in Figure 2.5.

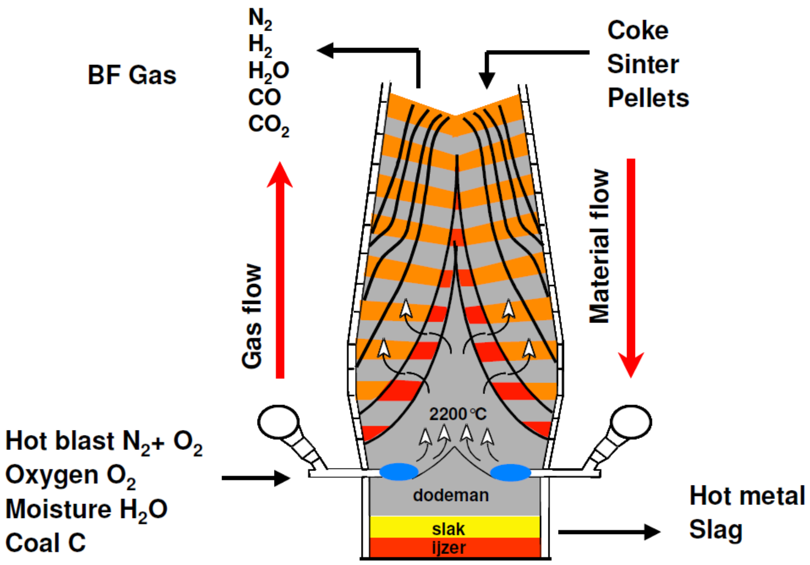


FIGURE 2.5 - BLAST FURNACE PRINCIPLE (TATA STEEL, 2016)

The main processes happening are as follows. First, the agglomerates and cokes are screened and weighed. Afterwards, the sinter and pellets need to be mixed. These iron-bearing agglomerates are charged in a separate layer than the cokes. The blast furnace is charged from the top with alternating layers of coke and the mixture. The hot blast stoves take a cold blast from blowers, enrich the O_2 levels to typically 32-35% and heat it up to create a hot blast. Each blast furnace has 4 hot blast stoves. The hot blast is directed to the tuyeres. Each tuyere is equipped with a pulverised coal injection lance that injects coal into the lower furnace. This coal is gasified instantly forming the reducing gases, CO and H_2. Due to these gases, sinter and pellets start reducing while descending forming CO_2 and H_2O. The descending material is also dried and heated by this ascending gas flow. This process is visualized in Figure 2.6.

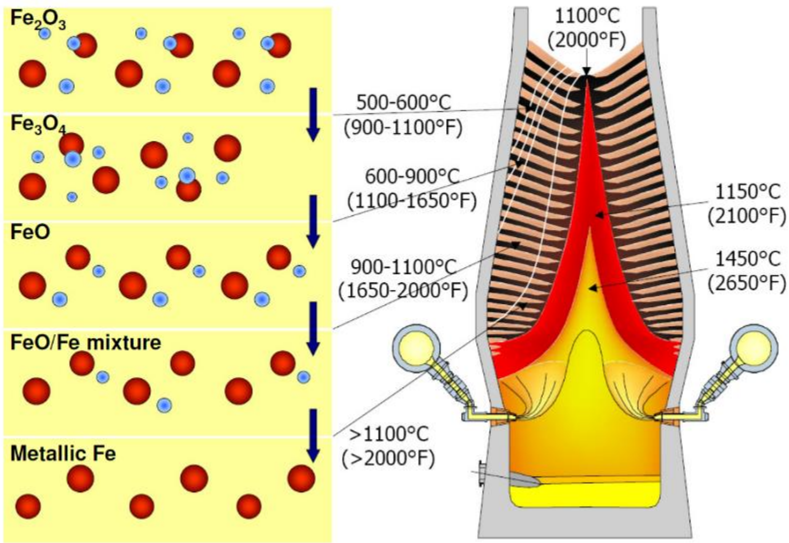


FIGURE 2.6 – REDUCTION PATH OF IRON OXIDES IN THE BLAST FURNACE (TATA STEEL 2016)

The now liquid hot metal is drained through the coke bed into the heart of the blast furnace. Each blast furnace has 3 tapholes, where the metal exits the blast furnace. The typical production of this pig iron is 8000 ton/day for BF6 and 10500 ton/day for BF 7. The slag is rapidly quenched to avoid damaging the conveyer belt and crystallised in the slag granulation. The resulting product is slag sand used for high-quality concrete. Lastly, the blast furnace produces a low calorific gas, because not all CO and H_2 gas has reacted.

STEEL PRODUCTION, CASTING AND MILLING

The hot metal produced in the blast furnace is transported using torpedoes to the Basic Oxygen Steel (BOS) Plant, called OSF2 (OxyStaalFabriek) at Tata Steel IJmuiden. OSF2 is the successor of OSF1 and uses the Linz-Donawitz-process to produce steel. Steel is defined as an alloy of iron with a carbon content between 0.001% and 2.1%. The pig iron from the blast furnaces has a carbon content of 3.5% to 4.5%, so this needs to be reduced. This is realized by blowing pure oxygen through a water-cooled lance in the hot metal. The molten iron is held by a pear-shaped vessel lined with refractory bricks. The oxygen reacts exothermically with the carbon. Therefore, scrap is added to control the temperature. Another purpose of a BOS plant is to remove all unwanted elements from the steel and adding alloying metals to create the desired chemical composition. This makes OSF2 the first step in the product diversification, 280 different qualities can be produced. The molten steel goes either through the continuous casters and leaves the plant as a slab. Or the liquid steel is delivered to the Direct Sheet Plant, where steel rolls are made. The slabs are further processed in hot and cold rolling mills to produce steel rolls.

COKE AND GAS PLANT

There are two coke plants in Tata Steel IJmuiden: Coke and Gas Plant 1 (CGP 1) and Coke and Gas Plant 2 (CGP 2), which locations can be seen in Figure 2.3. Coke is used in the blast furnace to reduce the iron ore into iron and it provides permeable support so the gases can flow freely. Coal can not be used, because unlike coke it doesn't retain its strength at high temperatures.

Coal straight from the mines are shipped to the Tata Steel IJmuiden's harbour, where they are unloaded and stored on separate piles. Yearly, 3 billion kg of coal enters the site (U.S. Department of Energy, 2008). These coals are then ground coals to prevent segregation while blending and to control the bulk density. The aim is to grind 75% of the coal to a particle size of at least 2 mm. 30 shots of this coal are stacked on top of each other to form a blending pile. This pile is transported to Coke Plant 1 or to the coal tower of Coke plant 2. Here the coal is weighed and then charged into the coke oven using a charging car. 16 and 32 tons of coal are charged respectively in Coke Plant 1 and 2 for around 20 hours. In the oven coke pyrolysis or dry distillation takes place. This is a process in which the coal is anaerobically heated to 1000°C – 1100°C. The goal is to disintegrate the coal into solid carbon, tar and volatile matter. The solid carbon is referred to as coke and is the final product. Not every kind of coal can be converted to coke. It needs to have the right plastic properties, for example coking or bituminous coals. In Figure 2.7, a coke oven of CGP 1 can be seen in production. The volatile matter leaves the oven as coke oven gas, a highly calorific gas. The gas production and composition depend mainly on the coal consumption and coking time. The coking time also positively affects the coke quality and coke yield. This coke yield is normally 60% of the used coals. For CGP 1, this leads to a yearly production of 1.2 million tonnes cokes. CGP 2 annually produces 1.0 million tonnes of coke (De Vries, 2013). This coke exits the coke oven at around 1000°C and needs to be quenched quickly to prevent oxidation. This will be covered in Section 2.2.

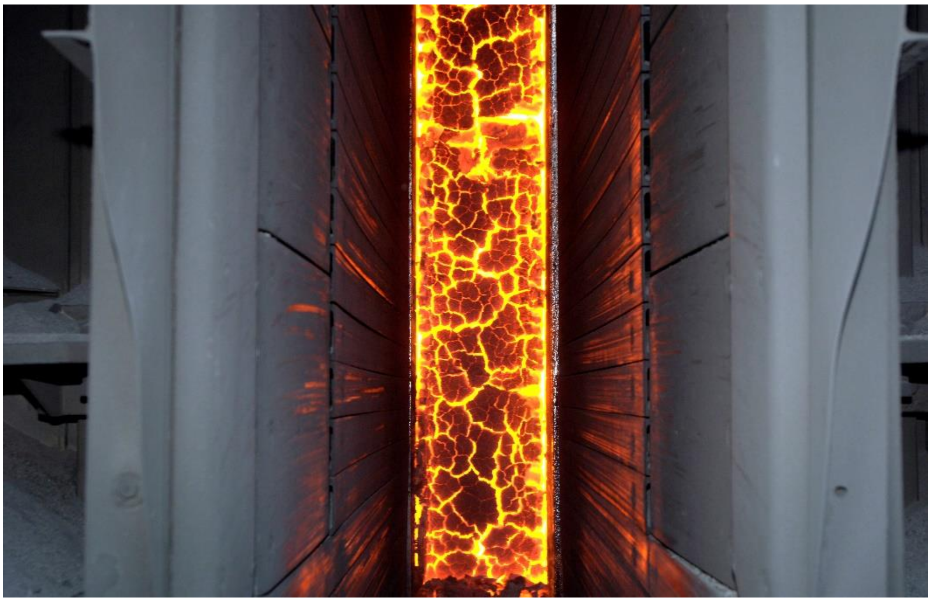


FIGURE 2.7 - COKE OVEN AT TATA STEEL IJMUIDEN CGP 1 (TATA STEEL ON BRAND, 2018)

As coal is abundant and relatively cheap and steel production is expected to grow especially in developing countries, it is expected that coal consumption and its environmental consequences will grow for the foreseeable future. It is therefore important to keep improving current technologies next to the development of new processes (Kienlen, 2007).

2.2. COKE QUENCHING

After the coking process, coke needs to cool down. This is traditionally done by quenching the coke using water. In this section, traditional wet quenching will be expanded on, thereafter coke stabilisation quenching will be explained. Next, the quenching situation at Tata Steel IJmuiden will be looked at. And lastly, an alternative method, where coke is quenching without water, will be elaborated.

2.2.1. TRADITIONAL WET QUENCHING

After the hot coke is being pushed out of the oven, it lands in a quenching car. This is a vehicle on rails, usually pushed or pulled by a locomotive or cable, as can be seen in Figure 2.8. The coke then arrives at the quenching tower. Generally, there are two types of towers. Coke wet quenching can be done by conventional (or traditional) wet quenching or by the more advanced Coke Stabilisation Quenching, which will be described in Section 2.2.2.

A conventional quenching tower can be seen in Figure 2.10. The structure has a concrete base and a wooden frame. Wood is chosen, because of the harsh conditions. Fast temperature changes in combination with an abundance of water and a plume containing highly abrasive materials makes the material choice quite limited. In Figure 2.9, the schematics are shown for this kind of tower. The quenching car is pushed along rails into the quenching chamber. This chamber has two openings, so the car can be pushed further along the rails to a safe space, if the tower malfunctions. These openings are hard to seal, because of the harsh conditions and how often they need to be opened.

FIGURE 2.8 - QUENCHING CAR AT CGP 2, TATA STEEL IJMUIDEN

If the car cannot escape in time, the wooden tower would catch fire due to the radiating heat of the quenching chamber. Another reason to quench as quickly as possible is to reduce the amount of cokes that is burnt, due to the temperature of the coke being higher than the ignition temperature. The benefit of having a slight delay of a couple of seconds after the car arrives, is to create a chimney draft. The quenching dome is located above the chamber. Here, the showers are located that swamp the coke from above. The water drowns the hot coke, blocking air from causing oxidation. Another way is to inject water directly into the car. This requires a more complicated set up. Another complication occurs, because steam bubbles are created below the cokes. The pressure build up can launch the coke particles. This phenomenon is known as “popcorn cokes”. When the water comes into contact with the coke, the heat is transferred to the water creating steam plumes. These plumes erupt with such a force, that pollution, mostly coke particulate matter, is drawn with the steam. This dust emission during wet quenching without reduction measures about 200 to 400 grams per tonnes cokes (Remus et al., 2013). This polluted steam is accompanied by air drawn in by the already present draft. The created white cloud travels up the tower through the baffles, before they exit the tower. The lamella stack baffles are the optimum solution to reduce the dust emissions and are comprised of individual plastic frames. The dust emission using these baffles can be reduced to at least 50 g/ton, but in practice it is as low as 25 g/ton (Remus et al., 2013). The baffles are flushed after every quench. This water, together with the majority of the quenched water, is collected in large settling tanks. The coke settles down and the water is pumped up to be reused. A quenching tower is usually in use every 15 minutes.

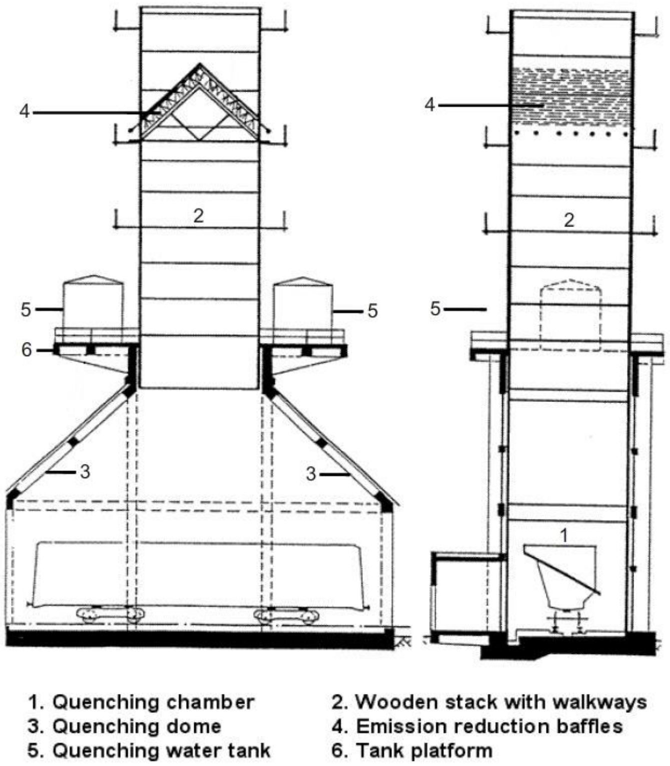


FIGURE 2.9 - SCHEMATIC OF A CONVENTIONAL QUENCHING TOWER (REMUS ET AL., 2013)

FIGURE 2.10 - CONVENTIONAL QUENCHING TOWER (BECHER & BECHER, 1978)

2.2.2. COKE STABILISATION QUENCHING

Coke Stabilisation Quenching or CSQ is designed to reduce particle emissions. They are also called Low Emission Quenching Towers (LEQT). These towers are larger than conventional towers to house the two emission control stages, as can been seen in Figure 2.11. Every stage consists of baffle plates and water sprays to reduce the dust in the plumes. The coke is quenched by water injected in the quenching car. A higher quenching rate follows from the extra quenching, but the coke moisture after CSQ is only 2% (The Institute for Industrial Productivity, 2007). This process results in a rapid reduction of the coke temperature and thus a better coke quality (Remus et al., 2013). Additionally, this fast cooling reduces the formation of unwanted gases (Schulz et al., 2015). The content of the plumes is discussed in greater depth in the appendix.

The dust emissions of CSQ can get as low as 6 g/t, but this is measured isokinetically according to VDI 2066, which is explained in the appendix. This method can result in higher measurement values. This relatively low emission number is the result of the following phenomena. The particulate matter (PM) that gets spalled from the coke gets trapped by the fast and intense cooling process. The distributed sprays ensure pre-condensation and separation of the ascending PM. The baffles further separate the coke dust. Lastly, to avoid horizontal flow at the bottom of the quench tower, a sealing between the tower and the quenching car is added (Huhn & Krebber, 2012).

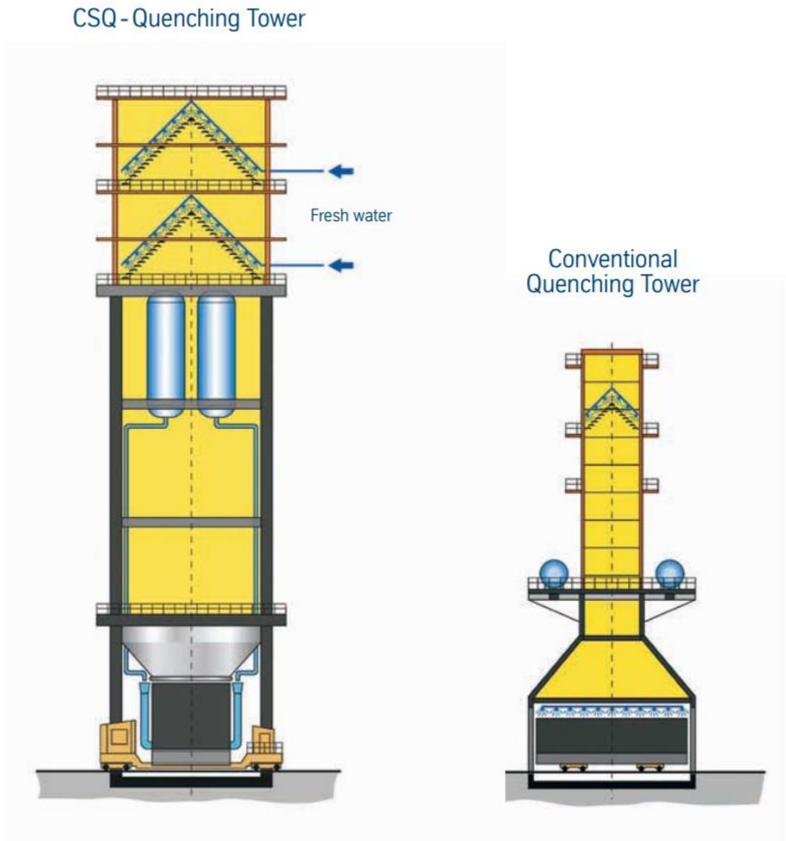


FIGURE 2.11 - CSQ COMPARED TO CONVENTIONAL QUENCHING. SCHWELGERN DESIGN (THYSSENKRUPP, 2014)

Examples of this technology can be found at the Hyundai and Schwelgern coke plants. In Schwelgern, where CSQ was implemented for the first time, two main components describe the quenching process. The first is the quenching car, which is both quenched with water from below and above. The major part of the water is fed from the bottom and creates a mixture of steam and water that propels the coke upwards from the 4 m deep car. When the coke drops down, the smaller particles are separated. The result is an evenly moistened and stabilized coke charge. The second component is the 70 m tall quench tower itself with its two levels of specially designed baffles for removing PM. The lower baffles are made of stainless steel, so it can withstand the high temperatures. The distances between the fins are designed to capture the coarser particles and are estimated to have a separation efficiency of 92%. The upper baffles are aimed to capture the fine dust. These polypropylene baffles have smaller inner distances between the louvers and have a separation efficiency of 74%. This results in a combined separation efficiency of 98%. To avoid accumulation, the upper baffles are scrubbed after every quench by a water spray. Clean water and not quenching water is used. Another PM capturing measure are two plume spraying devices, placed as seen in Figure 2.12. These cause the steam to partially condensate and the created water drops absorb the PM. The higher plume sprayer also acts as a scrubber for the lower baffles (Huhn & Krebber, 2012) (Thyssenkrupp, 2014) (Thyssenkrupp, 2014).

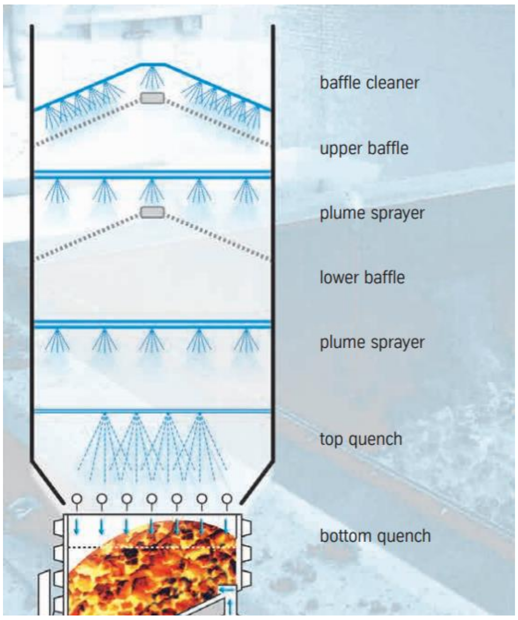


FIGURE 2.12 - CSQ QUENCHING PROCESS DIAGRAM (THYSSENKRUPP, 2015)

The CSQ quenching towers in the Hyundai Steel Coke Plant are of the same design. These 70 m high towers have concrete base lined by red bricks. The Bongossi wood structure supports the two baffle plates stages (Schulz et al., 2015).

2.2.3. Quenching towers at Tata Steel

As seen in Figure 2.3, there are two coke plants in Tata Steel IJmuiden: Coke and Gas plant 1 and 2. These are respectively abbreviated as CGP 1 and CGP 2.

CGP 1 currently has 3 towers: Quenching tower (QT) 11, 13 and 14. The first number corresponds to plant and the second to the tower in order of when it was built. QT 12 is demolished. QT 11 is the middle tower and is fed from the middle block, battery 19. QT 13 can be found in the eastern block, battery 16, 17 and 18. Lastly, QT 14 is in the west supplied from battery 11 and 12.

CGP 2 only has one tower, 21. QT 21 produces double the amount of cokes in comparison with the towers of CGP 1.

All quenching towers in both plants are traditional quenching towers and their layouts can be seen in Figure 2.13 and Figure 2.14. In Section 0 , more specifications are found about the different towers.

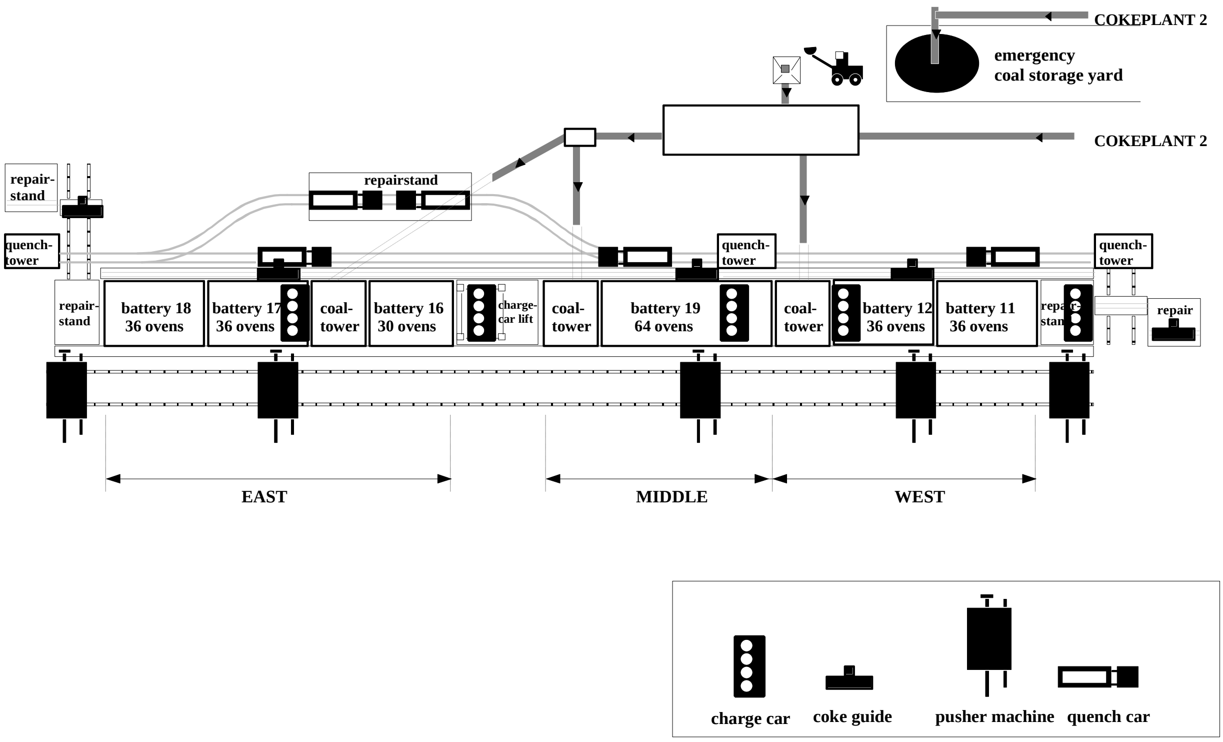


Figure 2.13 - Layout Coke and Gas Plant 1 (De Vries, 2013)

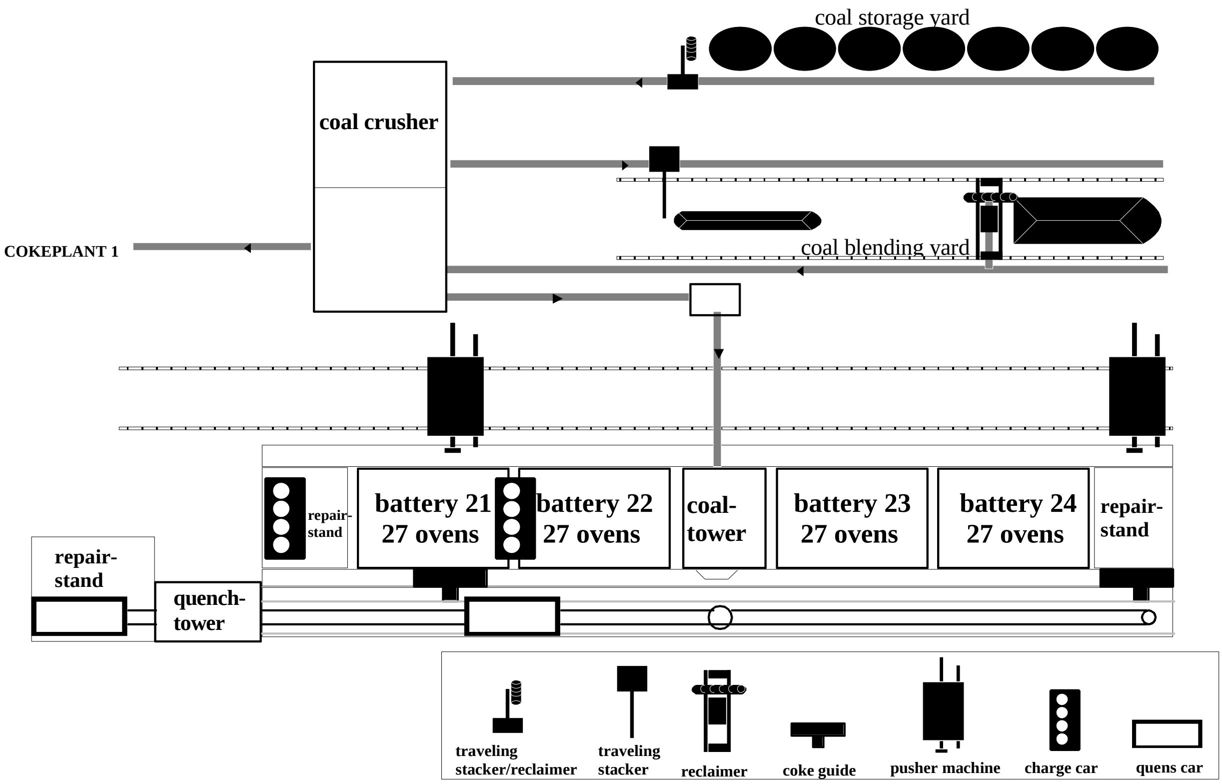


FIGURE 2.14 - LAYOUT COKE AND GAS PLANT 2 (DE VRIES, 2013)

2.2.4. Coke Dry Quenching

Quenching coke with water is presently the most popular process used in coke plants worldwide (Japan Innovation Network, 2006). Coke Dry Quenching (CDQ) is an alternative to the conventional wet quenching of coke, mostly installed in Japan and Russia. Coke is cooled using an inert gas in a dry cooling plant, instead of using water which may results in thermal losses. The circulation gas is a mixture of mainly nitrogen. In this process, the thermal energy is recovered and used for the production of steam and electricity.

With CDQ, less coke is needed in the blast furnace and the coke quality improves. As the product quality is improved, CDQ also allows for the use of lower cost coal in the process and thereby reducing costs (Remus et al., 2013). Because of the lower moisture content, water is usually added after CDQ. The process is depicted in Figure 2.15:

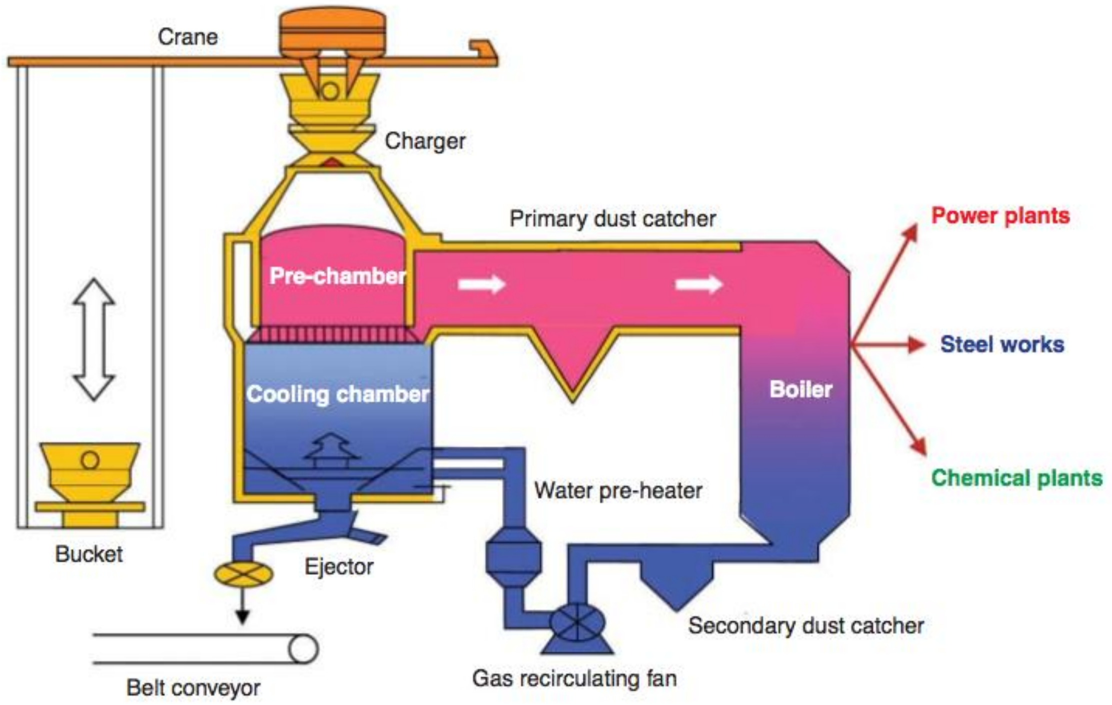


Figure 2.15 - CDQ process flow (NEDO, 2006)

The process is as follows. The quenching car arrives from the ovens and is lifted using a crane. After it is placed on top of the pre-chamber, the coke is charged inside this chamber. While nitrogen flows up into the cooling chamber, hot coke falls down and heats up the nitrogen. The nitrogen flows along the primary dust catcher, where most of the dust falls down, to the boiler. Here, the hot nitrogen exchanges its heat with water to produce steam. This steam will partly be used to generate electricity. The colder nitrogen is dedusted again, before reused in the cooling chamber. The cold coke is ejected by the ejector on a belt conveyer. The coke is very dry. To avoid dusting, water is sprayed on the coke to higher the moisture content.

Bisio and Rubatto state that it is possible to recover 44% of the exergy value of the coke thermal energy. Coke Dry Quenching is therefore the preferred method of quenching. This process has already been set as financially unfeasible for Tata Steel Ijmuiden (Tata Steel, 2012). CDQ is therefore outside of the scope of this research and will not be mentioned further in this report.

2.3. ATMOSPHERIC STEAM ENGINE

In this section, a short history of the atmospheric steam engine and its workings will be given. Then, the Synext engine will be discussed. Lastly, the benefits of an atmospheric steam engine, like the Synext engine, will follow.

2.3.1. HISTORY OF DIFFERENT STEAM ENGINES AND THEIR WORKINGS

Using steam to produce mechanical motion is not a new concept. Over 2000 years ago, the first devices popped up that showed the potential of steam power. The first recorded engine was the aeolipile or the Hero's engine. This was a simple radial steam turbine invented by Hero of Alexandria in the first century. A water vessel is heated, and the generated steam exits via two bent nozzles creating a rotary motion. This device is depicted in Figure 2.17.

FIGURE 2.17 - ILLUSTRATION OF THE WORKING PRINCIPLE OF THE AEOLIPILE (KNIGHT'S AMERICAN MECHANICAL DICTIONARY, 1876)

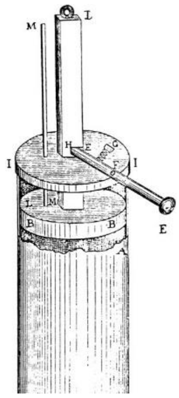


FIGURE 2.16 - FIRST PISTON STEAM ENGINE, BY DENIS PAPIN (VALENTI, 1979)

Denis Papin was the first to use a steam powered piston to raise weights in 1690. In his article "A New Method of Obtaining Very Great Moving Powers at Small Cost" he proposed using the power of condensing steam to move a piston. This new invention replaced the gunpowder in Huygens' cylinder with steam to create a better vacuum under the piston. This results in better utilization of the atmospheric pressure. This prototype is portrayed in Figure 2.16. Papin did recognize the inherent problem with the atmospheric steam engine. Since the source of force is not the steam itself, but the pressure of the atmosphere, the only way of increasing power is to increase the diameter of the cylinder.

In 1712, Thomas Newcomen continued on this idea and developed the first practical and commercially successful steam engine. In the late 16th century, Northern Europe started to mine deeper and deeper to find coal, minerals and ores. Consequently, groundwater became a large obstacle. Different pumps already existed, but these were human, animal, wind or even water powered. Newcomen looked for a more effective and cost-efficient answer to this challenge. His solution is known as the Newcomen Pumping engine and shown in Figure 2.17.

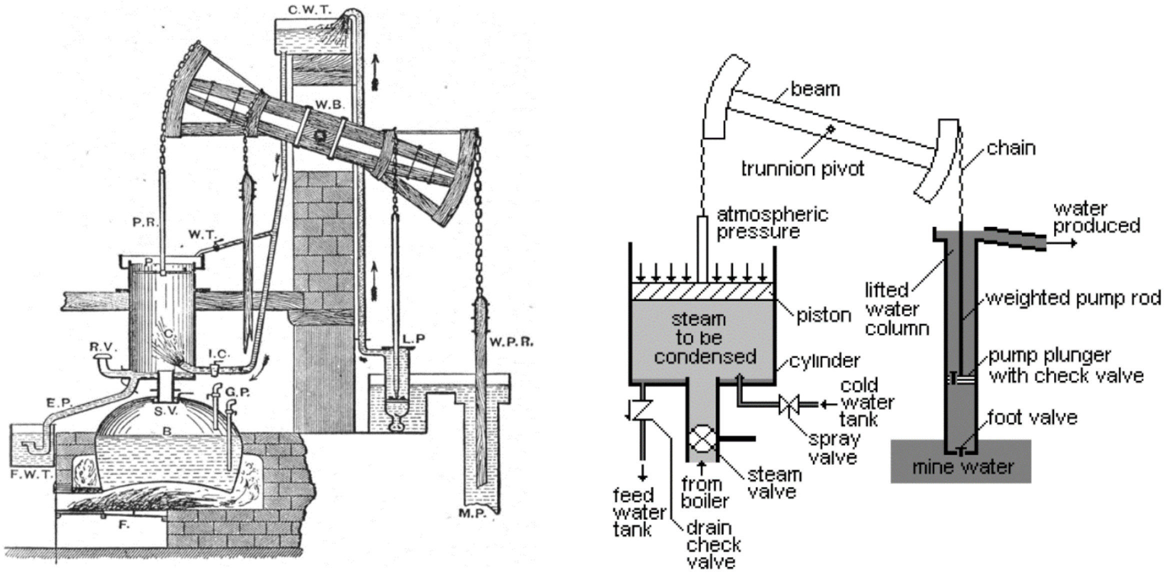


FIGURE 2.18 - THE NEWCOMEN PUMPING ENGINE AND A SCHEMATIC OF ITS WORKING (CARR & COWART, 2012)

The mechanism consists of a rocking beam with on one end a piston and on the other a reciprocating pump. It is designed for the piston to be raised due to the weight of the water on the pump in a non-work state. This allows steam at atmospheric pressure to enter the piston from the boiler. Pumped up mining water, stored in a raised cold-water tank, is sprayed directly in the cylinder to condense the steam. This creates a vacuum in the cylinder. The atmospheric pressure, now greater than the pressure in the cylinder, pushes the piston down. This results in water being pumped up on the other side. New steam is admitted into the cylinder and the cycle continues.

The next major step was the improvement of James Watt to Newcomen's engine. When experimenting with the engine, he discovered that most of the steam was wasted. Condensing the steam also cooled down the cylinder. So, when new steam is introduced in the now cold cylinder, it condenses against the walls until the cylinder is heated. To prevent these large temperature fluctuations, Watt added a separate condenser and a steam jacket around the cylinder. This increased the efficiency from 0.5% to 3.5% (Müller, 2015).

Later, high pressure steam engines were introduced to increase the efficiency, energy density and engine speed. This also paved the way for the double acting cylinder and the rotary type engine. These advancements made it possible to use steam to power many machines and vehicles. As the energy source in this research is atmospheric steam, pressurized steam engines are not further discussed. Because high pressure steam engines have higher efficiencies, no theoretical or experimental work was done on the atmospheric steam engine for over 200 years. Wang et al. developed a micro steam engine based on the Newcomen steam engine to power electronic devices. With its efficiency of 2.58%, it is above the 1% feasibility threshold for micro power systems. Although it is strictly speaking not an atmospheric engine, it is one of two recent application of the principle. The other one is done by Müller (Müller, 2013)(Müller, 2015), where respectively a theoretical and experimental re-evaluation is done of the atmospheric steam engine. This was extended with a forced expansion stroke.

2.3.2. Benefits of the atmospheric engine compared to similar technologies

Heat is generated in many industrial processes and in many areas of renewable energy. High temperature thermal energy (>400°C) is usually used for large scale energy generation installations. Cost-effective solutions for medium temperature waste heat (100°C to 200°C) for industrial applications still lack development. Stirling engines or other classic hot air engines need a temperature of 400°C or more to work efficiently. Organic Ranking Cycles (ORC) use different working fluids with lower boiling temperature than water. This makes them applicable for lower temperatures than regular Rankine Cycles. The turbines used in ORC however are complex, due to the pressurized fluid. An analysis of the different ORC's and their feasibilities is found in (Quoilin et al, 2013). There is a need for a simple and cost-effective engine to utilize low temperature thermal energy (Müller, 2013)(Müller, 2015)

2.3.3. Synext engine

Synext B.V. is a company situated in Delft, the Netherlands. Its mission is to help industries transition to a sustainable energy system by boosting energy efficiency. They want to accomplish this by tackling waste heat. The worldwide market for systems designed to recover this waste heat is substantial. It is estimated to be $44.14 billion in 2015 and growing to be $65.87 billion in 2021 (Synext, 2017).

The Synext engine is an atmospheric steam engine that converts low pressure saturated steam into electricity and water. The process is depicted in Figure 2.19.

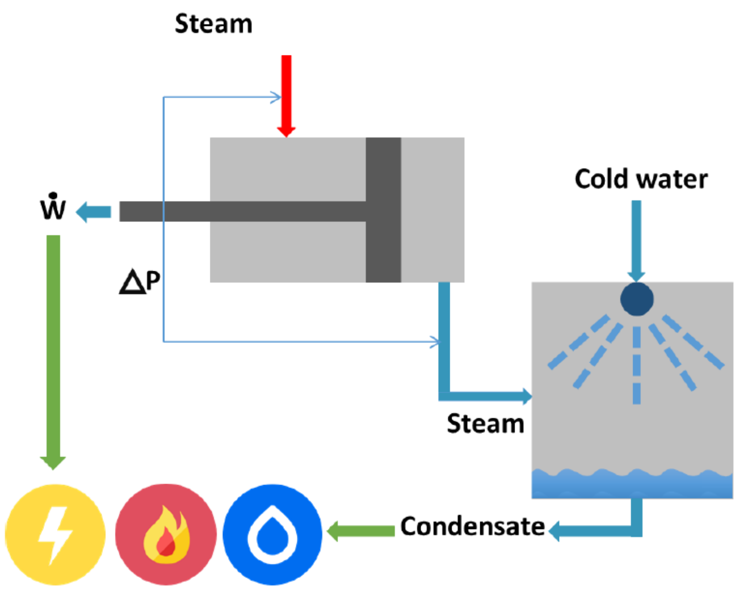


FIGURE 2.19 - SYNEXT ENGINE (FATEH, 2017)

The device consists of a double acting cylinder and a condenser. This cylinder can be fed steam from both sides. There is also a connection to the cylinder at both sides. The cycle starts with both sides of the cylinder filled with steam and the piston in the middle of the cylinder. A valve stops the steam inlet from supplying steam to the right side of the cylinder. At the same time, another valve opens the connection between the condenser and the right side of the cylinder. The steam is condensed, creating a vacuum in the condenser and subsequently in the right side. Because of the pressure difference between the two sides, the piston moves to the right. Now, the valves change orientation and the right is disconnected from the condenser and connected to the steam inlet. While the right side of the cylinder is filling up with steam, the left side is cut off from steam and connected to the condenser. This makes the piston move to the left and de cycle continues. The reciprocating motion of the piston is converted to electricity using a rotary generator.

The spray keeps the condenser cold and a steam jacket around the cylinder keeps it warm for optimal efficiency. In contrast to a conventional atmospheric steam engine, the force is not related to the ambient pressure, but the steam pressure. If the steam pressure is higher than saturation pressure, this will increase the efficiency. A steam temperature lower than 100°C is also possible, but the correlated lower steam pressure does affect the efficiency negatively. This is a range of waste heat that is usually hard to recover as discussed in Section 2.3.2. The other output of the engine is water and its quality depends on the steam properties.

The Synext engine can be optimized to produce electricity or to produce electricity and supply hot water for heating purposes.

3. CONCEPTS

In this chapter, the concepts are described that provide a waste heat recovery solution for the coke quenching towers. The different concepts will be elaborated on, assessed and thereafter the optimal solution will be chosen.

3.1. MAIN REQUIREMENTS

The main goal of the design is to utilize the waste heat generated by cooling down the coke. The coke is cooled down by water in de quenching tower creating steam. This steam is therefore fouled with coke particles of varying sizes. A secondary goal would be to clean this steam to prevent the dust particles from going to the environment.

3.2. MAIN CHALLENGES

The steam, where the energy needs to be extracted from, comes free in harsh conditions. Firstly, there are very large temperature differences in the process. The hot cokes start off at a temperature of 1000°C and because of the condensation of the steam, the entire system cools down rapidly. Secondly, the steam is atmospheric. This makes it very susceptible for condensation. Furthermore, there are small coke particles floating in the steam. These are hard and this abrasive fouling can have a negative effect on the durability of the materials used. Lastly, the process is in batch form and relatively fast. This could add additional challenges.

3.3. DIFFERENT CONCEPTS

The main concepts to accomplish the goals mentioned above are described in this section. The first two concepts use the Synext engine to reuse the heat. The other concepts use different techniques to achieve these goals.

3.3.1. CONCEPT 1 – USING THE SYNEXT ENGINE IN BATCH

The most simple solution would be to simply capture the steam, clean it and immediately direct it to the Synext engine, as can be seen in Figure 3.1.

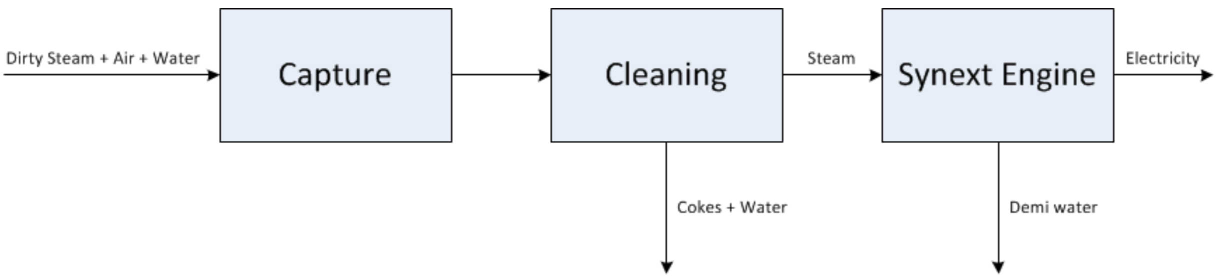


FIGURE 3.1 - DIAGRAM OF CONCEPT 1

The steam plumes also contain air and small coke particles. This mixture needs to be captured, so it will not escape into the environment as occurs in a conventional quenching tower. The particulate matter needs to be extracted from this batch before it enters the Synext engine, where condensing the steam generates electricity.

As the steam emitted is saturated, capturing steam before it is condensed can be a challenge. Also, as the steam is used directly, this batch process has big mass flows and therefore needs a considerably large Synext engine to manage this. The generated electricity will also be fluctuating.

3.3.2. Concept 2 – Using the Synext engine in a continuous process

Concept 2 also entails capturing and cleaning the steam. However, the steam is also stored. The process can be seen in Figure 3.2 - Diagram of Concept 2.

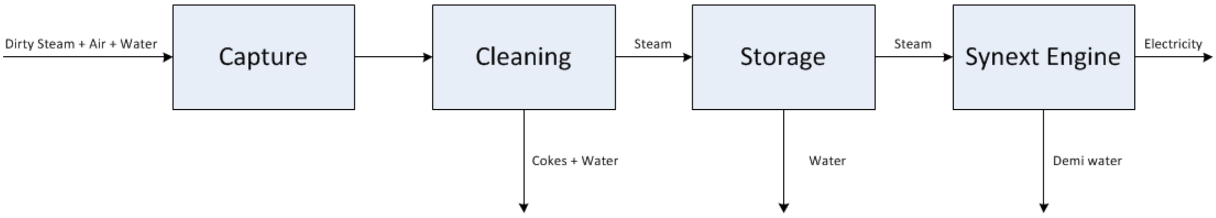


Figure 3.2 - Diagram of Concept 2

Storing the steam can ensure a continuous process. Another benefit is that the output mass flow is considerably small and therefore easy to handle. Also, lower velocities increase the cleaning efficiencies. A drawback would be that more condensation will take place, lowering the overall efficiency.

3.3.3. Concept 3 – Building a new tower

Another approach would be to fully optimize the design to make steam for the Synext engine. This would result in the following design, schematically depicted in Figure 3.3. Here, hot coke is put in the vessel together with nitrogen to prevent oxidation. Water is pumped into the mantel of the vessel and converted to steam due to the heat exchange with the coke. This clean steam is then fed into the Synext engine. The hot nitrogen is led through the water to lose its heat and then recycled back into the system. The water produced by the Synext engine can be supplied back into the system. The mantel does lack a large heat exchange area between the coke and water. Multiple vessels may be applied.

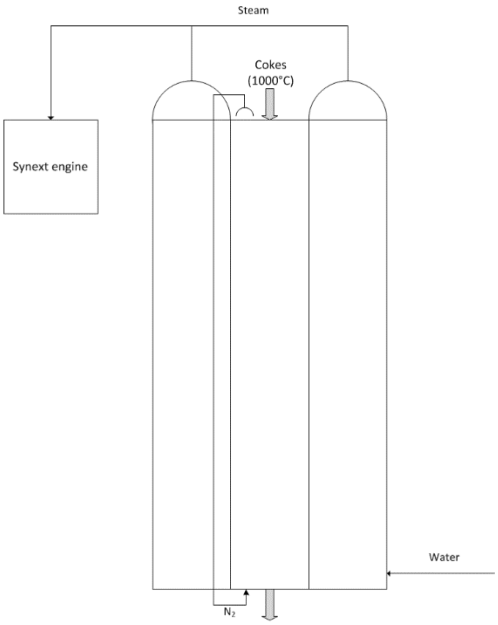


Figure 3.3 - Diagram of Concept 3

3.3.4. Concept 4 – Upgrading the heat using a heat pump

The escaping steam plume can be led through a heat exchanger, where a working fluid is pumped through a heat pump. The produced higher temperature medium can be used in the Synext engine or for other purposes. The higher quality heat is more easily converted and is without fouling. The process is depicted in Figure 3.4.

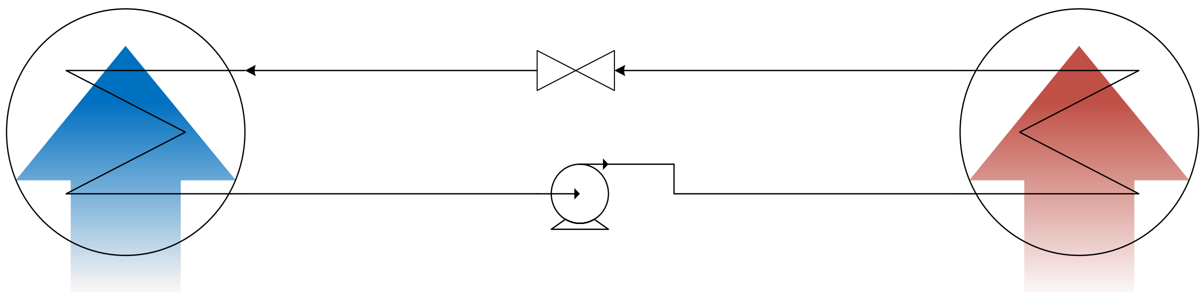


FIGURE 3.4 - DIAGRAM OF CONCEPT 4

The steam plumes flow past the first heat exchanger, shown left above. This evaporator evaporates the working fluid and is thereafter pumped by the compressor to the second heat exchanger. This condenser is shown to the right. The heat is transferred to another medium, which now has a higher temperature than the original steam plumes. The working fluid is then expanded, and the cycle continues.

A heat exchanger inside the abrasive steam plumes could pose serious problems for its life expectancy. Due to the high mass flow of the steam, either a large part of the heat will not be exchanged or a substantial large heat exchanger is needed for a reasonable efficiency.

3.3.5. CONCEPT 5 – USING A STEAM TURBINE

In this concept, a steam turbine is directly used to recover the energy. As atmospheric dirty steam enters, the exiting water would be of sub atmospheric pressure. This would be compensated by setting the turbine up at a certain height.

A turbine capable of handling the abrasive steam would be expensive. Also, as the steam is fed into the turbine in batches, this will make the turbine quite inefficient. The turbine starts and stops at every quench. The actual time the turbine will work at optimum efficiency will therefore be very short.

3.3.6. CONCEPT 6 – USING AN AIR TURBINE

Concept 6 uses the draft, created by the pressure drop during condensation of the steam, to drive an air turbine. This process is described in Figure 3.5.

Steam contaminated with particulate matter flows into the condenser, where it is condensed. This creates a vacuum. Air then flows through a turbine into the condenser raising the pressure inside the condenser. Air is flushed out with new steam and condensed again.

The benefit of this concept over concept 5 is that it can be made so no abrasive particles enter the turbine. Also, using air instead of steam inside the turbine would make it cheaper. The turbine would still be turning discontinuously. On top of that, the pressure of the steam must always be higher than the atmospheric pressure.

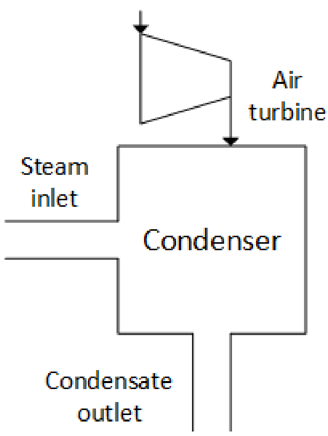


FIGURE 3.5 - DIAGRAM OF CONCEPT 6

3.3.7. Concept 7 – Using a water turbine

Here, the plumes are condensed at the top at the tower and the gravitational energy is used to drive a water turbine. A simplified drawing can be seen in Figure 3.6.

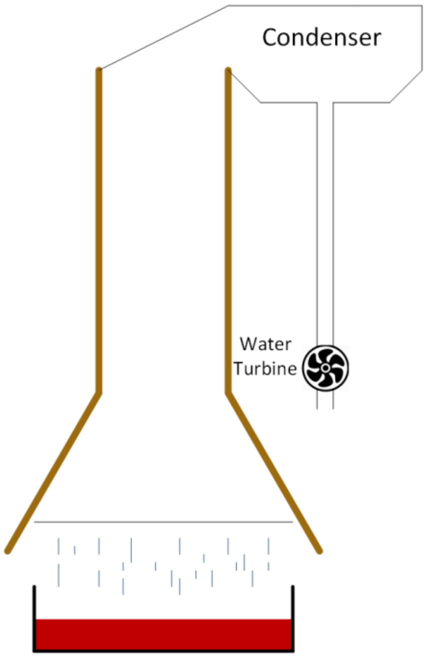


Figure 3.6 - Diagram of Concept 7

The steam plumes rise in the tower through buoyancy. By condensing the steam at the top, the created water and its contamination can be held inside a vessel. This water flows down a water turbine to the settling tanks in the ground.

Certain remarks must be made concerning this design. A benefit would be that less water is needed for the quenching, because it is not lost to the environment. However, to condense the steam, it should all be captured which is complicated. Nevertheless, if the steam is captured, it does not have to be cleaned. The fine particles would flow down with the condensed steam. Another problem would be the construction. Tons of water and additional equipment need to be kept over 30 meters high. This can only be done by reinforcing the tower.

3.3.8. Concept 8 – Using a condenser

Concept 8 simply condenses the steam without energy recovery. Steam still needs to be captured. Even though the waste heat is not utilized, several advantages need to be mentioned. Condensing the steam plumes give an opportunity for recycling the water. This saves water that would otherwise be emitted to the environment. The lack of steam plumes has safety benefits too. Also, less steam plumes give a less industrial feel, as they are often confused with high pollution smoke. This could benefit relations with neighbouring residents and clients. Lastly, the fine coke particles will also be captured when condensing the steam. This will make it possible to go near a zero-pollution situation.

3.4. CONCEPT CHOICE BY MULTI-CRITERIA EVALUATION

Now the different concepts are elaborated, selection criteria can be layed out to use in a decision matrix. This decision matrix will rank the different concepts.

3.4.1. Selection Criteria

In this section, different criteria will be explored while grouped by topic along with the reasoning behind either a low or high score for a specific criterion.

ECONOMIC CRITERIA

INSTALLATION COSTS - What are the costs to realize the technology? Particularly, what investment is required to simply install the system? The lower the implementation costs, the higher the score.

OPERATION AND MAINTENANCE COSTS - The running costs of the system should be considered. If maintenance is required more regularly, this increases costs. A simpler system results in easy maintenance and less downtime. Lower operation and maintenance costs means a higher score.

TECHNOLOGICAL CRITERIA

EFFICIENCY - One of the main goals is to recover the waste heat. If the most waste heat can be recovered using a minimal amount of resources, a system is deemed efficient. An efficient system obtains a high score on this criterion.

POSSIBILITY FOR AUTOMATION - Is personnel required or can the system run automatically? An automated plant is preferred by Tata Steel, since it cuts the human risks and costs. If the prospects for automation are better, the score is higher.

APPLICABILITY - Is the technology universally applicable? Can it be adapted to local conditions in the steel industry? Can it benefit from scaling? A higher score for this criterion corresponds with a better applicability.

TECHNICAL MATURITY- How mature is the technology? Is there a proof of concept? A high score means the system is mature and has been thoroughly tested in practice.

IMPLEMENTATION TIME - How long will it take before the technology is up and running? What is the construction time? If the implementation time is short, the system gets a high score.

SUSTAINABILITY CRITERIA

SUSTAINABILITY - Tata Steel has environmental goals and regulations that should be achieved. To accomplish this objective, particulate matter emissions and the exhaust of greenhouse gases have to be reduced. The technology should not be a strain on the environment in the near nor distant future. The higher the score, the more sustainable the design.

LIFETIME - What is the technological lifetime of the system? Is this aligned with the rest of the plant? Are the investments put into the system then regained? A high score matches with a long lifetime.

POTENTIAL FOR RECYCLING - Can the installation be used after its lifetime? Are the materials still of the same value after the first life cycle? A high potential for recycling corresponds with a high score.

OTHER CRITERIA

HEALTH AND SAFETY - Is the design sufficiently safe to meet all regulations? What are the risks for workers, nearby installations and the production? Are these risks looked into to limit them as much as possible? Risks can not only occur during operation, but also during assembly, downtime and deconstruction. A higher score will be given, if a safer method for using the waste heat is proposed.

REGULATORY OBSTACLES AND ADVANTAGES - Will implementing the system encounter resistance due to local or national government paperwork and certifications? Or will there be incentives in the form of subsidies and mitigation? A high score is attained if the technology can be realized without much negative interference from the government.

3.4.2. Decision matrix

Table 3.1 - Concept Choice Decision Matrix

	Economic		Technology					Sustainability			Other		
Criteria	1	2	1	2	3	4	5	1	2	3	1	2	**Total**
Concept 1	4	4	3	2	4	2	3	4	3	4	4	4	41
Concept 2	3	3	4	4	5	2	2	5	4	3	4	4	**43**
Concept 3	1	1	5	4	2	1	1	3	2	1	2	4	27
Concept 4	2	2	3	3	4	4	3	3	3	2	3	3	35
Concept 5	2	2	4	3	2	3	2	2	3	2	2	3	30
Concept 6	2	2	3	3	2	2	2	2	3	2	2	3	28
Concept 7	3	2	2	2	2	2	2	3	2	2	2	2	26
Concept 8	5	4	1	3	3	2	4	5	5	4	4	1	41

3.4.3. Ranking elaboration

ECONOMIC CRITERIA

As the economic criteria are connected to the system complexity, a completely new design like Concept 3 will score badly, but Concept 8, a condenser, will have a much better score.

TECHNOLOGY CRITERIA

A new design does have better efficiency and here Concept 3 and 8 are now reversed in scoring. Concept 2 is a modified version of Concept 1 with the goal of changing the batch process to a continuous one. Logically, Concept 2 scores better than Concept 1 on this point. The turbine concepts (5, 6 and 7) get a lower score, because they are less scalable and modular. They have to be designed for a very specific range. Lastly, if a concept is less proven, this will also affect its design and construction time. Concept 3 therefore gets a low ranking for both points.

SUSTAINABILITY CRITERIA

As the steam contains the particulate matter, open systems that can let the steam escape are more pollutant. Hence, Concept 5 and 6 get a lower score. A simpler design goes together with a longer life time. Here, Concept 8 ranks high. As Concept 3 is a complete redesign starting from the cokes, materials are needed that can handle high temperature. This result in a lower score.

OTHER CRITERIA

Except the high temperatures of the steam, the concepts are fairly safe. This explains the overall higher scores for the safety criterion. The aim of most concepts is sustainable waste heat utilization. This is encouraged by the government and thus awarded with points.

3.4.4. Concept choice

From Table 3.1, concept 2 scored the highest. This concept entails using the Synext engine in a continuous process. The remainder of this research will mainly focus on this design and its elaboration.

Concept 1 came second. The batch process will make the entire system bigger and thus more expensive. The generated electricity will also be fluctuating.

Concept 8 scores fairly high, but because this concept only meets the second requirement of Section 3.1, it will not be further discussed as it does not generate any power directly from the steam. It does output water of approximately 80°C, which could be used.

4. THEORY AND MODELLING

This chapter will expand further on utilizing the steam from the quenching towers for the Synext engine using Concept 2 from Chapter 3. The system is broken down into three sections, which will be delved into separately.

4.1. INTRODUCTION

4.1.1. OVERVIEW

The goal is to use steam from the quenching towers in the Synext engine, solving the problems stated in Chapter 3. After the steam is released by quenching the coke, it needs to be captured first. Then, the steam needs to be separated from its pollution, before the steam is temporarily stored. From this storage, the Synext engine is continuously fed. The flow of steam is divided into three sections as shown in Figure 4.1.

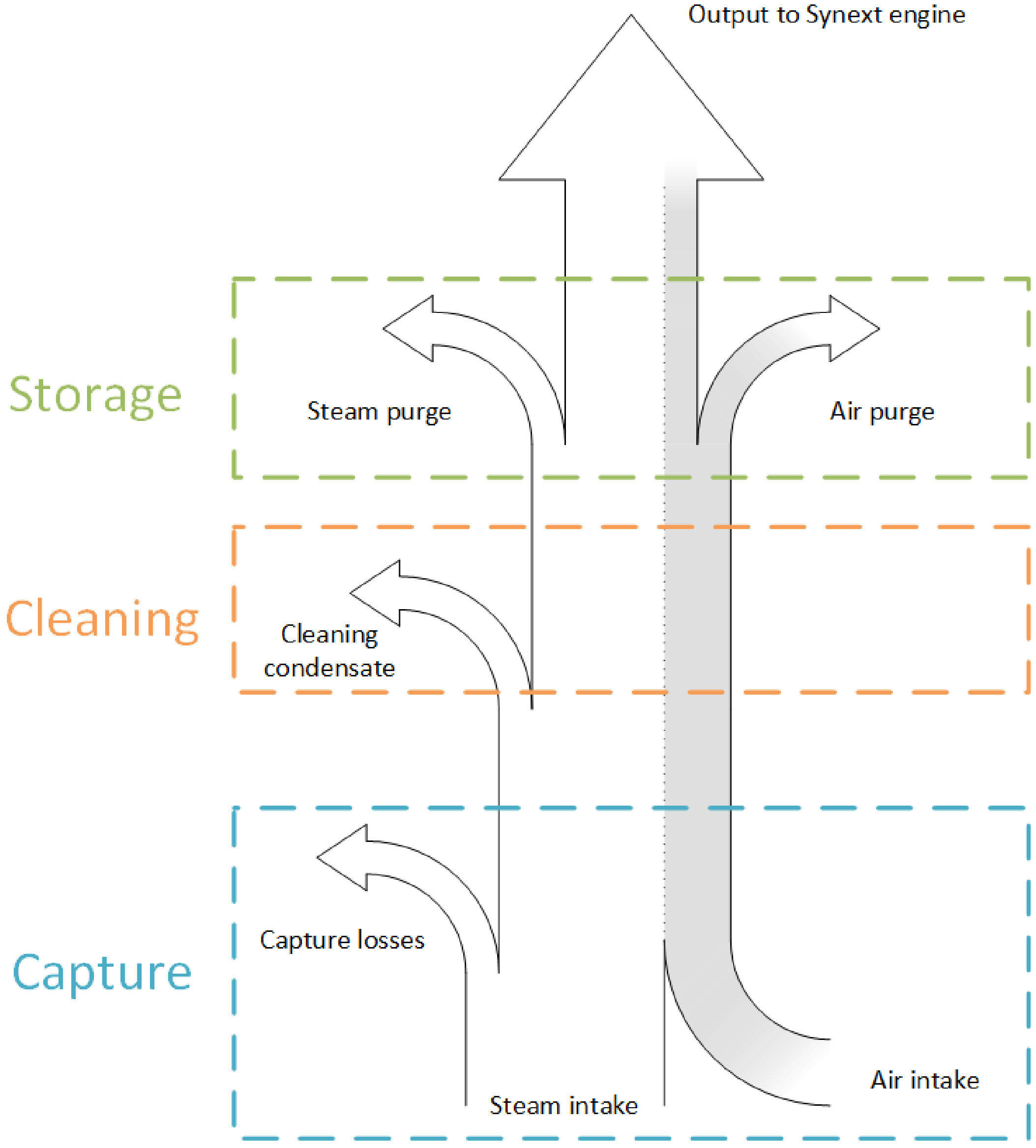


FIGURE 4.1 - SYSTEM OVERVIEW

Next to steam, there is also air present in the system as can be seen from the figure above. In this chapter, the manner of capturing, cleaning and storing the steam will be elaborated on. These sections will be individually quantified and then put together to obtain the output of the system for different circumstances.

CAPTURE

Capture exists of gathering the quenching steam and ensuring that it enters the system so that it is not released into the environment. To accomplish this objective, the steam properties need to be known. Next, the effect of air is investigated. At last, the changes needed in the tower will be closer examined.

CLEANING

Cleaning comprises of separating the particulate matter from the steam. First, the extent of the pollution needs to be explored. Before looking into cleaning methods, an acceptable cleaning efficiency is chosen. Different cleaning or separating mechanisms will be analysed in order to select one. The chosen method will affect various properties of the steam. A part of the steam may condense. This could for example influence the flow and pressure. This should be taken into account.

STORAGE

Storing the steam is necessary to ensure a continuous working of the Synext engine, because the steam is generated at intervals. It is important to first calculate how much steam needs to be stored before selecting the storage method.

OVERALL

When each individual section is evaluated, a model can be made of the entire system to evaluate the steam output in different scenarios. But first, preliminary calculations must be done to attain an estimation of the steam output. This preliminary analysis will be done in the next section, Section 4.1.2.

4.1.2. Preliminary analysis

For a better scale of the problem, a preliminary calculation must be made. No data is collected from the steam. Because of the abundance of water, the steam is not deemed important for the process, if the quality of the cokes is sufficient.

QUENCHING TOWERS

As stated in Chapter 2, Tata Steel has two coke plants; Coke plant 1 and 2. Coke plant 2 is newer and has one quenching tower called 21. Coke plant 1 has three towers, called 11 (Middle), 13 (East) and 14 (West).

BASIC HEAT CALCULATIONS

Because little is known about the steam itself it is necessary to focus on the cokes. The only measured value to determine the flow is the charge weight of the coal. This is coal with 10 % moisture content a [% mass]. Firstly, the amount of cokes per batch using the dry coke/coal yield b is calculated in equation Eq. 4.1. 71% is used for b [% mass]. (Van der Molen, 2016)

$$m_{cokes} = m_{coal} \cdot (1 - a) \cdot b \tag{4.1}$$

The cokes are quenched from 1000°C to 250°C. Hereafter, the cokes are cooled by ambient air. The heat content released from the cokes can be calculated, using Eq. 4.2:

$$Q_{cokes} = m_{cokes} \cdot c_{p_{cokes}} \cdot \Delta T_{cokes} \tag{4.2}$$

This heat is absorbed by the water turning into steam. The water is recycled and is therefore around 80°C. The heat needed to turn the water into steam can be calculated, using equation 4.3:

$$Q_{steam} = m_{steam}(c_{p_{water}} \cdot \Delta T_{water} + \Delta h_{lg,water}) \quad (4.3)$$

The mass of steam per quench, m_{steam}, can now be calculated. By using the average amount of quenches, the mass flow can be obtained. Using the mass flow rate and the conversion factor $40 \left[\frac{kW}{tonne/_{hr}}\right]$ (Bahamonde, 2016), the power of the Synext engines is calculated. Finally, an estimation of the revenues can be made assuming an industrial electricity price of 0.03 €. The values used are listed in the Appendix C.

TABLE 4.1 - PRELIMINARY ESTIMATION OF WASTE HEAT SOLUTION.

	Steam mass per quench [kg]	Mass flow [kg/s]	Power [kW]	Revenue [€/yr]
CGP 1, West tower	2657	2.83	407	107 060
CGP 1, Middle tower	2659	2.55	368	96 680
CGP 1, East tower	2800	3.86	555	145 940
CGP 2	5338	6.73	970	254 860
Total	13454	16.0	2300	604 550

Table 4.1 shows the theoretical maximum amount of steam that can be produced. Losses are not taken into account. Also, an average mass flow is calculated, but the process is transient. A more detailed look at the actual steam production will be discussed in Section 4.2.

4.1.3. MODEL OVERVIEW

In this section the model describing the chosen concept will be elaborated. The proposed model is a dynamic open loop model, since the quenching of the coke and the resulting steam flow is a very transient process.

MODEL PURPOSE

The purpose of this model is to quantify the steam output to the Synext engine for the generation of electricity. Another goal is to understand the dynamics of the system and by this means serve as a tool to decide the feasibility of the proposed concept with different parameters. Furthermore, the model could be used to design the equipment needed in detail. Lastly, the model can be of value for future research into coke quenching and related processes.

SYSTEM BOUNDARIES

The model is formed to study the steam outlet to the Synext engine. Water enters the system and is turned into steam by the hot coke and leaves the system at different points as either condensed water or unevaporated water. As shown in Figure 4.2, the system is divided into three sections. The process variables that couple these sections with the surroundings can be found in Table 4.2. The mass flow ($\dot{m}$), specific enthalpy (h) and pressure (p) describe the flow of water and steam, while the heat transfer is described by the temperature (T) and heat transfer rate ($\dot{Q}$). The arrows in Figure 4.2 represent the flow of information.

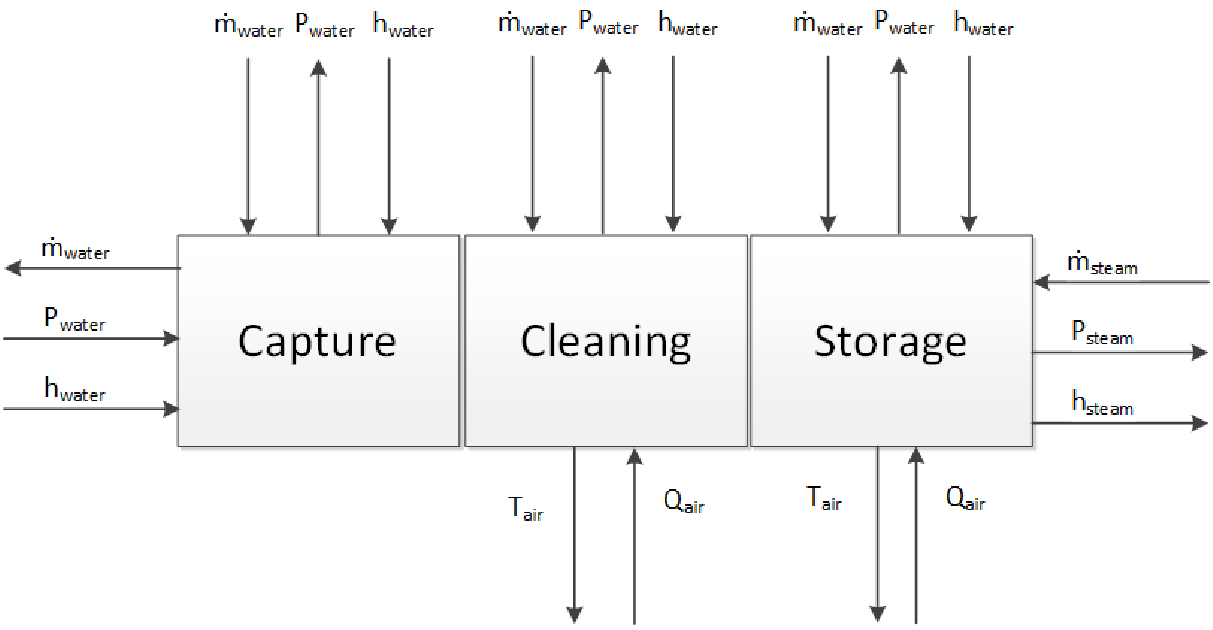


FIGURE 4.2 - SYSTEM PROCESS VARIABLES

TABLE 4.2 - SYSTEM VARIABLES

Capture
Entering water mass flow ($\dot{m}_{Cap,E}$)
Entering water enthalpy ($h_{Cap,E}$)
Entering water pressure ($p_{Cap,E}$)
Leaving water mass flow ($\dot{m}_{Cap,L}$)
Leaving water enthalpy ($h_{Cap,L}$)
Leaving water pressure ($p_{Cap,L}$)
Cleaning
Leaving water mass flow ($\dot{m}_{Cle,L}$)
Leaving water enthalpy ($h_{Cle,L}$)
Leaving water pressure ($p_{Cle,L}$)
Heat flux from cleaning section to ambient air ($\dot{Q}_{Cle}$)
Temperature of ambient air near the cleaning section (T_{air})
Storage
Leaving water mass flow ($\dot{m}_{Sto,L}$)
Leaving water enthalpy ($h_{Sto,L}$)
Leaving water pressure ($p_{Sto,L}$)
Heat flux from storage section to ambient air ($\dot{Q}_{Sto}$)
Temperature of ambient air near the storage section (T_{air})
Synext engine
Leaving steam mass flow ($\dot{m}_{Syn,L}$)
Leaving steam enthalpy ($h_{Syn,L}$)
Leaving steam pressure ($p_{Syn,L}$)

RELEVANT PHENOMENA AND GENERAL ASSUMPTIONS

The following phenomena are relevant in this research:

- Film boiling heat transfer occurs between the cokes and the water due to a wall superheat of $\Delta T > 120°C$ during the most of the quench, which is discussed further in Appendix D.
- Mass and energy accumulation happen in all three sections.
- Steady flow is assumed, so there is no accumulation of momentum. This is conventional in literature, as for momentum accumulation the time constant is smaller than for energy and mass accumulation. (Colonna & Van Putten, 2007)
- There is pressure drop over the Cleaning and Storage section.
- Energy accumulation is present in the walls of the Cleaning and Storage section.
- Heat loss to the environment occurs in the Cleaning and Storage section.

As it is not feasible to take every phenomenon into account, it is chosen to exclude the following:

AIR

In reality the system is open and it is possible for air to enter the system and accumulate. However, due to the large steam production, it is assumed that for now only steam is present. The system always starts filled with steam without any air entering the system. The effect of air will be further discussed in section 4.2.2.

COMPRESSIBILITY OF THE STEAM GAS

The steam is treated as an incompressible gas for the operated pressure range. The compressibility can be taken into account by making the gas not ideal and thus specifying a compressibility factor, Z.

CHEMICAL REACTIONS

The chemical reactions that occur, are discussed in Appendix B. These reactions have almost no effect on the process and are thus neglected.

CHANGES IN POTENTIAL AND KINETIC ENERGY OF THE CONTROL VOLUMES

Changes in kinetic energy and potential energy will not be taken into account in the model. Potential energy can be taken into account later when the geometry is specified.

PARTICLES IN THE GAS STREAM

Coke particles are present in the steam. Particles will not be modelled in the overall model but will be discussed in Section 4.3. The cleaning choices will then be implemented in the model.

More points will be elaborated, when the model is discussed in detail further on in this chapter.

MODEL DECOMPOSITION

The model consists of a modular, hierarchical and causal paradigm. The modelled system consists of different components which can be broken down into modules which are predefined with equations followed from physical relations and conservation laws.

Bilateral coupling in combination with the causality principles are applied to obtain low index algebraic and differential equations, following the method of Colonna and Van Putten.

LUMPED PARAMETER APPROACH AND LOW INDEX DIFFERENTIAL AND ALGEBRAIC EQUATION OF SYSTEMS (DAES)

The lumped parameters approach leads to DAES in the form of Eq. 4.4:

$$F\left(t, y\frac{dy}{dt}\right) = 0 \tag{4.4}$$

However, it is more straightforward and mathematically easy to solve a system of ordinary differential equations in the form of Eq. 4.5:

$$\frac{dy}{dt} = \mathrm{G}(\mathrm{t}, \mathrm{y}) \tag{4.5}$$

Transforming differential and algebraic systems of equations to ordinary differential equations is achieved by differentiation of differential and algebraic systems of equations. Index is defined as the minimum number of time iterations that the differential and algebraic systems of equations must undergo to convert the system to a set of ordinary differential equations.

Low index models have an index of one and zero, high index models have an index larger than one. In order to overcome the well-known ''index problem'', a low index model is preferred.

MODULAR APPROACH AND CONSERVATION EQUATIONS

The different modules are described by differential equations based on the fundamental conservation laws, see Eq. 4.6, Eq. 4.7 and Eq. 4.8:

Mass conservation

$$\frac{dm}{dt} = \dot{m}_E - \dot{m}_L \tag{4.6}$$

Energy conservation

$$\frac{du}{dt} \;=\; \dot{m}_E h_E - \dot{m}_L h_L \;+\; \dot{Q} - P_s - p\frac{dV}{dt} \tag{4.7}$$

Momentum conservation

$$\frac{dG}{dt} = \dot{m}_E v_E - \dot{m}_L v_L + \;(p_E A_E - p_L A_L \;+\; F) \;+\; Ag\rho\,(z_E - z_L\,) \tag{4.8}$$

The constitutive equations must be derived to solve the unknown variables. The derivations apply within certain system boundaries of so-called modules and are therefore discussed when the modules are expanded in sections 4.2.4, 4.3.5, 4.4.3 and 4.5.2. These correspond respectively with the capture, cleaning, storage and overview modules.

CATEGORIZATION OF MODULES

A storage module (S) can accumulate mass, momentum and/or energy. On the opposite, accumulation can be neglected in a resistive module (R).

The storage module, delivering a certain potential as output, is generally defined as:

$$S\frac{dp(t)}{dt} \;=\; f(t) \tag{4.9}$$

The resistive module, delivering a certain flow as output, is defined by Eq. 4.10:

$$f(t) = \; R\,p(t) \tag{4.10}$$

CAUSAL MODELS AND BILATERAL COUPLING

A causal model describes causal relations. The model consists of a system of computational related block diagrams. Each block describes a variable of the system. In short, the model can be summarized as input, reaction and output. The inputs of the causal model are decisive for the output and therefore must have the highest priority. The resulting equations of the system are approached conform the explicit state-space form.

The state variable of the system describes the mathematical state of a dynamical system. The state variable can give insight in the current or future state of the model. The density ρ and the internal energy u are usually selected as state space variables in the modules. The pressure p and enthalpy h are picked as connecting variables for the modules and both can also be chosen as state variables. p and $\dot{m}$ are bilaterally coupled parameters, the adoption of the connecting parameters is usually constrained to $p, \dot{m}$ and h. Mass flow, velocity, force, pressure, temperature and heat flux are examples of bilaterally coupled variables.

In a system where causal modelling is approached and bilateral coupling is respected, the model will deliver the lowest possible index.

HIERARCHAL METHOD

The system is hierarchically divided into three sections and each section is subdivided into modules, which will be built in a Simulink model. The following modules are used:

- Solid thermal storage modules are used to model thermal inertia of solid process equipment.
- Fluid thermal resistive modules are used to model heat transfer between fluid flows and solid segments.
- Fluid flow storage modules are used to model mass and energy accumulation in a fluid.
- Fluid flow resistive modules are used to model pressure and temperature change in a fluid.

In the following sections of this chapter, these modules will be used to describe the system.

4.2. CAPTURE

Capture will entail the steam production by quenching. The effect of adding air to the system will be discussed. The capture equipment needed will be chosen and described. Lastly, the capture section will be modelled.

4.2.1. STEAM PRODUCTION

COKE QUENCHING

A simultaneous study is performed on the coke quenching towers of TATA Steel IJmuiden, where an emission control solution is proposed (Feng, 2019). In that study, the capture section is regarded as a closed boiling container. A constant heat transfer is chosen between the hot coke and water. During the 60 seconds long quenching, a constant mass flow of inlet water enters the system and a constant mass flow of water leaves the system. This water keeps flowing after the quench.

Another method of modelling is proposed in the appendix. Here, spherical cooling of the coke particles is proposed.

4.2.2. EFFECT OF AIR

In this section the effect of air on the system will be elaborated.

MIXING OF AIR AND STEAM

Air enters the system with an ambient temperature. This would cool down and even condense part of the steam. Maximizing the steam output is the main goal, so this is not desired. When steam condenses on the other hand, energy is released in the form of heat.

The mixture of steam and air loses heat when passing through the system, condensing more steam. This causes the ratio of air to increase, which lowers the efficiency of the Synext engine.

As steam condenses in the storage vessel, air will accumulate here. This vessel should be flushed with the steam mixture to counter this effect, before the flow enters the engine. This will be further discussed in Section 4.4.

Separating near atmospheric steam and air is technically not feasible, because most separators require pressure to function. Adding a compressor to the system would negate the energy recovered from the steam.

CASE: QUENCHING TOWERS OF COKE PLANT I

To understand the effect air will have on the system, an estimate on the quantity of air that enters the system at this moment is required. The current situation will be evaluated to gain better insights of the effects of air on the proposed novel system. This evaluation will be done by creating a simplified draft model of the quenching towers.

ASSUMPTIONS

The following assumptions are made for this model:

- The air has a temperature of 20°C.
- The air is assumed to be dry.
- Steady state is assumed, so there is only one velocity.
- Air and steam are well mixed
- A constant steam velocity is taken.
- The steam is saturated.

AIR MODEL GOAL

This simplified draft model of the quenching towers calculates the following properties:

- Mass flow of air that enters the quenching tower
- Exit temperature of the gas mixture
- Exit velocity of the gas mixture

AIR MODEL EQUATIONS

Steam enters the quenching chamber with a constant mass flow. The gas has a lower density than the ambient air and its buoyancy results in a force. The baffles and other imperfections in the tower create draft losses. When there is an equilibrium between these two forces, a constant velocity can be calculated. Starting with the Bernoulli equation:

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g z_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g z_2 \tag{4.11}$$

it is derived that the pressure difference due to buoyancy is:

$$\Delta p_{draft} = gz(\rho_{air} - \rho_{mixture}) \tag{4.12}$$

and the pressure loss due to the geometry of the tower and its baffles are categorized by:

$$\Delta p_{losses} = \sum K \frac{1}{2}\rho v^2 \tag{4.13}$$

When air enters the quenching chamber it mixes with steam. This changes the mixture density affecting the draft equilibrium. The air velocity entering the system can hereby be calculated iteratively. Another result of the mixing of steam and air are the temperature changes. An enthalpy balance from the air heating up, steam cooling down, and the heat of condensation is formulated. The condensation phenomenon causes energy to be added to the system, effectively heating up the system. By using the thermodynamic formulas for enthalpy, the end temperature of the gas mixture can be derived in the model.

$$\frac{dQ}{dt} = \dot{Q}_{cond} + \dot{Q}_{steam} - \dot{Q}_{air} = 0 \tag{4.14}$$

Eq. 4.14 uses the heat transfer rate of condensation, steam cooling down, and of air heating up, as depicted by their respective formulas below:

$\dot{Q}_{cond} = \Delta h_{vap} \dot{m}_{cond}$	Heat transfer rate of condensation
$\dot{Q}_{steam} = \dot{m}_{steam}\, {C_p}_{steam} (T_{vap} - T_{mixture})$	Heat transfer rate of steam cooling down
$\dot{Q}_{air} = \dot{m}_{air} {C_p}_{air} (T_{mixture} - T_{air})$	Heat transfer rate of air heating up

An iterative loop to ensure the balance, depicted in Eq. 4.14, equals zero is created in the model to derive the steady state gas mixture temperature.

AIR MODEL RESULTS

Two important plots are derived from the simplified draft model of the quenching towers. This model is implemented for the current situation. It is applied to the four towers, mentioned in Section 2.2.3. The gas temperature in [°C] is plotted against the steam mass flow in [kg/s], seen in Figure 4.3. In this figure it can be seen that the air has almost no effect on the mixture temperature. This is mainly because the cooling effect resulting from the entrained air is counteracted by the heating effect of the condensing steam.

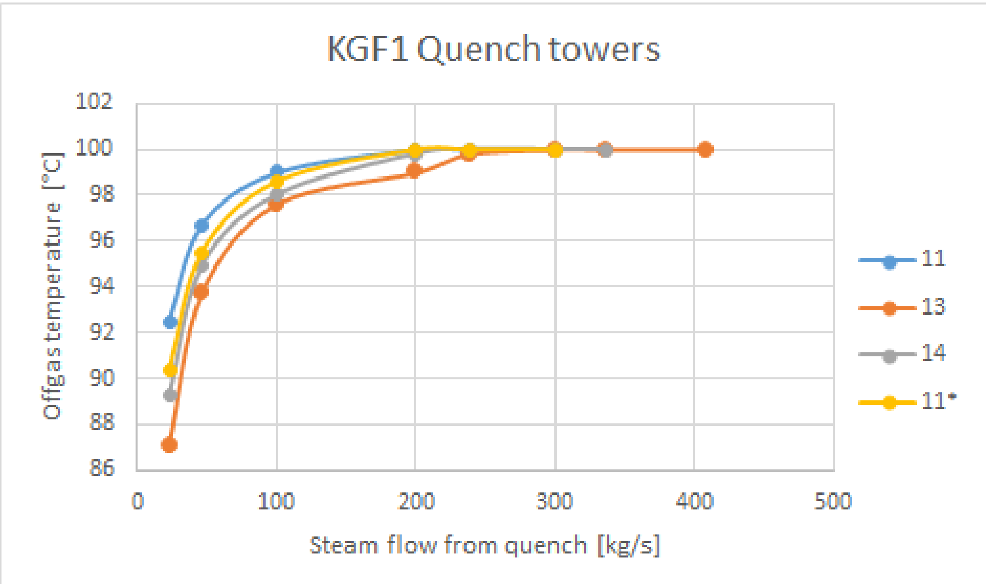


FIGURE 4.3 - TEMPERATURE OF THE MIXTURE EXITING THE TOWER OVER THE STEAM MASS FLOW.

The entrained air flow in [kg/s] is plotted against the steam mass flow in [kg/s], see Figure 4.4. In this figure it is visible that the entrained air flow reaches zero, when the steam flow is too high. This means that the tower is unable to handle the steam flow and instead of air entering the tower from the sides and mixing with the steam, the steam leaves the tower. This happens for a steam flow of 240 kg/s for Tower 11 and is taken as a maximum for the proposed system. This is undesirable for the current situation since the steam then does not pass along the baffles and does not get cleaned.

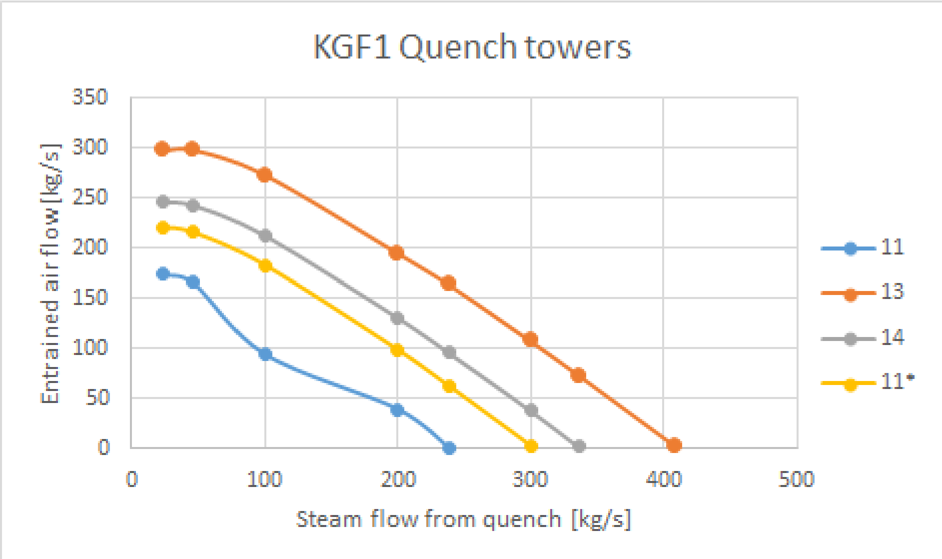


FIGURE 4.4 - AIR MASS FLOW ENTERING THE QUENCHING CHAMBER OVER THE STEAM MASS FLOW.

In summary, air has a negative effect on the efficiency of the new total system. If air enters the system, it induces condensation. The model shows that the temperature is barely affected and a maximum steam flow is now set. To keep the model feasible, air is not included in the model, but will be discussed further on.

4.2.3. CAPTURE EQUIPMENT

WATER CURTAIN

To maximize the output to the Synext engine, it must be prevented that steam can be released to the environment. The quenching chamber cannot be permanently closed, because the quenching car and locomotive need to drive through the tower. Due to the harsh conditions, mechanical doors that fully close the chamber, require substantive maintenance. This would greatly decrease the operating hours of the quenching towers and is therefore undesirable. If mechanical solutions are discarded, a fluid solution has to be taken into consideration. Steam can also be trapped by a flow of air or water. As water is already abundant in the quenching tower, this solution has been chosen to capture the quenching steam. The required water needs to be estimated.

ASSUMPTIONS

The following is assumed:

- The water falls down uniformly and straight down.
- There is no wind.
- There is no air resistance.
- The water has an atmospheric pressure.
- The width w of the wall is 1 cm.

CALCULATIONS

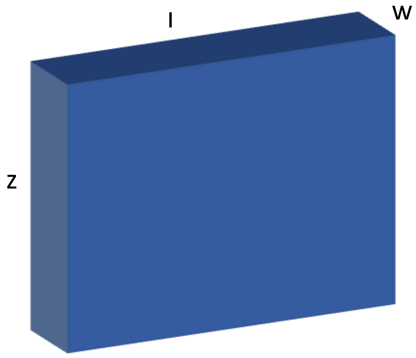


FIGURE 4.5 - WATER CURTAIN

The water curtain is depicted in Figure 4.5. The flow rate needed can be calculated using $\dot{V} = A \times v$ where A is the surface area of the beam and v the average velocity. A is calculated by $A = l \times w$ and v by $v = \frac{z}{t}$. Here t is the time required to reach the ground and calculated by $t = \sqrt{\frac{2z}{g}}$. Consequently, the required flow rate $\dot{V}$ is calculated by Eq. 4.15:

$$\dot{V} = l \times w \times \frac{z}{t} = \frac{l \times w \times z}{\sqrt{\frac{2h}{g}}} = l \times w \times \sqrt{\frac{z \times g}{2}} \tag{4.15}$$

RESULTS

One side of quenching tower 11 is taken as an example. The height and length of the beam are respectively 5.9 and 4.2 m. The flow rate Q thus becomes 0.23 m^3/s. The water curtain should start 5 seconds before the quenching, so the curtain will then be active for 65 s. This ensures that the steam will not escape. The required water per quench then amounts to 15 m^3 for one side.

CAPTURE VALVES

The steam generated by the hot cokes is now stopped from exiting through the sides of the quenching chamber. The next step is to guide this steam to the cleaning section over a distance as short as possible to minimize condensation. It is chosen to use the concept visualized in Figure 4.6. This mechanical valve directs the steam from the quenching chamber to the pipe heading towards the cleaning section. If this valve closes, no steam can flow back into the quenching chamber. Another function of this design is to provide an emergency exit. If the quenching starts while the valve is in its closed state, the steam can go through the original tower and still be partly cleaned before entering the environment. This is useful when the system cannot take any steam due to maintenance or a malfunction.

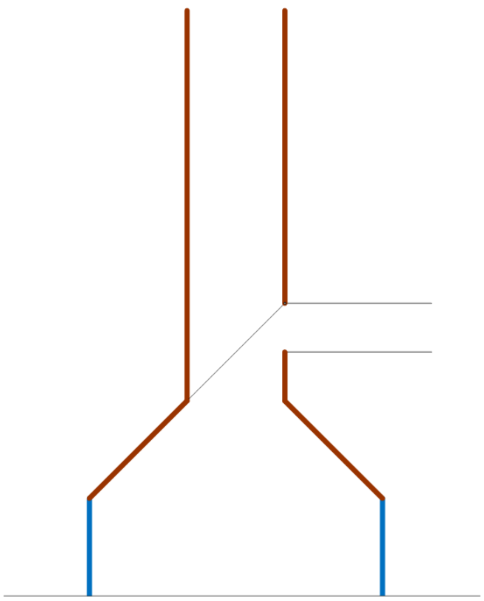


FIGURE 4.6 - CAPTURE VALVE

4.2.4. CAPTURE MODEL

The goal of the capture section of the model is to quantify the steam output flowing towards the cleaning section. Three modules are used to model the capture section. The first module describes the thermal mass of the hot coke. The second module represent the heat transfer between the coke and the quenching water. The third module describes the mass and energy accumulation of the water and steam in the quenching car.

ASSUMPTIONS

Except the assumptions stated in 4.2.3, the following assumptions are made for this section:

- Phase change can occur inside the quenching car.
- No heat can escape the quenching chamber.

COKE THERMAL STORAGE MODULE

The accumulation of heat by the cokes is defined by the following storage module represented in Figure 4.10:

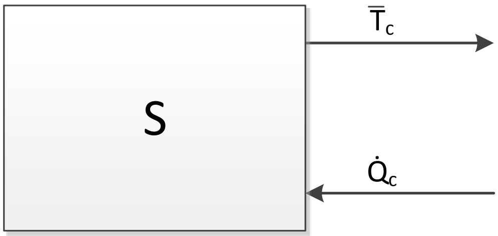


FIGURE 4.8 - SCHEMATIC REPRESENTATION OF COKE THERMAL STORAGE MODULE

The chosen state variable is the average temperature of the cokes $\bar{T}_c$. The inputs, outputs and parameters are presented in Table 4.3.

TABLE 4.3 - INPUT, OUTPUT AND PARAMETER SYMBOLS

Inputs	$\dot{Q}_c$
Outputs	$\bar{T}_c$
Parameters	$m_c,\ c_{p,c},\ T_{0,c}$

The decline of the temperature of the cokes is expressed with the constitutive equation represented by Eq. 4.16:

$$\frac{d\bar{T}_c}{dt} = \frac{\dot{Q}_c}{m_c c_{p_c}} \tag{4.16}$$

The system is closed, as there is only one unknown and one equation.

COKE THERMAL RESISTIVE MODULE

The heat transfer that occurs between the coke and the quenching water is defined by the following resistive module:

FIGURE 4.7 - SCHEMATIC REPRESENTATION OF THE COKE THERMAL RESISTIVE MODULE.

The inputs, outputs and parameters are presented in Table 4.4.

TABLE 4.4: INPUT, OUTPUT AND PARAMETER SYMBOLS OF THE COKE THERMAL RESISTIVE MODULE

Inputs	$\bar{T}_c, \bar{T}_w$
Outputs	$\dot{Q}_c, \dot{Q}_w$
Parameters	U_c, A_c

There is no energy accumulation and the cokes cool down and the water heats up and evaporates, so:

$$\dot{Q}_c = \dot{Q}_w \tag{4.17}$$

The heat transfer from the coke is defined by Eq. 4.18:

$$\dot{Q}_c = U_c A_c (\bar{T}_c - \bar{T}_w) \tag{4.18}$$

With 2 unknowns and 2 equations, the system is closed.

WATER THERMAL AND FLOW STORAGE MODULE

The thermal storage and the flow storage of the water in the quenching car are combined in the following module, shown in Figure 4.8.

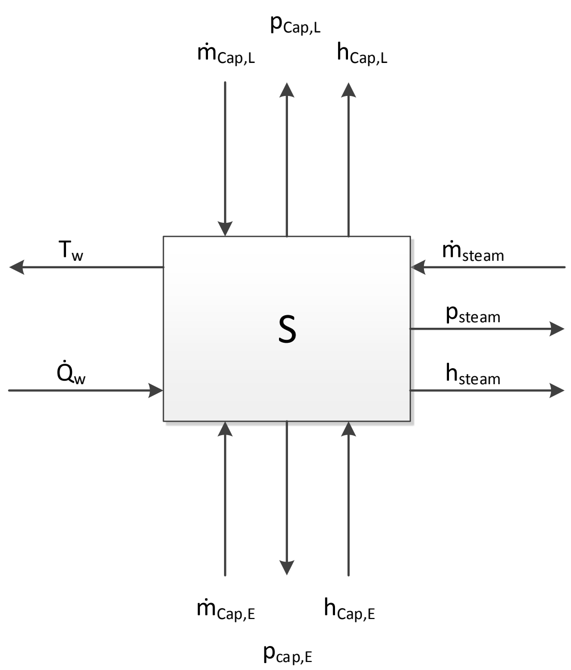


FIGURE 4.8 - SCHEMATIC REPRESENTATION OF THE WATER THERMAL AND FLOW STORAGE MODULE.

Inputs	$\dot{m}_{Cap,E}$, $h_{Cap,E}$, $\dot{m}_{Cap,L}$, $\dot{m}_{steam}$, $\dot{Q}_w$
Outputs	$p_{Cap,E}$, $p_{Cap,L}$, $h_{Cap,E}$, $\bar{T}_w$
Parameters	V_{Cap}
Internal variables	$V^v, V^l, \rho^v, \rho^l, h^v, h^l, s^v, s^l, \frac{dh^v}{dp}, \frac{dh^l}{dp}, \frac{d\rho^v}{dp}, \frac{d\rho^l}{dp}$

Changing the mass conservation equation in terms of ρ and then converting it to form coupled equations with state variable p and h, result in the following equation:

$$\frac{dV^v}{dt} = \frac{(\dot{m}_{Cap,E} + \dot{m}_{steam} - \dot{m}_{Cap,L}) - (V^l \frac{d\rho^l}{dp} + V^v \frac{d\rho^v}{dp}) \frac{dp}{dt}}{(\rho^v - \rho^l)} \tag{4.19}$$

The pressure derivative is calculated numerically using:

$$\frac{d\rho^v}{dP} = \frac{\rho^v(p_{\text{sat}} + \Delta\text{p}) - \rho^v(p_{\text{sat}})}{\Delta\text{p}} \tag{4.20}$$

The same equation is used for ρ^l and these vapor and liquid densities are functions of saturated pressure.

The energy conservation equation is simplified, and the following equation follows from it:

$$\frac{dp}{dt} = \frac{(\dot{m}_{Cap,E}\, h_{Cap,E} + \dot{m}_{steam} h_{steam} - \dot{m}_{Cap,L} h_{Cap,L}) + \dot{Q}_w - \left[\frac{(\dot{m}_{Cap,E} + \dot{m}_{steam} - \dot{m}_{Cap,L})(\rho^v h^v - \rho^l h^l)}{(\rho^v - \rho^l)}\right]}{\left[V^l\left(\rho^l \frac{dh^l}{dp} + \frac{\rho^v(h^l - h^v)}{(\rho^v - \rho^l)}\frac{d\rho^l}{dp} - 1\right) + V^v\left(\rho^v \frac{dh^v}{dp} + \frac{\rho^l(h^l - h^v)}{(\rho^v - \rho^l)}\frac{d\rho^v}{dp} - 1\right)\right]} \tag{4.21}$$

The pressure derivative of enthalpy at saturation are calculated similarly to Eq. 4.20.

Lastly, the momentum conservation dictates:

$$p_{Cap,E} = p_{Cap,L} \tag{4.22}$$

4.3. CLEANING

This section deals with the specifics of cleaning the steam plume. As stated before, the steam generated during a quench contains many solid particles that are not wanted in the engine. This requires the removal of these particles from the steam. However, no literature on the cleaning process of atmospheric steam is found. Additionally, the “cleanliness” of the steam is not an easily defined parameter. One needs to define how much of the particles is to be removed from the steam to deem it clean. This leads to the questions; ‘how many particles does the steam contain?’. The specific parameters that affect the cleanliness of the steam are discussed in this section. In the following section 4.3.1, the preferred collection efficiency is defined. In section 4.3.2 the cleaning efficiency is defined, and the cleaning methods are described. In Section 4.3.3 Section 4.3.4 elaborates on the chosen method.

4.3.1. PARTICLE DISTRIBUTION

To establish how much of the particles should be removed from the steam, one needs to know how many particles there are to begin with. Figure 4.9 shows two particle distributions from two distinct sources. Source 1 is derived from measurement by a Tata Steel employee at the coke oven. Source 2 is provided by measurements performed by the manufacturer of the quenching tower.

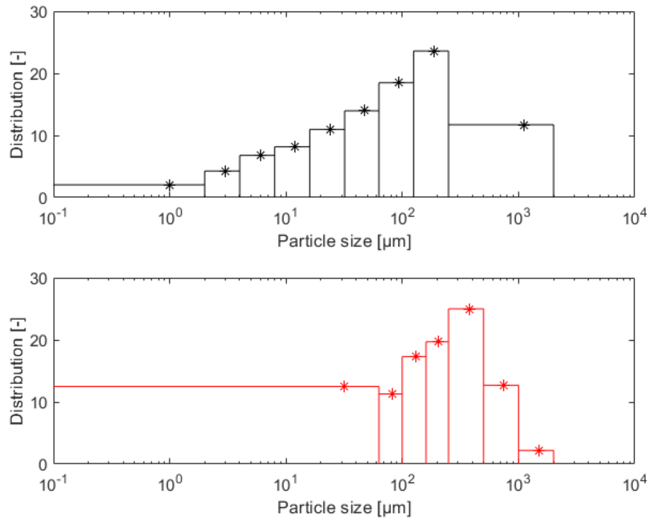


FIGURE 4.9 - PARTICLE SIZE DISTRIBUTION OVER PARTICLE SIZE. SOURCE 1 (TOP). SOURCE 2 (BOTTOM).

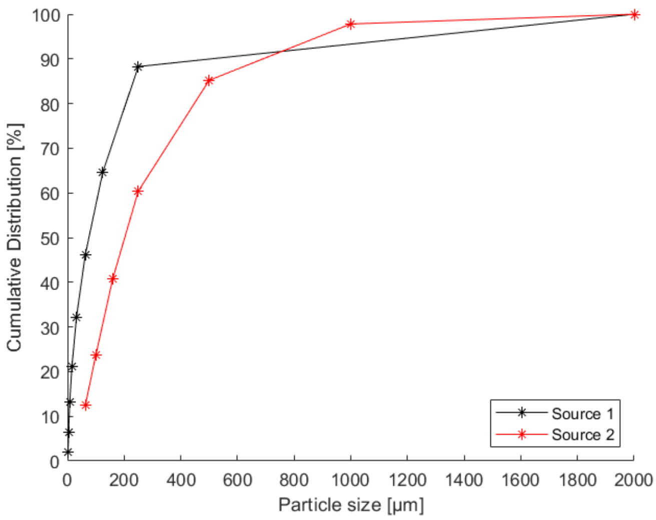


FIGURE 4.10: PARTICLE DISTRIBUTION VERSUS PARTICLE SIZE.

Both sources consist of coke particles, but source 2 is the only source where the particles are created due to quench spalling. The choice is made to limit the passage through of the particles to 5% using Source 2, so to remove 95% of the solids. Using Figure 4.10, this coincides with a particle size limit of 50 μm.

4.3.2. CLEANING EFFICIENCY AND METHODS

In Section 4.3.1 the particle diameter is defined to be the main parameter with which the distinction is made between allowable and unallowable particles in the steam plume. However, this distinction can be based on various parameters that describe the particle dimensions and physical properties. Most relevant of these parameters are:

- Number of particles
- Volume of particles
- Mass of particles

- Area of particles

Any of these parameters can be utilized to establish a cleaning efficiency, which is defined by the following equation:

$$\eta_{cle} = 1 - \frac{particles\ out}{particles\ in} \qquad (4.23)$$

Penetration is defined as the particle share that is not retained and thus emitted. The penetration Pen is expressed with the following formula:

$$Pen = 1 - \eta_{cle} \qquad (4.24)$$

The cleaning efficiency shows how well the cleaning system works. The general train of thought behind it is to select a parameter to define the allowable particles from the method of energy generation. Then this parameter is used to calculate a required cleaning efficiency with which the generation of energy can be performed stably and smoothly. After the required cleaning efficiency is known, a cleaning system that achieves this efficiency is designed.

Removing particles from a gas stream by any type of device is operating basically in the same principle. A certain gas flow with solid particles flows with a certain velocity through a volume where the flow is averted and therefore the solid particles are intercepted by collision on the walls of the cleaning system. Or an external force/medium is exerted on the gas flow to remove the particles out of the system.

The selection of the suitable cleaning device is commonly based on:

- Particle size distribution (PSD)
- Particle concentration in the flow
- Gas flow rate
- Allowable emission particle concentration

The selection of the required system is generally based on design, build, operating and maintenance cost of the cleaning system. The size and cleaning efficiency of the system is directly proportional with the final cost of the system. Furthermore, the choice of a passive or active cleaning system is decisive for the final cost of the system.

The operating cost varies by the pressure of the gas flow through the system and additionally in an active system the required power or the quantity of liquid is influencing the cost of the cleaning system.

In general, there are 4 physical mechanisms that can remove particles from a gas stream:

- **Sedimentation:** The gas stream flows into a certain volume where the solid particles can settle under the gravitational force.
- **Inertial deposition:** The particles in the gas flow are separated by inertial forces introduced in a cyclone shaped structure, cyclones are widely used for this separation method.
- **Migration of charged particles:** The gas stream flows through an electrostatic field, the electrostatic force working on the particles forces the particles to move to the surface of the device, where they are collected.
- **Brownian diffusion:** The gas stream flows through a system of obstacles, the particles will adhere and will be collected against the surface of the obstacles.

SETTLING CHAMBERS

In settling chambers, solids are separated from gases using gravitational forces. The settling chamber is a large box through which the mixture of particles and steam flows and wherein the particles settle to the floor. The key factor in this separation principle is that the steam velocity is low enough to give the particles the time to settle to the floor. A velocity that is too high will keep the solids suspended in the steam and will carry them further into the process. The main benefits of this concept are simple constructions, low costs, small pressure drops and the absence of a need for a cleaning agent. The main drawback is the fact that it generally occupies a large space.

CYCLONE SEPARATORS

In cyclone separators, suspended solids are separated from the gas that carries them using centrifugal forces. The mixture flows into the circular shaped separator and follows its curved geometry. In this circular flow the greater the mass of a certain matter, the greater the outward radial force this matter is subjected to. So, the particles, that of course have the greater mass, move closer to the outward wall of the separator, after which they will slide down the separator wall to the outlet below. The remaining cleaned steam forms an inner circular flow path and will exit the separator through the top. The main advantage of the cyclone separator over the other methods is that it generally occupies less space. The main disadvantage, however, is the issue of solids building up and plugging the separator.

INERTIAL IMPACTION AND INTERCEPTION

The basis of this method is that solid particles of a certain size or greater that cannot follow the curved path that a gas flows in. The particles will tend to follow a straight path wherein an obstacle can intercept them and separate them from a gas. The main advantage of this method is that its construction is relatively simple and cheap. The disadvantage is the possibility of local accumulation of solids and plugging of the separator.

BAFFLES

Baffles separate solid particles from the steam by acting as an obstacle in their path. Baffles are basically plates perpendicular to the flow direction of the mixture of steam and solids with a spacing between them that is narrow enough to block the passage of particles of a certain size or greater. The dirty steam must rise through the baffles and will leave behind (most of) the solids. The quenching towers at Tata Steel IJmuiden already contain baffles that clean the steam well enough that the emission of steam satisfies environmental standards. These existing baffles unfortunately do not clean the steam well enough to suit the demands for any manner of generation of electricity. An added advantage to this solution is the effect of electrostatic precipitation, which has been observed in the current quenching tower baffles. Here the baffles acquire an electrostatic charge due to the friction between the baffles' plastic and the coke particles, which exerts an attractive force on the particles. Main disadvantage in this method is the build-up of solids on the baffles and the consequential blocking of the flow of steam; this is already the case in the current baffles and it is such that the baffles require cleaning after each quench.

WET COLLECTORS AND SPRAY CHAMBERS

Wet collectors and spray chambers basically spray gas with water to wash out the solids. In this study this cleaning method contains one major disadvantage: the heat of the steam is needed to generate energy, which would be very much counteracted if the steam is cooled down by the water from the wet collectors. One could mitigate this issue by employing warm water during spraying in the separator, but this would be a costly endeavour, both financially and within the framework of energy efficiency. One point of note is the fact that cleaning by washing out solids will take place to some extent with or without wet collector. As the steam plume travels it will undoubtedly lose some of its heat to the environment and condensation will take place. The condensed water will likely flush out some of the solids.

CONCLUSION

It is chosen to use inertial impaction as the main cleaning method for the larger particles. This is the method that most passively cleans the gas stream, as other options would require fans or compressors due to the high pressure drop. A cyclone would ensure the smaller particles are separated from the gas stream. The mixture will be stored in a storage vessel, which will be discussed in Section 4.4. This storage vessel will also act as a settling chamber, cleaning the gas mixture even further. Thus, the entire cleaning procedure will not exclusively happen in the cleaning section and the cleaning efficiency can be chosen lower than required for the Synext engine. In the next section, the exact size will be elaborated on.

4.3.3. Cleaning calculations

Now the cleaning method and equipment have been chosen, calculations can be made to define the dimensions of the equipment. The cleaning efficiency however comes at a price, as a high efficiency results in a higher velocity and therefore an increased pressure drop. This effect should be taken into account.

CURRENT CLEANING

First, the current situation will be evaluated. From (Remus et al., 2013), dust emissions during wet quenching measure approximately 300 g/t coke without cleaning measures. With a coke charge of 10.6 t per quench, one arrives at a dust load of 3180 g/quench. At the exit of the tower, a maximum of 25 g/t coke and thus 265 g/quench can be measured. This coincides with a cleaning efficiency of 92%. This is achieved by removing the larger particles. The smaller particles left behind form an issue for the Synext engine. Also, the baffles induce a pressure drop that is mitigated by the draft, which is not present in the new closed system.

PARTICLE COLLISION CLEANING

According to Flagan and Seinfeld, the motion of a particle in a fluid can be characterized by the following equation:

$$m_p \dot{v}_p = F_g + F_r + F_{th} + F_d + F_e + F_f \tag{4.25}$$

Here, F_g stands for the force of gravity corrected for buoyancy. The second term represents the viscous resistance of the fluid. F_{th} describes the thermophoretic force, which is driven by the temperature gradient. The diffusiophoretic force expresses concentration gradient and is the fourth term, F_d. The fifth term describes the electrostatic force. The last term is also known as the Basset term and describes the pressure gradient.

A stochastic three dimensional Eulerian-Lagrangian approach, as done by Sommerfield or Schade et al., is needed to model the path of the particles. This would result in a cleaning efficiency for the particles colliding with multiple bends in the flow path. This model would be outside the scope of this thesis. Therefore, similar results in literature will be looked at. Watanabe and Hamasaki studied adding one collision wall to the outlet of a CDQ facility, as seen in Figure 4.11. This resulted in cleaning all the larger particles and 25% of the total particles. Now, only smaller particles are left. This could be handled by a cyclone.

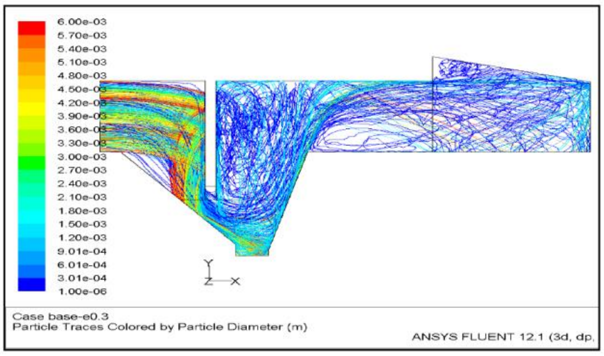


FIGURE 4.11 - IMPACT SEPARATOR (WATANABE & HAMASAKI, 2017)

CYCLONE CALCULATIONS

To implement a cyclone separator, some calculations need to be performed pertaining to its effectivity in the overall process. One important measure for its effectivity is the in equation 4.23 defined parameter of cleaning efficiency. The relevance of the importance of its cleaning efficiency stems from the requirement of the Synext engine to minimize the particle intake as much as possible. Another relevant aspect of the separator is the pressure drop it causes in the flow of the steam. If the separator has a pressure drop that is too big, the remaining pressure gradient in the system may be inadequate in order to allow the flow of steam.

To quantitatively analyse these two aspects of the issue, Leith and Licht theory is invoked. This piece of theory provides a set of both theoretical and empirical equations that give insight into the performance of a cyclone separator. Starting with the cleaning efficiency of a cyclone separator, which is expressed with the following equation:

$$\eta_i = 1 - e^{-2(C_{cycl}\psi)^{\frac{1}{2n+2}}} \tag{4.26}$$

Here, n_i stands for the efficiency for a particle diameter i, which was defined to be 50 µm in Section 4.3.1. Equation 4.26 is a fairly complex equation that depends on several intermediate calculations, which will be discussed in the rest of this sections. First relevant parameter C_{cycl}, which denotes the cyclone dimension factor, can be calculated with the equation:

$$C_{cycl} = 8\frac{K_{cycl}}{\left(\frac{H_{cycl}}{D_{cycl}}\right)\left(\frac{B_{cycl}}{D_{cycl}}\right)} \tag{4.27}$$

The cyclone geometry is specified following the design of Shepherd and Lapple, found in Figure 4.11. In this figure the definitions of the physical dimensions of the cyclone geometry, D_{cycl}, H_{cycl} and B_{cycl}, can be found. K_{cycl} denotes the cyclone volume constant and its equation is:

$$K_{cycl} = \frac{V_s + \frac{V_{nl}}{2}}{D_{cycl}^3} \tag{4.28}$$

D_{cycl} denotes the cyclone diameter and is depicted in Figure 4.10. The annular shaped volume above the exit duct to the entrance duct, V_s, is calculated using:

$$V_s = \pi\left(\left(\frac{D_{cyc}}{2}\right)^2 - \left(\frac{D_e}{2}\right)^2\right) \tag{4.29}$$

The diameter of the cyclone outlet, D_e, is also seen in Figure 4.10. The volume of a cyclone at natural length is defined with the following equation (Santana et al., 1975):

$$V_{nl} = \frac{\pi D_{cycl}^2}{4}\left(L_{cycl} - H_{cycl} - S_{cycl}\right) + \left(\frac{\pi D_{cycl}^2}{4}\right)\left(\frac{L_n + H_{cycl} + S_{cycl} - L_{cycl}}{3}\right)\left(L_n + \frac{D_n}{D_{cyc}} + \frac{D_n^2}{D_{cycl}^2}\right) - \frac{\pi D_e^2}{4} \quad (4.30)$$

S_{cycl} is dimensional parameter of the cyclone and is also seen in figure 4.10. The natural length of the vortex, L_n, is stated as:

$$L_n = 2.3D_e\left(\frac{\pi D_{cycl}^2}{H_{cyc}B_{cyc}}\right)^{\frac{1}{3}} \quad (4.31)$$

And the diameter of the central core, D_n, is defined as:

$$D_n = D_{cycl} - (D_{cycl} - S_{cycl})\left(\frac{L_n + H_{cyc} + S_{cyc} - L_{cyc}}{Z_{cycl}}\right) \quad (4.32)$$

Again, the dimensions Z_{cycl} and L_{cycle} are seen in Figure 4.10. ψ is the impaction parameter and is calculated using:

$$\psi = \frac{\rho_p D_p^2 v_{c,tan}(n+1)}{18\mu_{gas}D_{cyc}} \quad (4.33)$$

ρ_p and D_p denote the particle density and diameter, respectively. So, to remove all particles with a diameter equal to or greater than 50 µm, D_p should be assigned a value of 50.10^{-6} m. μ_{gas} denotes the viscosity of the steam passing through the cyclone. $v_{c,tan}$is the tangential velocity of a particle at the cyclone wall and is expressed with the following equation:

$$v_{c,tan} = \frac{\dot{m}_{gas}}{\rho_{gas}H_{cyc}B_{cyc}} \quad (4.34)$$

Lastly, n describes the vortex exponent and is expressed as follows:

$$n = \frac{(12D_{cycl})^{0.14}}{2.5} \quad (4.35)$$

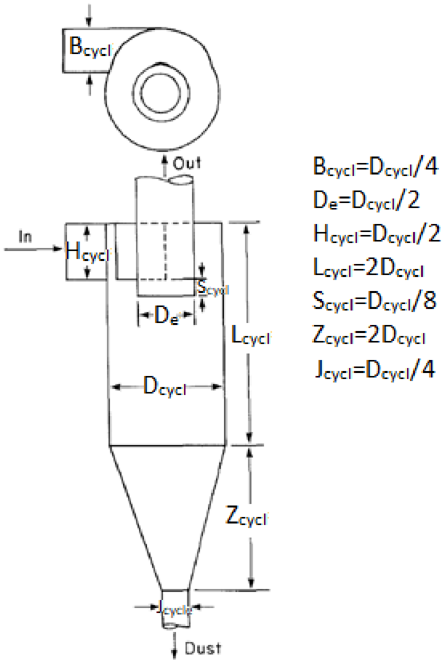


FIGURE 4.12 - CYCLONE DIMENSIONS (PERRY & CHILTON, 1973)

Most of the input parameters for Equations 4.26 to 4.35 are either known or can be estimated. Some parameters, much like the dimensions of the cyclone separator have to be defined retroactively. These dimensions will be used as tuning parameters and will be improved iteratively as the system draws closer to a final design. The specific ramifications of the separator dimensions will be discussed in Chapter 5.

With respects to the pressure drop caused by a cyclone separator, Leith (1973) gives the following empirical equation for its definition:

$$\Delta P = K_{cycl}\rho_{gas}v^2 \qquad (4.36)$$

Much like in the equations for cleaning efficiency, this equation contains parameters that depend on the separator dimensions. Again, these dimensions will be used as tuning parameters and their final values will be such that they provide an adequate compromise between allowable pressure drop and realizing the minimal required cleaning efficiency.

4.3.4. Cleaning equipment

CLEANING EQUIPMENT AND MATERIAL

The capture valve, introduced in 4.2, acts as a hood closing the open system. By changing the velocity vector of the steam, it also cleans the dirty steam before entering the cleaning section. This section consists of ducts, the impact seperator, the cyclone and piping. Lastly, the storage section also acts as a settling chamber for particles that managed to pass through and separates these particles from the steam entering the engine. A sketch of the cleaning section is provided in Figure 4.13.

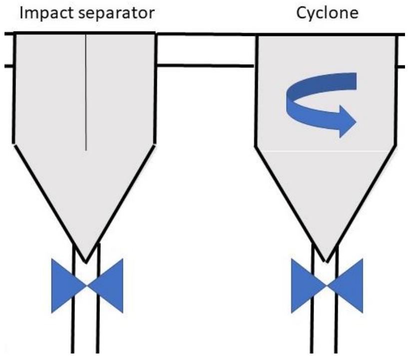


FIGURE 4.13: SCHEMATIC REPRESENTATION OF THE CLEANING SECTION

The duct and impact separator are made out of Bongossi wood. This equipment has to deal with the roughly the same condition as the original quenching tower. The only material being used and thus which has stood the test of time in quenching towers is this kind of wood. The ducts are rectangular as the cyclone demands a rectangular input and changing this midway would be troublesome. Also, due to the chosen material, a circular pipe would be challenging. When the steam arrives at the cyclone, it is cleaner, thus other materials can be chosen. A cyclone is traditionally made from concrete plated with steel. Insulation is added to reduce heat loss. The piping leading to the storage section are made from insulated steel.

The duct dimensions and pipe dimensions choice depend on the mass flow of the steam, so these are iteratively chosen in Chapter 5.

CLEANING INSULATION

Insulation is added to the cleaning section to reduce the heat loss. A common insulation consists of a layer of 50mm PUR (Bilfinger Tebodin, 2018). This has a thermal conductivity of 0.026 W/mK (Mills, 1999).Convective heat transfer from condensing steam to the wall is assumed to be 10000 W/m2 K (Mills, 1999). For heat transfer to the outside, resistivity of the insulation is dominant, thermal conductivity of the inner material has been ignored. So, the overall heat transfer coefficient from the wall to the environment is determined with:

$$\frac{1}{U} = \frac{1}{\alpha_c} + \frac{L}{k} \tag{4.37}$$

With α_c for free convection air of 13 (Mills, 1999), U from the wall to the outside is calculated to be 0.5 W/m^{2}K.

4.3.5. Cleaning model

The goal of the cleaning section of the model is the provide the steam output towards the storage section and calculate the deciding parameters in the module. This section is described by six modules. The first module expresses the pressure change between the capture and cleaning section. The second module describes the mass and energy accumulation of the steam in the cleaning section. The third module depicts the pressure change between the cleaning and storage section. The fourth expresses the heat transfer between the wall and the cleaning section. The fifth module describes the thermal mass of the wall. Lastly, the sixth module depicts the heat transfer between the wall and the environment.

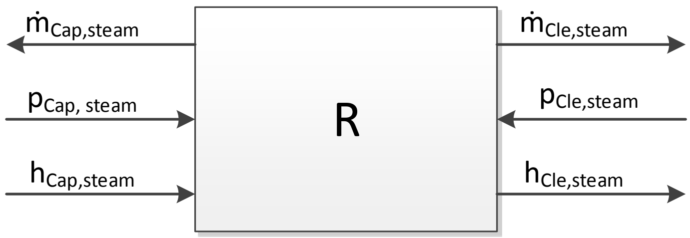
ASSUMPTIONS

The assumptions used for the cleaning section are as follows:

- Phase change can occur inside the cleaning section.
- Thermal energy and mass accumulation are present in impact separator and cyclone.
- Thermal energy is accumulated in vessel walls due to the significant mass.
- Convective heat transfer is present between the walls of the cleaning section and the fluid.
- Convective heat transfer is present between the wall and the ambient air.
- Cleaning calculations and their effects will be taken into account, but the model itself will have no particles in the gas stream.

CAPTURE SECTION FLOW RESISTIVE MODULE

The instantaneous pressure difference between the capture and cleaning section is defined by the following module:



Inputs	$p_{Cap,steam}, p_{Cle,steam}, h_{Cap,steam}$
Outputs	$\dot{m}_{Cap,steam}, \dot{m}_{Cle,steam}, h_{Cle,steam}$
Parameters	c_{cap}
Internal variables	ρ_{Cap}

As there is no mass accumulation, the mass conservation equation is depicted by:

$$\dot{m}_{Cap,steam} = \dot{m}_{Cle,steam} \quad (4.38)$$

No energy accumulation results in the following expression, using the energy conservation equation:

$$h_{Cap,steam} = h_{Cle,steam} \quad (4.39)$$

Before the momentum conservation equation can be implemented, friction must be looked into. The pressure drop according to the Darcy-Weisbach formula expresses the loss due to friction with the following equation:

$$\Delta p = f \frac{l}{D} \frac{\rho v^2}{2} \quad (4.40)$$

Here, f stands for the Darcy friction factor. The non dimensionless constant K is defined as:

$$K = f \frac{L}{D} \quad (4.41)$$

The friction force can now be obtained with the following equation:

$$F_{ff} = A\Delta p = A\left(f\frac{l}{D}\frac{\rho v^2}{2}\right) = AK\frac{\rho v^2}{2} = K\frac{\dot{m}}{2\rho A} \tag{4.42}$$

If the velocity is rewritten as a function of the mass flow and Eq. 4.41 is used. Combining this equation (4.42) and the momentum conservation equation (Eq 4.8), the following equation can be derived:

$$\dot{m} = \sqrt{\frac{2A^2}{K}\left(\rho_E(p_E - p_L) + \rho_E^2(z_E - z_L)\right)} \tag{4.43}$$

A new constant is introduced, flow conductance, c. It represents how effectively fluids are transported through a medium and its equation entails:

$$c = A\sqrt{\frac{2}{K}} \tag{4.44}$$

Heights are neglected and if Eq. 4.44 is plugged into Eq. 4.43, the following equation rises:

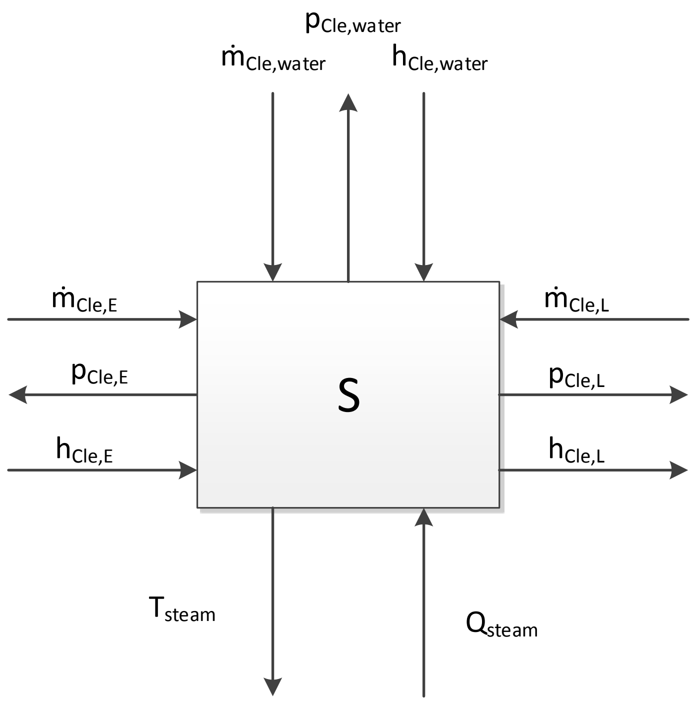
$$\dot{m}_{Cap,steam} = c_{cap}\sqrt{\rho_{Cap}(p_{Cap,steam} - p_{Cle,steam})} \tag{4.45}$$

Equation 4.45 is from now on referred to as the valve equation. Eq. 4.45 together with Eq. 4.38 and Eq. 4.39 now close the system, as all outputs are now known.

The flow conductance will be further discussed in Chapter 0.

CLEANING SECTION THERMAL AND FLOW STORAGE MODULE

The follow module expresses the accumulation of mass and energy in the cleaning section combined with the flow storage:

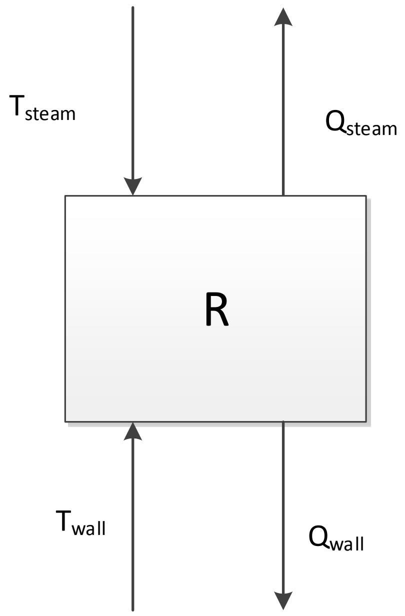


Inputs	$\dot{m}_{Cle,E}, h_{Cle,E}, \dot{m}_{Cle,L}, \dot{Q}_{steam}$
Outputs	$p_{Cle,E}, p_{Cle,L}, h_{Cle,E}, \bar{T}_{steam}$
Parameters	V_{Cle}
	$V^v, V^l, \rho^v, \rho^l, h^v, h^l, s^v, s^l, \frac{dh^v}{dP}, \frac{dh^l}{dP}, \frac{d\rho^v}{dP}, \frac{d\rho^l}{dP}$

As a similar module has been worked out, this module and other modules like it will not be elaborated.

CLEANING SECTION TO WALL THERMAL RESISTIVE MODULE

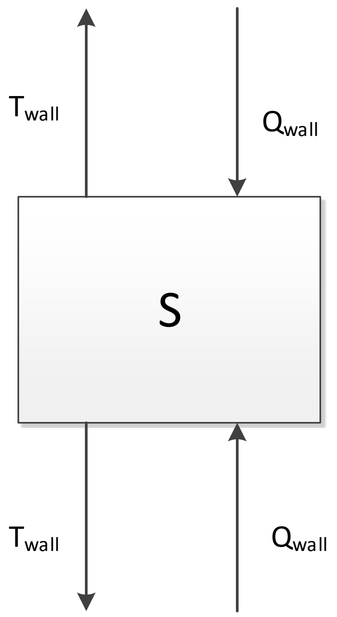
This module expressed the heat transfer between the cleaning section and the cleaning section wall:



Inputs	$\bar{T}_{steam}, \bar{T}_{wall}$
Outputs	$\dot{Q}_{steam}, \dot{Q}_{wall}$
Parameters	$U_{cle,1}, A_{Cle}$

CLEANING SECTION WALL THERMAL STORAGE MODULE

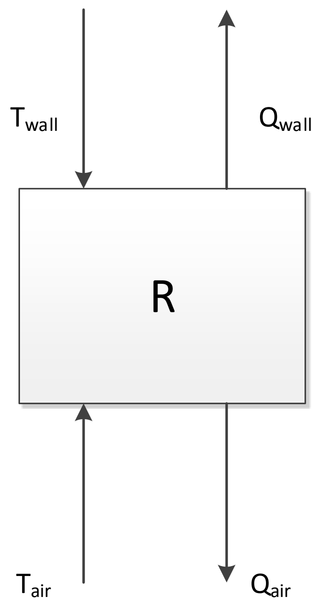
The thermal mass of the cleaning section wall is described by the following:



Inputs	$\dot{Q}_{wall}$
Outputs	$\bar{T}_{wall}$
Parameters	$m_{Cle,wall}$, $c_{p,Cle,wall}$, $T_{0,wall}$

CLEANING SECTION WALL TO ENVIRONMENT THERMAL RESISTIVE MODULE

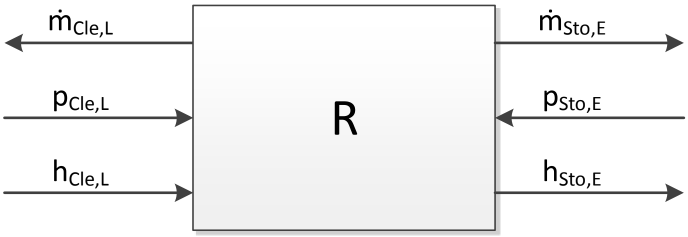
This module expressed the heat transfer between the cleaning section wall and the environment:



Inputs	$\bar{T}_{air}$, $\bar{T}_{wall}$
Outputs	$\dot{Q}_{air}$, $\dot{Q}_{wall}$
Parameters	$U_{cle,2}$, A_{Cle}

CLEANING SECTION FLOW RESISTIVE MODULE

The following module describes the instantaneous pressure difference between the capture and cleaning section:



Inputs	$p_{Sto,E}, p_{Cle,L}, h_{Sto,E}$
Outputs	$\dot{m}_{Sto,E}, \dot{m}_{Cle,L}, h_{Cle,L}$
Parameters	c
Internal variables	ρ_{Cle}

4.4. STORAGE

In this section, the storage of the steam for the Synext engine is discussed.

The main reason for storing the steam is to turn the batch process into a continuous process. This allows for a steady flow towards the Synext engine. This mass flow is also considerably smaller and therefore a significantly smaller Synext engine is needed.

4.4.1. STORAGE CAPACITY

The storage volume needed for the system is mainly dependent on the steam volume of one quench and the down time between quenches. Data from Appendix C and Section 4.1.2 dictate that 2500 kg of steam must be released over 15 minutes, which results in a maximal capacity for the storage vessel of 4100 m^3. 10% losses are assumed, so only 3690 m^3 is actually required in terms of capacity. It is assumed that the pressure averaged over time is near atmospheric, so the effect of pressure changes is neglected for the storage capacity choice. A point of note is that the cleaning section harbours space that could be utilized as extra capacity. This brings the vessel capacity to about 2000 m^3.

4.4.2. STORAGE EQUIPMENT

EQUIPMENT CHOICE AND SIZING

As a cylindrical vessel is the most common apparatus to hold pressure above or below the atmospheric pressure, it is chosen as the final design for the vessel. The cylinder shape is chosen over the spherical design to give ample opportunity for the condensed water to flow downwards. Except storage, another function of the vessel is to regulate the flow of steam from the cleaning section to the vessel. The main challenge is to make sure no backflow occurs from the storage to the cleaning section. This is achieved by placing a valve here, that is regulated by checking the pressure at the storage and cleaning section. Except this inlet, there are three other outlets. The first one is the most important outlet directing the flow to the Synext engine. Here, another valve is placed to regulate the flow and make sure backflow does not take place. The second outlet resides at the bottom of the vessel and its function is to drain the condensate that might contain particles to the basins. The third outlet is for safety reasons. If the vessel filled with steam is left unattended, for example due to a system malfunction or maintenance, the pressure would keep dropping. This could lead to an implosion. The valve on this outlet checks the pressure and opens when it reaches a critical low. Then, the vessel is purged with air, which can be purged out during the next quench.

Using the volume, mentioned above, it is derived that the diameter of the cylinder is 10 m and the length is 20 m.

These dimensions are unrealistic and would render this project unfeasible. It is however interesting to carry these values forward in this study to see their effects on the model, as it is the best course of action without adding new components such as a compressor.

Two points are important to notice. In Chapter 5, a smaller vessel will also be considered. And in the recommendations, the steam network of Tata Steel IJmuiden will be mentioned as a potential solution to the vessel disproportionate dimensions.

EQUIPMENT INSULATION

The equipment insulation for the storage section is taken the same as for the cleaning section, which can be seen Section 4.3.4.

4.4.3. Storage model

The aim of the storage section of the model is to determine the steam flow heading towards the Synext engine. This section is described by four modules. The first module expresses the mass and energy accumulation of the steam in the storage vessel. The second module represents the heat transfer between the steam and the storage vessel wall. The third module describes the thermal mass of the wall. Lastly, the fourth module depicts the heat transfer between the wall and the environment.

Assumptions

The following is assumed for the storage section of the model:

- Phase change can occur inside the storage vessel.
- Thermal energy and mass accumulation is present in the vessel.
- Thermal energy is accumulated in vessel walls due to the significant mass.
- Convective heat transfer is present between the walls of the storage vessel and the fluid.
- Convective heat transfer is present between the wall and the ambient air.
- The safety purge is not needed under normal conditions and is therefore excluded from the model.

As the modules are similar to the cleaning modules, they are not presented.

4.5. System overview

In this section the overall system will be summarized and reviewed.

4.5.1. Overview system

Now all the concepts are chosen, a flow overview of the system can be viewed in Figure 4.14.

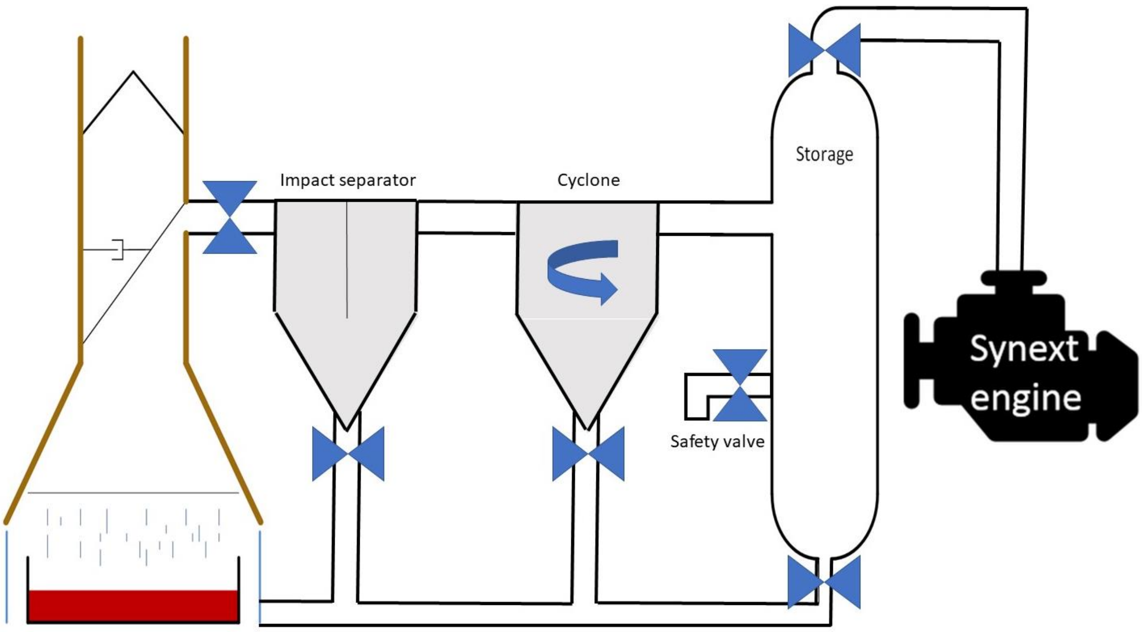


FIGURE 4.14: SCHEMATIC REPRESENTATION OF THE SYSTEM OVERVIEW

In summation, steam is generated in the quenching chamber by quenching the hot coke. The steam is prevented from exiting the system horizontally by the water wall. The steam travels upwards and is guided by the capture valve towards the cleaning section. The ducts lead the steam towards the collision wall in the impact separator separating the larger particles in the gas. Then, the steam flows in the cyclone, where it is cleaned further. Through the upward exit of the cyclone, the steam pipe leads to the storage vessel. Here, the steam is stored, while it continuously enters the Synext engine.

4.5.2. Model Overview

The different modules needed to model the system are now defined. The overall model can now be put together and displayed. This is done in Figure 4.15.

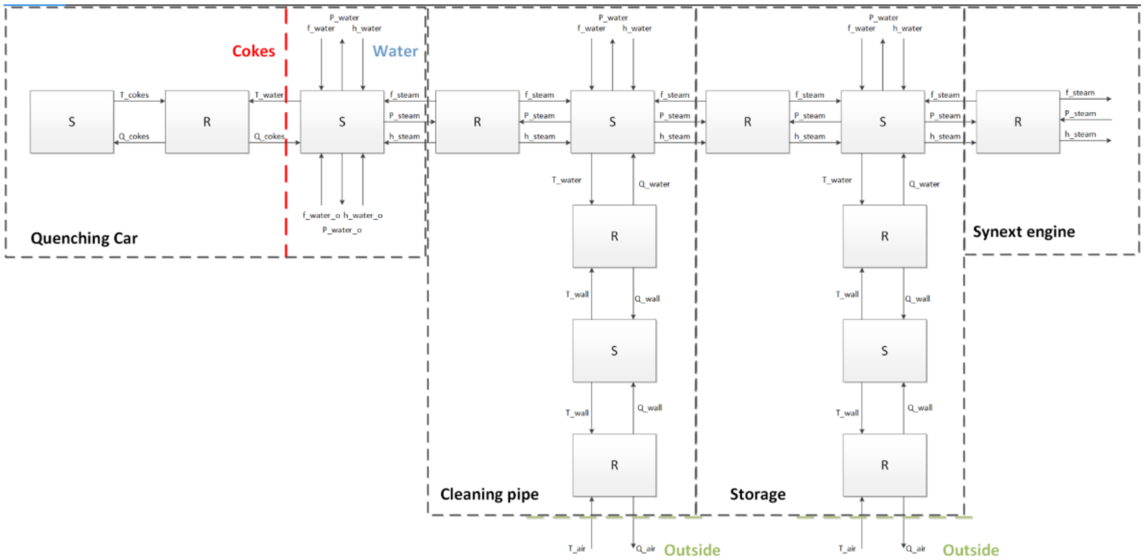


FIGURE 4.15: MODEL OVERVIEW

Three flow storage modules are present, so the system has three pressure levels. The flow towards and from these storage modules are determined by the three flow conductances. In the next Chapter results of this model are presented.

5. RESULTS AND DISCUSSION

In this chapter, the defining parameters of the model will be chosen. Implementing these parameters in the model will show results for a single quench and multiple quenches. These results will be discussed and analysed.

5.1. TUNING PARAMETERS

To run the model, several variables need to be defined. Firstly, the variables related to the geometry will be discussed. Then, the three flow conductances will be chosen. Lastly, it needs to be confirmed, if adequate cleaning occurred with the chosen parameters.

5.1.1. EQUIPMENT GEOMETRY

In Section 4.3, the impact separator and cyclone are chosen as the cleaning method. The geometry of the duct leading to the impact separator is not defined and thus the width and height of this duct need to be determined. It is preferred to have similar cyclone inlet area and duct area in order to minimize pressure drop over this section. The area of the cyclone is related to the cleaning efficiency and should therefore be checked. This will be done in Section 5.1.3. The area of the duct is related to the flow conductance between the capture and cleaning section, which will be discussed in Section 5.1.2. The flow conductance determines the mass flow. To calculate the velocity from the mass flow, the geometry is needed. The geometry influences the flow conductance. First, the flow conductance will be assumed. This will be done in Section 5.1.2.

The pipe area after the cyclone is equal to the area of the entrance of the vessel. This area is coupled with the flow conductance between the cleaning and storage sections. By defining the flow conductance, also the inlet flow area to the storage vessel will be known.

The vessel outlet to the Synext engine harbours the last important area. This area is defined, when the flow conductance between the storage section and the Synext engine is known.

5.1.2. FLOW CONDUCTANCE

The flow conductance is introduced in Section 4.3.5. This constant will be determined by iteration. The same steam mass flow as Feng needs to be achieved. This mass flow is confirmed by Tata Steel specialists. By iterating the flow conductances, a maximum mass flow of 14.5 kg/s is attained from the capture to the cleaning section, which corresponds with Feng's model. If this mass flow is achieved, most of the steam will enter the system before the valve is closed. For this mass flow, a flow conductance C_{cap} of 0.08 is found. This has been chosen for all three flow conductances, c_{Cap}, c_{Cle} and c_{Sto}. A_{cap} is now defined using Eq. 4.44. The capture area is calculated to be 25 m^2. This is unrealistic and only shows the technical issues of this design. However, this model could give insight into dealing with similar problems, a case with for example more acceptable parameters for example.

5.1.3. CYCLONE COMPUTATIONS

Now the flow conductances and geometry are known, calculations can be made to confirm adequate cleaning done by the cyclone separator. The cyclone has a diameter of 0.8 m, at this diameter the cyclone approaches a zero-pollution output, see Figure 5.1. This figure corresponds with literature where 50 µm is set as a threshold for zero-pollution output. Using Eq. 4.36 and an average steam mass flow of 2.5 kg/s of steam, a pressure drop of 0.1 bar has been calculated.

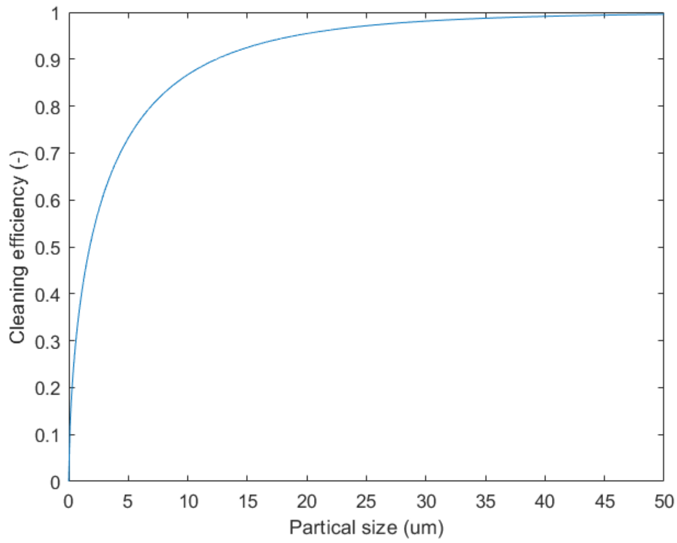


FIGURE 5.1 - CLEANING EFFICIENCY CYCLONE OVER PARTICLE SIZE

5.2. RESULTS

In this section, the results of the model will be presented. To understand the broader scheme, one quench will be evaluated. Then results will be shown for multiple quenches in a continuous process to show the transformation of a batch to a continuous process, the design capabilities and its potential for other applications.

5.2.1. ONE QUENCH

The results for one quench show trends that will be discussed now. As this is the most important parameter, the mass flows are discussed first. These are presented in Figure 5.2.

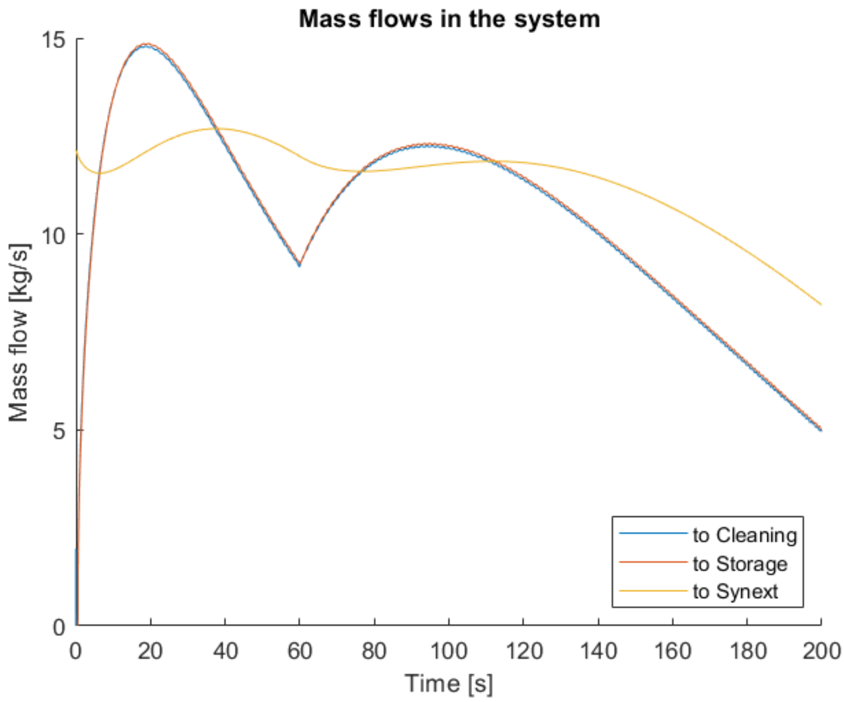


FIGURE 5.2 - MASS FLOWS IN THE SYSTEM.

For 60 seconds, the cokes are submerged in water generating steam and increasing the pressure in the quenching car. This results in a rapid increase in the mass flow for both the cleaning and storage sections. The coke temperature and its gradient over time decline, as can be seen in Figure 5.3. The power generated by the heat therefore declines, which is why a maximum mass flow is observed. After 60 seconds, the quenching stops and thus the cokes are no longer submerged in water. This generates and second increase in mass flow rate.

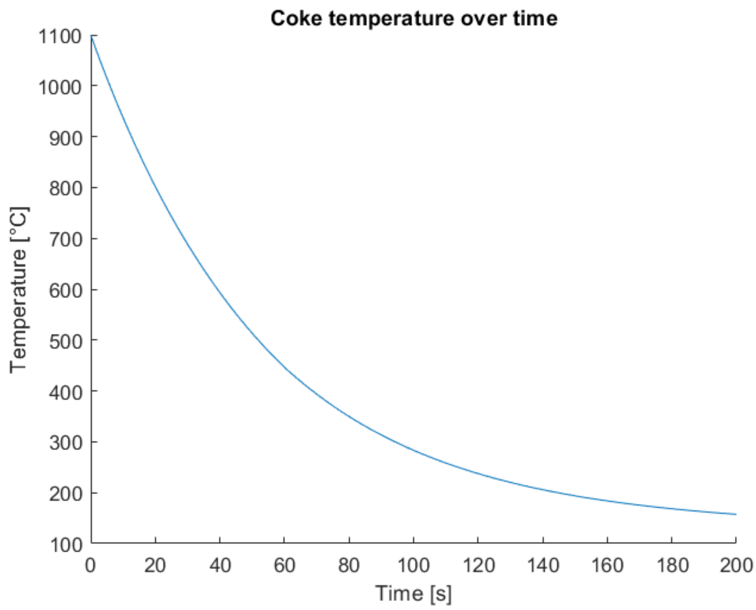


FIGURE 5.3 - COKE TEMPERATURE OVER TIME

The storage vessel, already prefilled with steam, slowly empties into the Synext engine, decreasing its pressure. This can be seen in Figure 5.4. This pressure loss yields a mass flow decrease to the Synext engine. Due its large volume, this section acts as a damper. The thermal power of the cokes reaches the storage sections later. So, a delayed response can be seen in pressure and mass flow. The second increase is also mildly present in the storage pressure and mass flow.

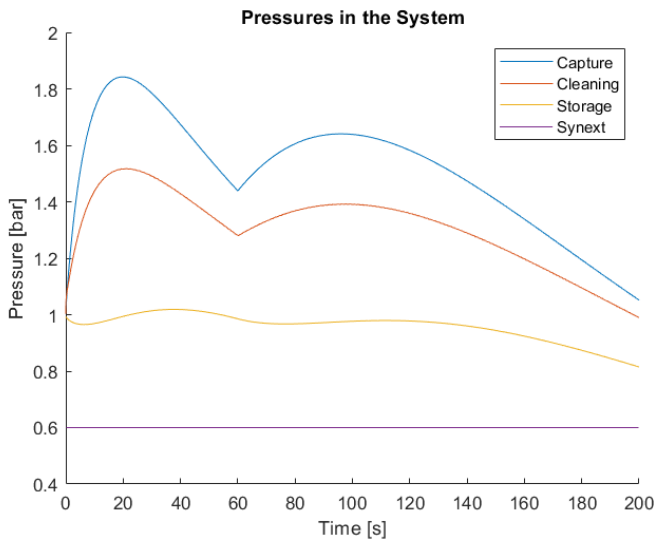


FIGURE 5.4 - PRESSURES IN THE SYSTEM

The three pressure levels of the proposed system, shown in Figure 5.4, all have the same characteristic shape agreeing with Feng's study and thus suggesting a similar quenching characteristic. The pressure levels of the system and of the Synext engine do not cross each other during the quench. This means that a steady flow through the system is achieved.

The quenching car leaves 200 seconds after the beginning of the quench. The valve towards the cleaning section closes and the car leaves. The system is hence closed. The assessment of multiple quenches will be investigated in the next section.

5.2.2. Continuous process

To evaluate the performance of the system, multiple quenches must be simulated. The mass flows will again be the first to be examined. The capture mass flow, shown in Figure 5.5 is zero between quenches, as the capture valves are then closed.

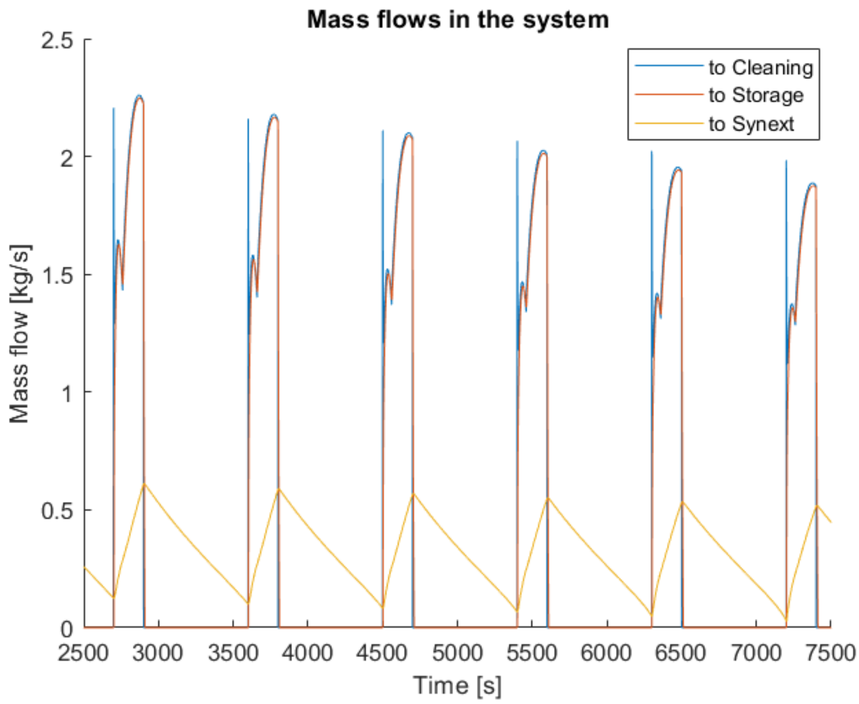


Figure 5.5 - Mass flows in the system

During this off-time, the capture area is atmospheric. The cleaning mass flow goes up quickly. This is beneficial. Correlated to this mass flow is the velocity and a high velocity is needed to clean the steam. The mass flow then quickly goes down, when no steam is fed into the system. The reason for the high spike in mass flow to the cleaning section is the lower cleaning pressure that occurs between quenches, because of condensation. The pressure levels are presented in Figure 5.6.

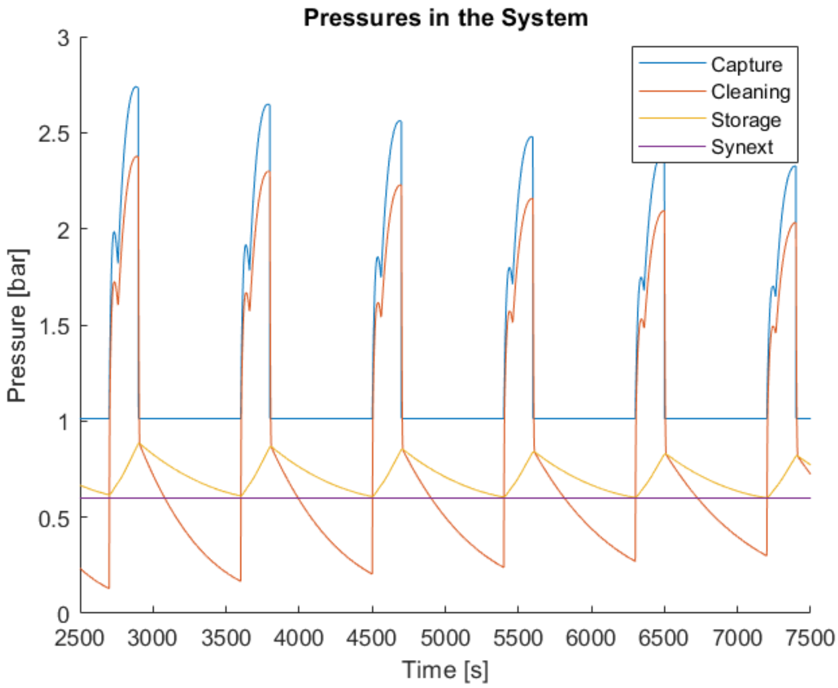


FIGURE 5.6 - PRESSURES IN THE SYSTEM.

This lower pressure ensures a high cleaning efficiency, but on the other hand increases the chance of air in the system. This is detrimental for the system, as stated in Section 4.2.2. The storage vessel has a more stable mass flow, due to its volume. This mass flow conversion from a batch process to continuous one can be observed in Figure 5.5. As this is a different case, other values can be see compared to the one quench simulation in Section 5.2.1.

5.3. ANALYSIS

The implication of the results on the feasibility will be further analysed in depth in this section.

5.3.1. MAIN LOSSES

Due to the design choices, not all the steam generated by the hot cokes can be collected in the system. These are the main losses. The choice to reduce condensation ended up being detrimental for the flow.

The losses to the wall are high, until the wall of the cleaning and storage section are at the same temperature as the steam. This renders these quenches as lost energy. After heating up, the walls show an oscillating temperature.

5.3.2. STEAM OUTPUT AND PRESSURE

Average steam output equals 0.5 kg/s for the favourable design parameters and outcomes. One of these outcomes is the steam pressure, which is lower than atmospheric when entering the engine. This lowers the Synext efficiency. The lower pressure could also lead to large fluxes of air into the system, which is also disadvantageous for the efficiency.

5.3.3. EQUIPMENT AND FOCUS

The equipment needed in this study to fulfill the wide array of requirements of the system ended up being unrealistic. These requirements are detrimental for the waste heat recovery, as the needed passive system resulted in a small cyclone and a large system. The small cyclone has a high chance of clogging up and not functioning. The large system is costly, which will be analyzed in detail in Chapter 6.

If the focus was only on cleaning the gas, a venturi scrubber could be used. This would condensate a significant portion of the gas, which would waste a substantial share of the energy. Also, a high velocity would be sustained, if cleaning was the main goal. The fan needed would negate the recovered energy.

A total system overhaul would occur, if the emphasis was only on waste heat recovery. The generated steam would be clean from the start and in a closed system. An example would be concept 3 from Chapter 3. All this would affect the coke quenching, coke quality and cost.

5.3.4. Conclusion

The steam output achieved in the model is low, even though several points were not taken into account. The points would only have an even more negative effect on the steam output. The equipment and its size are not realistic. This all results in an unfeasible technical solution.

6. ECONOMIC ANALYSIS

This chapter describes the analysis on the economic part of the system. This chapter is important for the choice on the feasibility study, since it is desired that the cost benefit of the system will deliver an economic benefit over a certain period. Furthermore, the return on investment will be discussed.

Based on the results of the study in the previous chapters an estimation on the cost-benefit of the system will be presented. The total expected investment on the system will be estimated and compared with the estimated benefits the system will deliver. The investment on each subsystem, capture, cleaning and storage, will be determined based on cost benefit studies conducted in the literature and final estimated annual cost-benefit results will be presented. Since the main part of the capture system already exists and the storage system will have a fixed volume, the main and decisive part of the investment study is based on the cleaning section.

6.1. INSTALLATION COSTS

6.1.1. CAPTURE SECTION

WATER WALL

The capture system consists of the sub-systems and compartments as described in Section 4.2. This subsystem requires an investment on the water wall. The water wall requires pumps which must meet a volumetric flow of 0.23 m^3/s. The system requires each quench of 60 seconds a volume of 13.8 m^3 of water. The required pumps are already integrated in the quenching tower, the study in Section 4.2 shows that an additional volume of 15 m^3 per section is required and therefore the capacity of the water wall storage bins has to be increased by 30 m^3. The required costs for the extra storage tanks have been estimated and given in Table 6.1

VALVE

The valve described in Section 4.2.3 is not present in the system and due to the high temperatures and the moisture in the flow, it is recommended to manufacture this valve from Bongossi wood controlled by a motor for opening and closing. Based on the required dimensions and the Bongossi wood (heat and moisture resistant) given price 681 €/m^3 (Wang, 2004), it is expected that the valve will cost in the order off a few hundred euro per year.

6.1.2. CLEANING SECTION

IMPACT SEPARATOR

The impact separator is not included in the consisting system. The duct consists of a horizontal straight part and rectangular bends which bend the flow in vertical space moving towards the cyclone cleaning section. The steam flow at the rectangular part will be captured by wall collision and will mainly eliminate the larger fraction of the particle size distribution.

CYCLONE INVESTMENT COSTS

The cyclone in this system will eliminate the fraction of the particles of smaller size. The cost correlations of Wang are used for the estimations for the cyclone:

- Cyclone support stand
- Fan
- Fan motor
- Collecting vessel/hopper

The estimation of the costs is conducted and estimated according to the cost correlations described in (Wang, 2004). The cyclone cost C_{cycl} is a function of the cyclone inlet area A_{cycl} (0.002m$^2 \leq A_{cycl} \leq$ 0.25m^2) and is defined as:

$$C_{cycl} = 6250\ A_{cycl}^{0.9031} \tag{6.1}$$

The total cost of the cyclone is a sum of $C_{cycl,total} = C_{cycl} + C_{ral}$, where C_{ral} is the cost of the rotary air lock and defined as:

$$C_{ral} = 2730\ A_{cycl}^{0.0985} \tag{6.2}$$

For $A_{cycl} = 0.24\ m^2$ this yields an estimation of 27.164 €.

FAN COST

Since the fan in the cyclone requires power, it is chosen to omit the fan out of the system. However, the cost analysis for the fan is conducted and described below:

The total cost for the fan $C_{fan,total}$ is defined as the sum of the fan C_{fan}, which is a function of the fan diameter and the required fan motor C_{motor}, which is related with the required fan power.

$$C_{fan,total} = C_{fan} + C_{motor} = 42.3 d_{fan}^{1.20} + 235 P^{0.256} \tag{6.3}$$

6.1.3. Storage section

The investment cost for the storage vessel is done according to the general cost estimation equation for processing equipment of Smith and is defined as:

$$C_E = C_B\ \left(\frac{V}{Q_B}\right)^M f_M\ f_P\ f_T \tag{6.4}$$

Where:

$C_E =$ Equipment cost for carbon steel at lower temperature and pressure with capacity Q

$C_B =$ Base cost for equipment with volumetric base capacity $Q_B = 6$

$M =$ Constant depending on equipment type

$f_{M/P/T} =$ Correction factors for materials, pressure, temperature

For relative low temperature ($T \leq 100\ C°$) and pressure ($0.5bar < P \leq 7bar$) and carbon steel as construction material, the correction factors are $f_M = f_P = f_T = 1$ delivering the equation:

$$C_E = C_B\ \left(\frac{V}{Q_B}\right)^M \tag{6.5}$$

The following parameters are applicable for a storage tank (Smith, 2005):

$C_B = 1.15 \cdot 10^4$ €

$Q_B = 5\ m^3$

$M = 0.53$

Delivers a storage tank cost of: $C_E =$126.164 €

COSTING INDEX

The formulas for the cost estimations do not take inflation into account, therefore the inflation of all estimated investment values is corrected by the formula:

$$\frac{C_1}{C_2} = \frac{INDEX_1}{INDEX_2} \quad (6.6)$$

$C_{1/2}$ =equipment cost for year 1 and year 2

$INDEX_{1/2}$ = Cost index in year 1 and year 2

TOTAL CAPITAL COST

The total capital cost of the system can be obtained by multiplying correction factors on the purchase cost C_E

$$C_F = f_I \sum C_{E,i} \quad (6.7)$$

Where:

C_F =Capital cost for the system

f_I = overall installation factor for the system

$C_{E,i}$ = cost of equipment i

The installation factor f_I contains utility investment factors, off-site investments factors and working capital. The overall installation factor is determined and customized according to the given estimations by Smith (Smith, 2005) and are corrected for example for piping and instrumentation, the correction factor is estimated to f_I = 2.5.

The investment costs are summarized in Table 6.1.

TABLE 6.1.1: DESIGN COST OVERVIEW

Estimated investment in cleaning equipment	Estimated price in [€]
Water wall	1000
Bongossi wood	300
Valve electromotor	900
Total cyclone cost	27 164
Storage tank/vessel	126 164
Total cost	155 528
Total capital cost (factor ≈ 2.5)	388 820

These are the total costs excluding the Synext engine.

6.2. ELECTRICITY PRODUCTION

The electricity production is a decisive parameter on the cost benefit analysis and the return on investment. The captured steam in the storage vessel flows gradually to the Synext Engine, the Synext Engine has a certain efficiency delivering a power. Since the power is generated in an industrial area, it has a low added financial value. In case the power was generated in urban areas the price of the power would have had more significant added value.

6.3. CO_2 REDUCTION

Since the Dutch governmental acceptance and push in 2019 on the reduction of the greenhouse gases, the CO_2 reduction is becoming more relevant and important than ever. The impact of the CO_2 reduction can increase the threshold for the acceptance of the system. Chapter 5 shows the power generated by the Synext engine in this in its final design. Generally, 0.526 kg CO2 is produced per kWh of energy generated using fossil fuels (Otten & Afman, 2015). If the system runs uninterrupted for a year, the design will generate a certain amount of energy. Having generated this amount of energy with a CO2 negative process, saves the generation of 160 tonne of CO_2 which would have been generated annually by fossil fuels like coal of natural gas.

6.4. POLLUTION CONTROL

This study shows that during the quenching process solids are present in the steam, the particle size distribution of the solids in the steam is determined. In the current quenching tower, the coke quenching process does not completely clean the polluted steam and some solids are expelled into the environment. This study shows that zero-polluted steam is achievable by including a cyclone in the cleaning section. Tata Steel intends to reduce any form of pollution as far as can be achieved and therefore this study would be of great added value by using the cleaning section.

7. CONCLUSION

In this section we summarize several conclusions derived from this study.

In Section 3 several novel ideas were presented as concepts for the generation of electricity using the steam from the Tata Steel quenching towers. Several of these ideas involved using turbines to be powered by steam, either directly or after condensation of the steam into water. The main objections to these turbine-based concepts is the fact that the steam released after a quench simply does not have a high enough pressure to power them. The concept based on a heat pump was found not to be technically viable due to the relatively high mass flow rate in the system, which would leave little time for heat to actually be exchanged; moreover, the abrasiveness of the dirty steam would damage the heat exchangers components, rendering it a not very suitable option. Ideally an entirely new quenching tower could be built wherein heat can be utilized with a process similar to coke dry quenching, but tailored for the Synext engine. This however, was found not to be economically viable. This saved the ideas where steam would be fed directly into the Synext engine. The issue here lies within the batch process with which steam is generated during quenching. One of two potential ideas is to feed the Synext engine an alternating steam supply and generate either a high or a zero amount of electricity. The other option is to catch and store the steam and feed it in a continuous process to the Synext engine.

From the concepts mentioned, one is chosen which meets the requirements given in this study as best as possible. This was capturing the dirty steam produced in the quenching chamber of the tower. Horizontal release of the steam is prevented by a water wall. Vertical release in the tower was hampered by a valve, guiding the steam to the next section. In this section the steam is cleaned. The larger particles are removed by a collision wall. The remaining particles are then extracted using a cyclone. The clean gas then flows in the storage section, where any remaining particles can settle and the mixture is stored in order that a steady flow can be provided for the Synext engine. In the case of a shutdown of this system, the quenching steam can still be sent to the original tower.

To calculate the steam output, a modular model is created in Simulink. In this model, the sections are divided into modules in which the mass, energy and momentum conservation equations are met. The average steam output of the Synext engine is 0.5 kg/s with the specific inputs as is the case in this study.

The installation costs of the system excluding the Synext engine sum up to 389 k€. With the steam output achieved, 12 k€/year of electricity production can be generated. The total costs exceed the economic benefits gained by the Synext engine. Thus, the proposed option is not financially viable.

In conclusion, it is not both technically and economically feasible to use the coke quenching steam of Tata Steel IJmuiden to generate electricity in the Synext engine.

8. RECOMMENDATION

While this study was performed many issues arose that did not have a quick solution at hand. Some of these issues were solved through great effort, but those that could not were worked around as delicately as possible. This led to the generation of values that were estimations rather than real measurements, assumptions that were substantiated as best as possible and workarounds that seemed to be open to improvements. In this chapter some of these issues that are believed to be solvable with more time and a wider scope are mentioned.

QUENCHING STEAM MEASUREMENTS

Contrary to expectations, while performing this study it was found that there is still much unknown about the steam from a quenching tower, even within Tata Steel itself. The inner workings of the quenching tower, are such an open process that it has never been measured how much steam is generated; this parameter had to be estimated by making certain assumptions and calculations. Other parameters like the temperature and mass flow rate of the steam and the mass, volume and size distribution of the particles in the steam are based on assumptions and estimative calculations. Deriving values for these parameters from real onsite measurements and using them as input for the model, would give a much more accurate depiction of reality by the model.

OTHER CONCEPTS

In chapter three several concepts on how to generate electricity from the quenching steam were presented. Throughout this chapter the concepts were evaluated by logically comparing their respective advantages and disadvantages and laying the results out in a decision matrix, after which one final concept was chosen. Point of note here is the fact that some of these eliminated concepts did in fact show promise, but were simply found to be the lesser options. Due to time constraints and in service of narrowing the scope of this study only one concept was chosen for further analysis, design and calculations. It would be interesting if some of the eliminated concepts were carried forward and developed further like the final concept in this study. Comparing the results of all the calculations and models for all concept may yield some insight on how to best tackle some consistent issues.

EXPERIMENTAL RESEARCH STEAM CAPTURE

The design of the steam capture concept left several questions with respect to its efficiency, feasibility and unknown parameters. One question revolves around the performance of the proposed water wall, whose function it is to act as an outer wall for a closed system. Experiments employing a water wall on a smaller scale could specify a required thickness or flow rate of the wall or may expose any overlooked parameter in its use. The proposed valve in the steam capture setup could be recreated on a smaller scale to evaluate its efficiency, how well it redirects the steam, if any leaks occur and again if any overlooked parameters exist.

CLEANER SOURCE

One recommendation stems from the belief that the Synext engine shows great concept for future work. However, it is believed that the Synext engine was given an unfair disadvantage within the framework of this thesis. The steam it is expected to run on is generally quite abrasive and was found to prove a challenge to the Synext engine. To properly benchmark the capabilities of the Synext engine experiments should be performed in a cleaner environment with a steam supply that is not as compromised as the steam from a quenching tower. In summation, the Synext engine has great potential, but the harsh environment in and around a quenching tower arose challenges that seemed to obscure the Synext engine's promise.

POLLUTION CONTROL

As the quenching towers were studied for this research it was found that while the waste heat recovery was a beneficial service to the environment, the control of particulate matter excluded from the towers is an equally pressing matter, if not more. The release of particulate matter to the environment occurs worldwide and is becoming an increasingly important issue, even more so with the ever tightening government restrictions. A study into an efficient and cheap method in cleaning the particles from the steam would without question be a valuable asset in making the quenching towers more environmentally friendly.

PARTICLE TOLERANCE SYNEXT

Section 4.3 discussed the cleaning process and how and to what extent this would be done. The thought behind the reasoning and calculations in this concept is to minimize the solid particle intake of the Synext engine. The question remained however, that not much is known about the capability of the Synext engine to handle these particles. If it turned out to be such that the Synext engine can indeed handle a relevant size, it would appear that the system in this study is overdesigned. Ideally, the Synext engine is able to function adequately with steam as it is expelled right after a quench, rendering the whole cleaning process unnecessary. This ideal scenario without a cleaning section would be much more beneficial, both financially and pertaining to the pressure drop in the system.

CLEANING EFFICIENCY EXPERIMENTS

While researching the cleaning efficiency and subsequent pressure drop of the various cleaning apparatuses, it became clear that there is not much literature on the specific calculations on the cleaning efficiency and pressure drop of some specific concepts. This proved to be challenging since an inadequate cleaning or a pressure drop that is too great could be detrimental to the feasibility of the entire system. To properly evaluate and quantify the advantages and disadvantages of the cleaning methods, cleaning experiments need to be performed with the exact same steam as it is expelled during a quench at Tata Steel. Alternatively, much knowledge could be obtained if these under researched cleaning methods were modeled in detail, using CFD models for example.

MODEL

The following recommendations aim to improve the Simulink model so that it better describes reality. One point of improvement is the role of air in the system. As it stands now the effects of air in the system are examined qualitatively, since excluding it completely would be a gross misrepresentation of reality. Ideally the role of air and its physical properties are based on real measurements from the quenching tower, an endeavor too time consuming for this study. Another parameter that has been simplified in favor of keeping the model manageable within the scope and timeframe of this thesis, is that of the compressibility of the steam-air mixture that enters the system. The model results show that the pressure changes along the system and with time, which would result in changes in density due to the compressibility of gas. To better approach a realistic scenario some studies should be performed on how to practically implement the compressibility's effect in the model. Employing the model wherein particles are modeled as a convectively cooled sphere in Simulink would help better simulate the particles' thermodynamic behaviour. The theory and equations mentioned in Appendix D could be used in the hope of better estimating the complex physical heat transfer between the cokes and the steam.

MULTIPLE QUENCHING TOWERS

Again, to keep the model as manageable as possible another major assumption was made, namely that the Synext engine is coupled to only one quenching tower. It would be interesting to evaluate a scenario where the Synext engine is coupled to three quenching towers, in the same fashion as was done in this study. At the Tata Steel site there are three quenching towers that lay relatively close together and could in theory be coupled together to direct their cumulative outflow of steam in one direction. The advantage gained in this scenario is that the quenching frequency is tripled, if the quenching of the towers is spread evenly over time. This increased frequency would result in a greater mass flow to the Synext engine, a quicker initial heating of the system and a faster reach of normal operating conditions.

PHASED QUENCHING

The largest part of the steam is emitted during the first part of the quench. This brings two problems: A very high mass flow at the start and a big range of mass flows. This is an unfavourable situation. The maximum draft is related to the mass flow. Until a certain point in the beginning the draft is insufficient for all the steam. But after this initial peak, the mass flow is well below this threshold. Phasing the quench will however lower the quenching frequency and could affect the coke quality, so more research is needed.

APPENDIX A: TEST PLANS

For better understanding of the occurring processes, various test plans have been made. These are presented in this section.

MEASUREMENTS ON TOP OF THE TOWER OR IN THE TOWER

Except measuring the particulate emissions, no other measurements are taken from the steam. This is done using the Mohrhauer method, which is discussed in Section 0. At the outlet, on top of the tower, or inside the tower the temperature and velocity of the flow can be measured. This gives more insight into the process, so better optimization can be achieved. These parameters can be measured during the mentioned emission measurement. On the frame, that is mounted on the top of the tower, a wireless measurement box can be added. Another solution is to install it permanently into the tower. If the latter is accomplished, the quenching parameters can be dynamically calibrated due to live information.

The temperature and fouling make it a harsh environment for delicate instruments that are needed. Measuring in a saturated steam flow adds further complications (Pessemier, 2016). The inevitable condensation can create disruption in the electronics. High temperatures only add to this problem by melting soldering. Abrasive fouling can damage the measuring equipment and therefore reduces reliability.

MEASUREMENTS IN A SCALED DOWN MODEL

As there is already a test facility where coke is being quenched on a small scale, setting up a measurement setup here for quenching is a logical step. The tests however mainly focus on coke quality, the test quenches therefore are not representative for the quenching in the tower. But coke of the right temperature is available. A scaled down tower should therefore be built. Measuring in this controlled situation here will be significantly easier, as it is more a controlled situation.

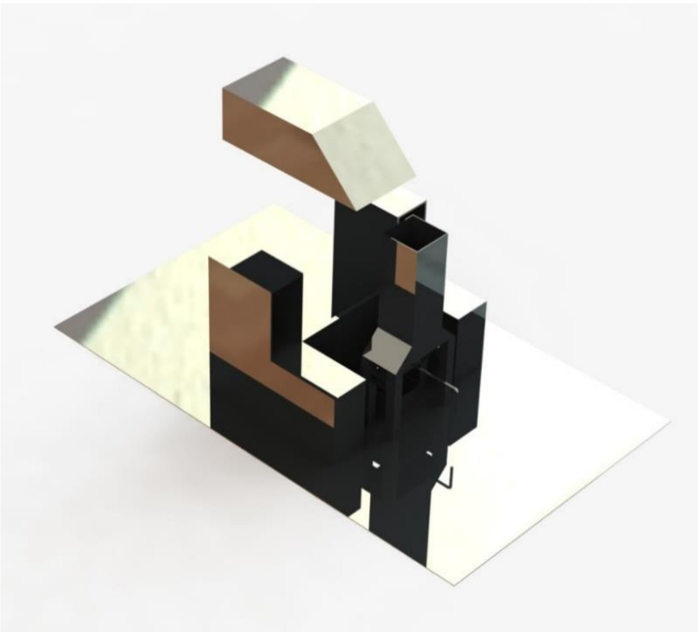


FIGURE 0.1 – MODEL OF SCALED DOWN QUENCHING TOWER BETWEEN THE TWO TEST COKE OVENS.

APPENDIX B: QUENCHING STEAM CONTAMINATION AND THE MOHRHAUER METHOD

This section elaborates on the particulate matter (PM) and other emissions that are emitted during quenching.

PARTICULATE MATTER AND OTHER EMISSIONS IN QUENCHING STEAM

According to the Environmental Protection Agency (EPA), two types of PM are emitted in a quenching tower: filterable and condensable PM. The first group is mainly emitted at the quench tower exhaust. The second group primarily condenses at the exhaust conditions and can be differentiated in inorganic and organic matter, like hydrocarbons. A smaller portion is emitted as vapor and can later condense in the atmosphere to form PM via complex photochemical reactions. The main focus though is on breathable PM 10, which is of the size 2.5µm or smaller (Huhn, 2013).

Origin of the emissions primarily can be found in (Huhn & Krebber, 2012):

- the spalling of the coke pieces from the contact of water with red-hot coke.
- PM deposits at the quench tower internals and baffles, if they were not cleaned in a regular manner after each quench and constitute a buffer for PM deposits
- Freshwater which is used for preparation of the quenchwater which contains a certain amount of the total dissolved solids
- the quench water itself

Other emissions that can be found in the exhaust are volatile organic compound, the earlier mentioned hydrocarbons, neglectable quantities of dioxines and nitrosamines, hydrogen and carbon monoxide from gasification reactions and H_2S, NH_3, CO_2 and SO_2 (Huhn, 2013).

APPENDIX C: QUENCHING TOWERS AT TATA STEEL

In this part of the Appendix, information about the different quenching towers at Tata Steel IJmuiden are expanded on.

SPECIFICATIONS QUENCHING CAR AND TOWER

In this Section, general specifications on the quenching car and quenching tower are listed.

QUENCHING CAR

TABLE 0.1 - QUENCHING CAR SPECIFICATIONS (HEIJNSBROEK, 2008)

	Coke Plant #1	*Coke Plant #2*
Design	Hoogovens	Hoogovens
Year	modernised in 1983	Built in 1972
Amount	6	2
Position control	manual	automatic computer device
Drive	diesel traction (6 ×)	electric winch
Coke temperature control	infra red measuring device recorded at quenching towers	same
Computer connected	no	yes

QUENCHING TOWER

TABLE 0.2 - QUENCHING TOWER SPECIFICATIONS (HEIJNSBROEK, 2008)

		Coke Plant #1			*Coke Plant # 2*
		West	*Middle*	*East*	
Design		Hoogovens Nathaus	Hoogovens Nathaus	Hoogovens Nathaus	Hoogovens Nathaus
Amount/Material		1 ×	1 ×	1 ×	1 × concrete structure + wood lining
Water capacity	m^3	2 × 65	2 × 50	2 × 65	2 × 80
Height	m	35	35	35	39
Quenching system		laminar flow 41 beams × 38 pipes	spray nozzles North side 8 South side 7	laminar flow 42 beams × 38 pipes	laminar flow
Quenching capacity	m^3	30 per quenching			± 60 per quenching
Quenching time	s	60 - 90			± 80 (coke moisture 4%)
Water consumption	m^3/t coke	0.8			0.7
Computer control		yes			yes

OTHER INFORMATION

Other important parameters concerning the quenching from different sources are tabulated in this section.

After averaging out the oven pushes (ovendrukkingen) and quenching times (blustijden) of 2015, they are listed in the following table:

TABLE 0.3 - QUENCHING INFORMATION

		Quenches per day [-]	Quenching time [s]	Water used per quench [m^3] *fout*	Water evaporated per quench [m^3] *fout*
CGP 1	QT 11 (middle)	83	60	30	10
	QT 13 (east)	119	58		
	QT 14 (west)	92	59		
CGP 2	QT 21	109	84	55	20

		Coke Plant #1			***Coke Plant # 2***
		West	*Middle*	*East*	
Quenches per day	-	92	83	119	109
Quenching time	s	59	60	58	84
Water used per quench	m^3	30			55
Water evaporated per quench	m^3	10			20

In CGP 1, 30 m^3 is used for every quench and 10 m^3 of this water does not recirculate and is thus evaporated. This is respectively 55 and 20 m^3 for CGP2. These values are added to Table 0.3 (De Vries, 2013).

APPENDIX D: SIMULATING A CONVECTIVELY COOLED SPHERE

BOILING CURVE

Boiling happens, when a surface is heated above the saturation temperature of the fluid. There are different boiling regimes depending on the wall superheat (ΔT), the difference between the wall temperature and the saturation temperature.

For water boiling at atmospheric pressure, free convection boiling occurs when ΔT < 5°C and now bubbles form. After this point, nucleate boiling starts. Small isolated bubbles rise and as the wall superheat increases beyond the inflection point (ΔT=10°C), additional nucleation sites generate bubbles that interact among each other. These jets and columns decrease the overall contact area between the surface and the fluid. Accordingly, the slope of the curve of Figure 0.1 decreases until the critical heat flux is reached at ΔT=30°C. An increase in temperature causes the surface to be covered by unstable vapor film. This is called transition boiling, because when the unstable film detaches, it reverts to nucleate boiling. When a stable film can be formed, the Leidenfrost point is reached. And after this point, the film boiling region is entered.

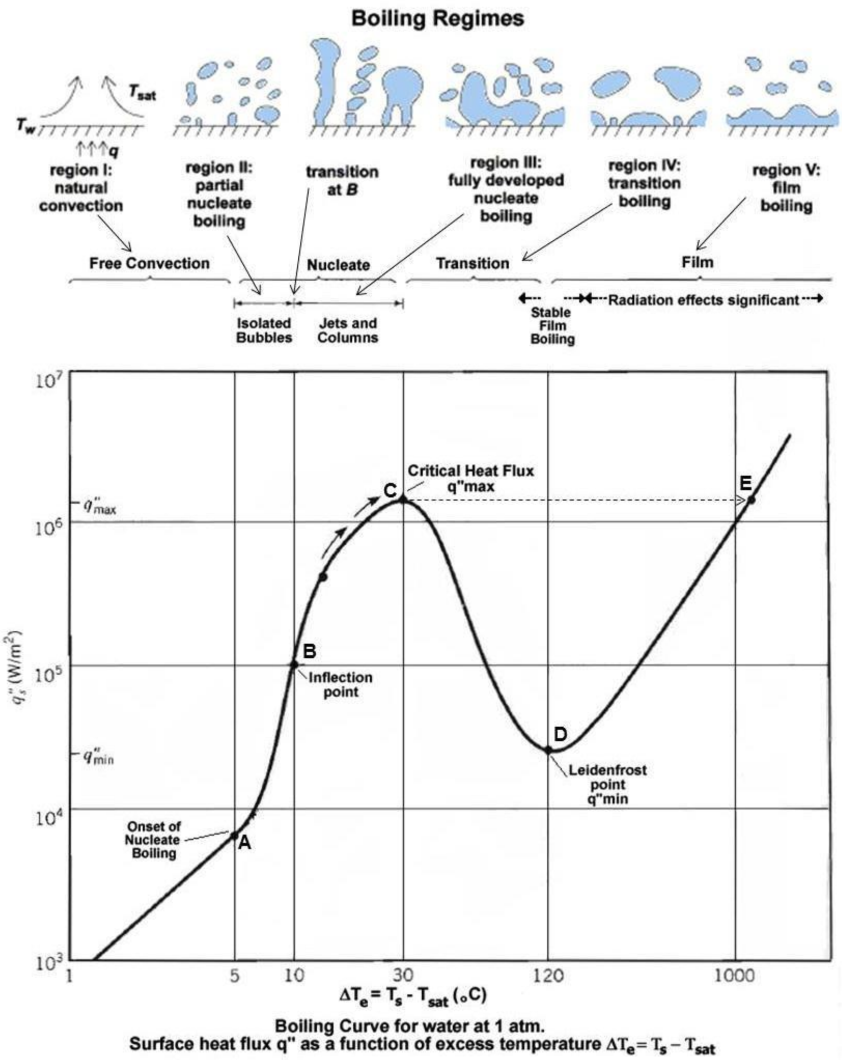


FIGURE 0.1 - BOILING REGIMES OF WATER

COKE PARTICLES

To calculate the steam flow, the source of the waste heat needs to be examined: the hot coke.

The heat flux from the hot coke particles to the evaporating water follows from:

$$q = h(T_{surface} - T_{fluid})$$

First, it is assumed that boiling happens at atmospheric pressure. The surface temperature at the start of the quench is 1000°C. During the quench, it is assumed the fluid is at saturation temperature, 100°C. Because the wall super heat is ΔT=900° at the start, film boiling will occur. The heat transfer coefficient is now assumed as 10000 W/m^{2}K and will be re-evaluated later on.

To simplify the heat problem, the coke particles are going to be taken as spheres, surrounded by water at saturated atmospheric temperature. The heat flux on the surface is taken as uniform, so the temperature in the coke particle will only be dependent on the radius and time.

The following heat equation governs the temperature in spherical coordinates:

$$\frac{\delta T}{\delta t} = \frac{\alpha}{r^2}\frac{\delta}{\delta r}\left(r^2\frac{\delta T}{\delta r}\right)$$

Here α is the thermal diffusivity, calculated using

$$\alpha = \frac{k}{\rho c_p}$$

The surface of the sphere cools down convectively, so the boundary condition at the surface becomes:

$$-\mathrm{k}\frac{\delta T}{\delta r} = h(T_{surface} - T_{fluid})$$

The entire coke particle starts at the initial temperature, so the initial condition is:

$$T(r, 0) = T_i$$

Using the following dimensionless variables for temperature, radius and time:

$$\theta = \frac{T - T_{fluid}}{T_i - T_{fluid}} \quad (4.9) \qquad r^* = \frac{r}{R} \quad (4.10) \qquad \tau = \frac{\alpha t}{R^2} \quad (4.11)$$

we come to the following analytical solution:

$$\theta^* = \sum_{n=1}^{\infty} C\, e^{(-\zeta_n^2 \tau)} \frac{1}{\zeta_n r^*} \sin(\zeta_n r^*)$$

where

$$C = \frac{4(\sin(\zeta_n) - \zeta_n \cos(\zeta_n))}{2\zeta_n - \sin(2\zeta_n)}$$

And ζ_n are the positive roots of the function

$$f(\zeta_n) = 1 - \zeta_n \cot(\zeta_n) - Bi$$

The Biot number is calculated as the ratio of the conduction resistance within the body and convection resistance at the surface of the body, using the following equation:

$$Bi = \frac{hr}{k}$$

Making the Bi >> 1. This means the lumped heat analysis can't be used. First, the temperature profile of the coke particle needs to be analyzed.

With the following properties of the cokes:

T_0 [°C]	**1000**
r [mm]	25
k [W/mK]	2
c_p [kJ/kg K]	1.5
ρ [kg/m³]	$0.9 \cdot 10^3$

The temperature profiles that are achieved, can be found in Figure 0.2 and Figure 0.3.

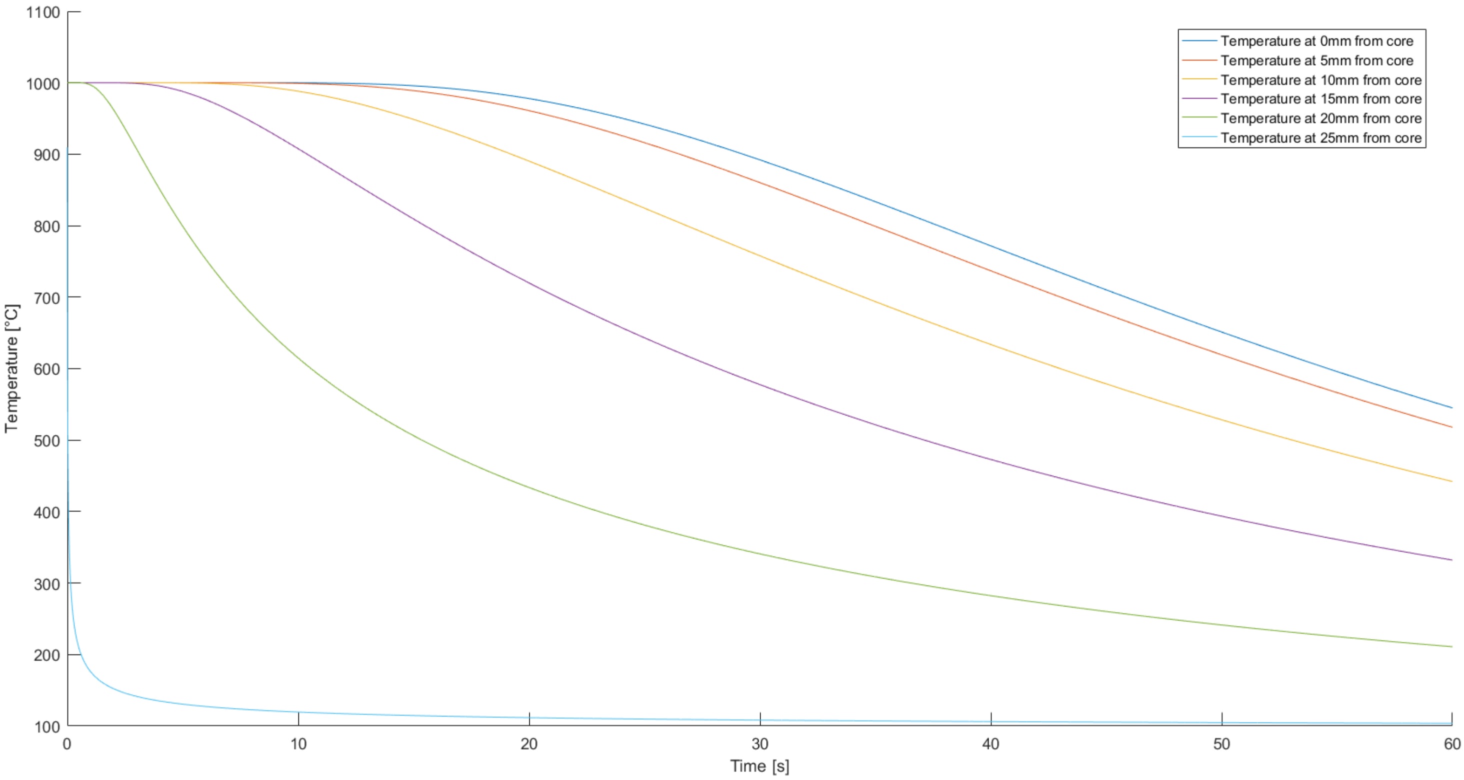


FIGURE 0.2 - TEMPERATURE PROFILE OVER TIME OF A COKE PARTICLE DURING A QUENCH.

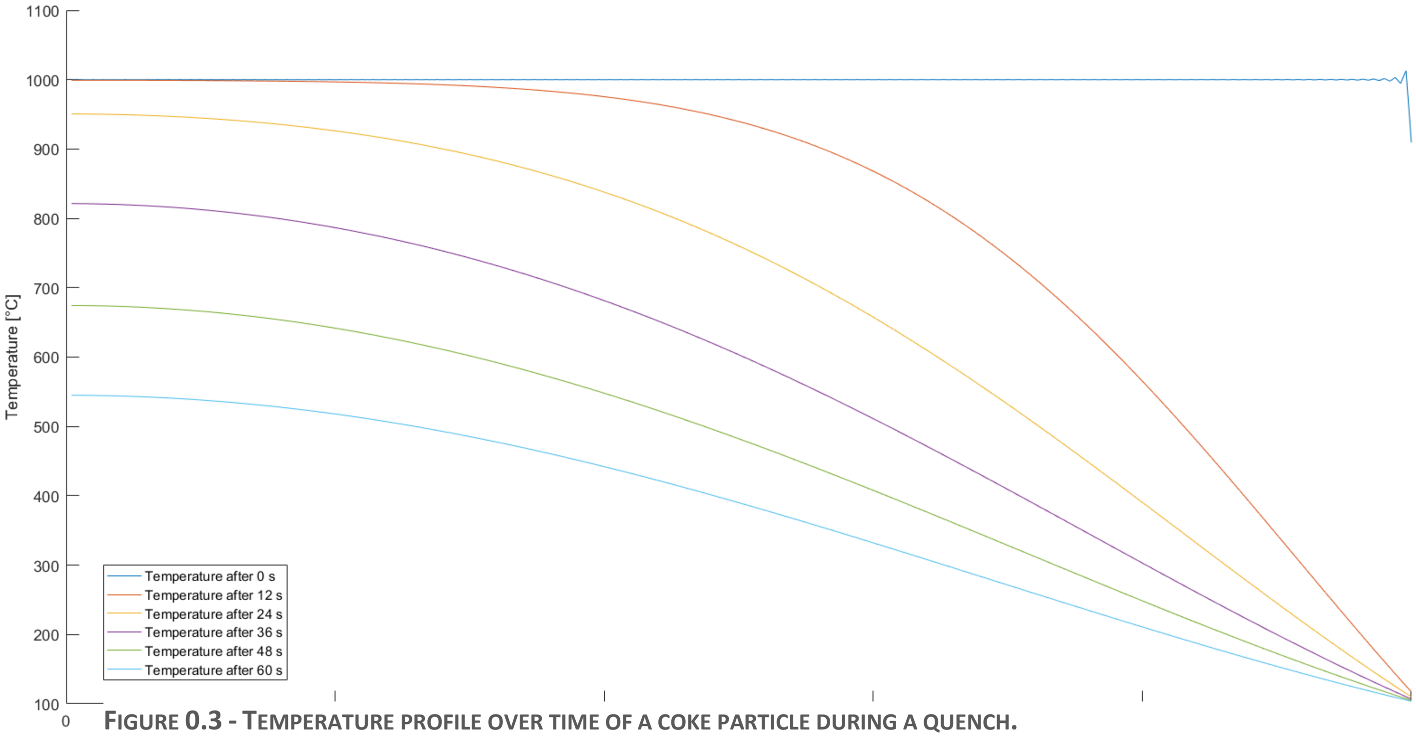


FIGURE 0.3 - TEMPERATURE PROFILE OVER TIME OF A COKE PARTICLE DURING A QUENCH.

From the temperature profiles, we can see that the temperature at the surface drops fast. The temperature of the core of the coke particle however stays above 500°C. This is however not an immediate problem, because there is no chance of an auto-ignition. The cooling down of the air inside the coke particle creates a suction effect for the surrounding water. The coke particle still holds water leaving the tower which keeps being evaporated even after the quench. This steam production can be seen on the slopes, where the coke is dropped after the quench. This steam is produced after the quench, so this can not be recovered. To find the actual steam production in the tower, we need to find the average temperature of the coke particle. Eq. 4.16 is used for this.

$$T(t) = \frac{\int T(r,t)\frac{4}{3}\pi dr^3}{\frac{4}{3}\pi r^3} \quad (4.16)$$

The average temperature of the coke can now be plotted in Figure 0.4. As the cooling down is now quantitively categorized, the steam production can now be calculated again using Eq. 4.2 and 4.3. The result is shown in Figure 0.5.

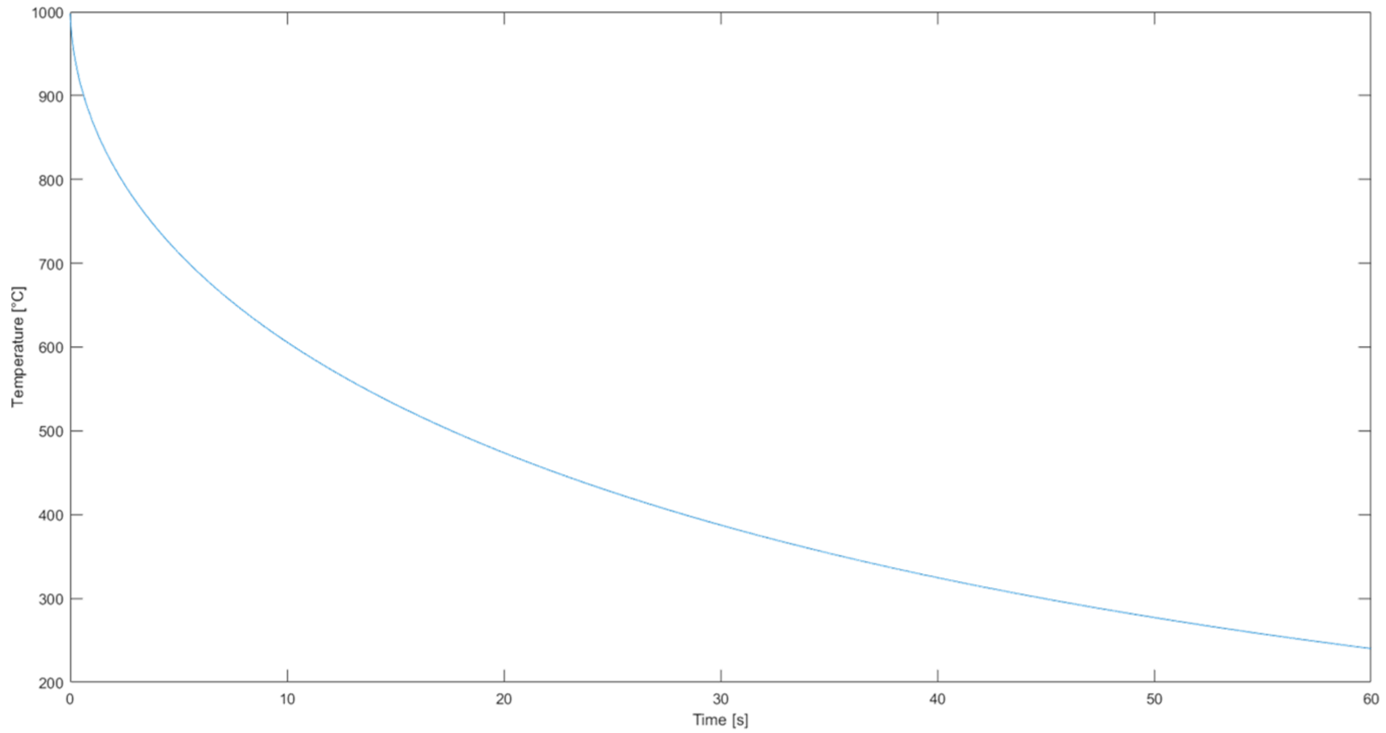


FIGURE 0.4 - AVERAGE COKE TEMPERATURE OVER TIME

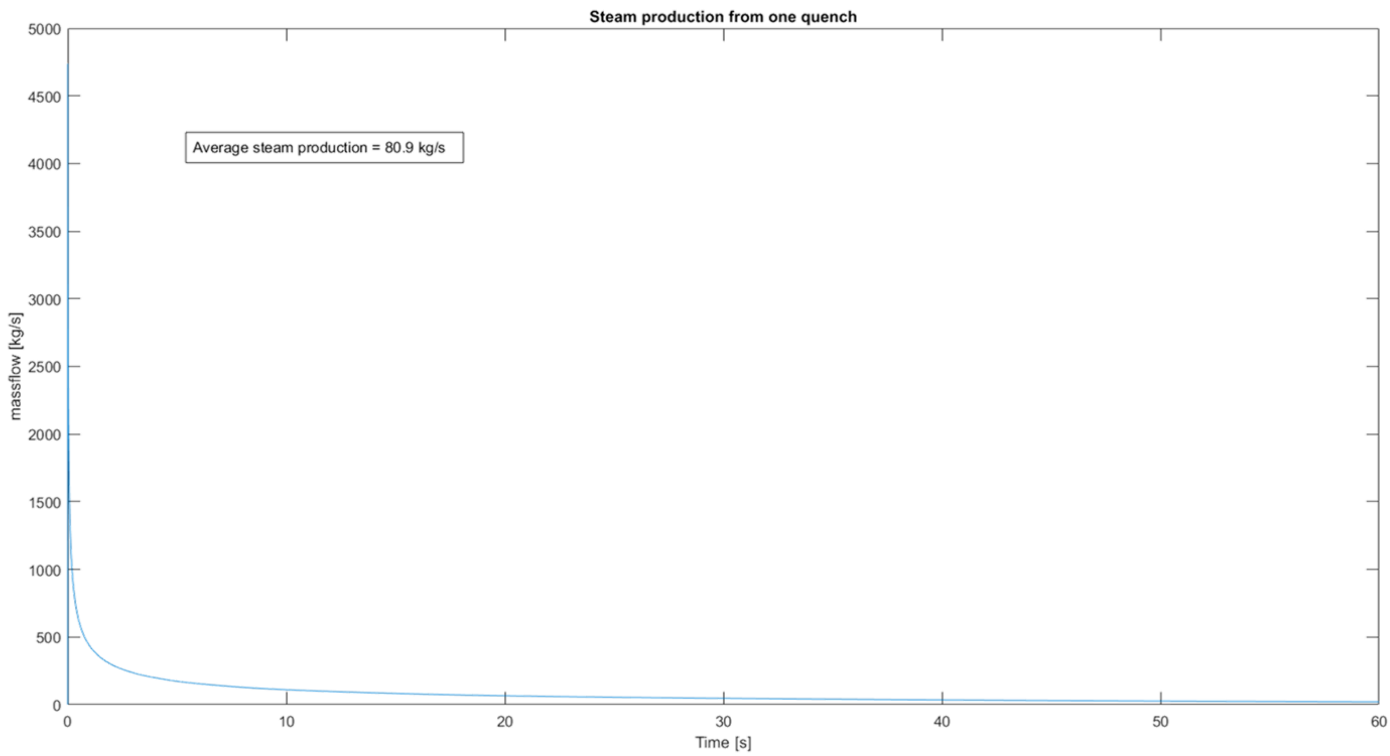


FIGURE 0.5 - STEAM PRODUCTION FROM THE COKE

ANALYSIS

Film boiling transfer coefficient

The film boiling transfer coefficient can be calculated using:

$$\overline{Nu_D} = C\left[\frac{g(\rho_l - \rho_v)h'_{fg}D^3}{\nu_v k_v (T_s - T_{sat})}\right]^{1/4}$$

Where

$$h'_{fg} = h_{fg} + 0.80c_{p,v}(T_s - T_{sat})$$

And

$$h = \frac{Nu_D k_v}{D}$$

h [W/m²K]	**84**

This is the heat transfer coefficient at the start of the quench. From the temperature profile, it can be seen that the temperature difference between the surface and the fluid goes to zero. This brings the heat transfer coefficient to an extremely large number.

Radiation

For radiation, the following equation can be used:

$$\overline{h}_{rad} = \frac{\varepsilon\sigma(T_s^4 - T_{sat}^4)}{T_s - T_{sat}}$$

h_{rad} [W/m²K]	**164**

This is the heat transfer coefficient when the quenching starts. Because the surface temperature drops fast, the radiation will as well. So, the radiation can be neglected for most of the quench.

Reflection

Several points can be noticed:

- The heat transfer coefficient can be chosen as a constant without a big error
- The massflow is too high in the beginning and this should be capped.
- Air in the system is unavoidable and should be tolerated.

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