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Interactions between the process and the lining in a silicon furnace

Modelling placments of thermocouples

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Abstract

The aim of this thesis is to investigate the interactions between the process and the lining in a silicon furnace. During operation of a silicon furnace incidents may occur that leads to the bottom of the furnace lining having a spike in temperature. In this paper two such incidences are found and studied. By the help of the simulating tool COMSOL ® the chain of events both on the top and inside the lining are modelled.

The result of the simulations was a better understanding of what is occurring inside the furnace in such incidents, and when. After a sudden temperature increase at the top of lining the heat front uses a long time from the top to the bottom of the lining. The simulations show that the delay time from the top to the bottom of the lining varied between 18 and 23 hours. The long delay reduces the probability that a sudden severe lining problem will be discovered and corrected. The information from the thermocouples may be strongly improved by installing thermocouples higher up in the lining. This will lower the reaction time and give indication of the heat flow in the lining, as in the simulations.

In addition, it was discovered that the needed temperature rise inside of the furnace to create the temperature curve of the bottom furnace lining was 250 °C, or between 400 – 450 °C, depending on assumptions made of the changes a furnace lining may have experienced in its lifetime.

Possible explanations of two cases sudden temperature increase have been presented and discussed. Where it seems that the most likely explanation is the reduction of an endothermic reaction occurring underneath the electrode. Other possible explanations like increased heat transfer to the lining or increased heat transfer in the lining was also discussed.

An even more likely explanation is a combination of two or more ex the above mentioned theories.

Sammendrag

Målet med denne oppgaven er å undersøke reaksjonen mellom prosessen og ovns foringen i en silisiumovn. Under drift av en silisiumovn kan det forekomme hendelser som resulterer i at forings bunntemperatur opplever et hopp. I denne utredningen er to slike hendelser funnet og undersøk. Og ved hjelp av simuleringsverktøyet COMSOL ® er hendelsesforløpet til både foringen og toppen av foringen simulert.

Resultat av simuleringene var en bedre forståelse av hva so skjer inne i silisiumoven når slike hendelser inntreffer, og hvordan. Etter en plutselig temperaturøkning i toppen av foringen, bruker varme fronten lang tid gjennom foringen. Simuleringene viser at tidsforskjellen fra en hendelse ved topp av foringen skjer til den blir observert ved bunnen foringen kan variere mellom 18 og 23 timer. Den lange forsinkelsen reduserer sannsynligheten for at et plutselig og vil bli kunne oppdaget og korrigert i tide. Informasjonen fra termometerne kan bli sterkt forbedret ved å installere de høyere opp i foringen. Dette vil redusere reaksjonstiden og vil kunne gi indikasjoner på varmestrømmen som skjer gjennom foringen.

I tillegg ble det oppdaget at den nødvendige temperaturstigningen inne i ovnen for å skape en temperaturkurve lik de i hendelsene analysert, var 250 °C eller mellom 400 og 450 °C, avhengig av hvilke antagelser som er gjort med tanke på endringer ovnsforingen har opplevd i sin levealder.

Mulige forklaringer på de to tilfellenes plutselige temperaturøkning har blitt presentert og diskutert. Hvor den mest sannsynlige forklaringen er at det forekommer en reduksjon av den endoterme reaksjonen som foregår rett under elektroden. Andre mulige forklaringer, som økt varmeoverføring til foringen, og økt varmeoverføring i foringen har også blitt diskutert.

En enda mer sannsynlig forklaring er en kombinasjon av to eller flere av de ovenfor nevnte teoriene.

Acknowledgments

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Elkem Thamshavn, and Elkem also deserve my gratitude, in both giving me this assignment, but also being open and helpful with any question that did arise.

I would also use this opportunity to thank my fellow students and friends for helping me stay focused and assist with relief activities when they where needed. And since this is the end of a several years long journey, all my other friends and family deserve my grateful thanks for their support.

List of symbols and abbreviations

Si	Silicon
SiC	Silicon carbide
SiO_2	Silica, quarts
C	Carbon
s	Solid
l	Liquid
g	Gas
kJ	Kilo joule
mol	Mole
ρ	Density (kg/m^3)
C_p	Heat capacity (J/(kg*K))
k	Thermal conductivity (W/(m·K))
h	Heat transfer coefficient ($W/(m^2$*K)
W	Watt
H	Enthalpy
Cm	Centimetre
M	Meter
M	Mass (Kg)
K	Kelvin
C	Celsius
h	Hours
V	Volume
TC	Thermocouple

1 CONTENTS

List of figures

List of tables

2 INTRODUCTION

This thesis builds on the work done by K. Strømmen in his paper “Interactions between the process and the lining in a silicon furnace”. The assignment for this paper was given by Elkem Thamshavn through Halvard Tveit. The goal was to understand the variations to the thermocouples placed on the outside of the lining of a silicon furnace. As stated in Strømmen’s paper:

“In this project, the goal was to discover the reason or reasons to why the bottom temperatures in a submerged-arc furnace vary. It was hypothesised that the temperatures vary as a reaction of different parameters variations inside the furnace. The different parameters that was thought to be the most relevant was electrode position in comparison to the different thermocouples position, the electrical load both on the whole furnace and the specific electrode, the shape and height to the electrode, and accumulation of metal in the furnace.” (Strømmen 2014)

In this thesis two of the cases that was discovered during the project is analysed closer, and simulations are done with the help of COMSOL ®. The goal is to better describe what is occurring inside the furnace at the time of the two incidents, and to give a more detailed description of how the lining transports the heat.

3 THEORY

3.1 SILICON

Silicon, or Si has the atomic number 14, and is classified as a metalloid. In the nature it combines with oxygen and other elements to form silicates. It is the second most abundant material in the earth's crust, estimated that about 28 % bound in SiO_2 or other silicates. (Schei et al. [1998]) Of these 28 % huge amounts are found as relative pure forms of SiO_2, in the form of quartzite or quartz sand.

3.2 THE SILICON FURNACE

The furnace used for the production of metallic silicon in large scale is the submerged-arc furnace. As a simplification, the submerged-arc furnace consists of three electrodes that supplies the energy and a rotating pot that contains the melt. Elkem Thamshavn has two furnaces with a capacity of about 50 000 tonnes per year. Since 2005, furnace 2 has been the largest Si furnace in the world. (Tangstad, 2013)

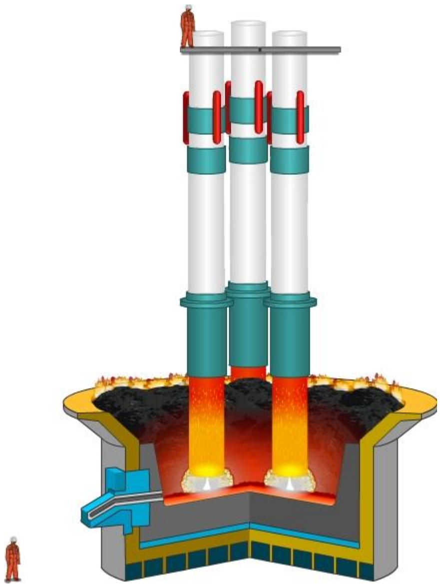

Figure 1 Submerged-arc furnace (Schei et al., 1998)

3.3 FURNACE REACTIONS

The raw materials needed to produce metallic silicon in a submerged-arc furnace is quarts (SiO_2) and carbon (C). Inside the submerged-arc furnace the raw materials goes through many different reactions that in the end results in metallic Si.

The following reactions are the general reactions occurring in the submerged-arc furnace under silicon production (Schei et al. [1998]):

$SiO_2(s, l) + 2C(s) = Si(l) + 2CO(g)$, $\Delta H = 870.241 kJ/mol$ (1)

$SiO_2(s, l) + C(s) = SiO(g) + CO(g)$, $\Delta H = 792.510 kJ/mol$ (2)

These two chemical equations are composed of a set of different chemical reactions, which are occurring in the charge. Since these main reactions are highly endothermic, it shows that the heat distribution inside the furnace plays a vital role to determine the rate of the different reactions at different zones inside the furnace. There has been done much research that all prove that the common chemical reactions in silicon production occur in specific zones. The furnace is generally divided into two parts. The inner part, with zones 1, 2, 3 and the lower part of zone 5, and the outer part, with zones 4 and higher part of zone 5.

The inner part of the furnace has according to (Schei et al. [1998]) these main chemical reactions:

$SiO_2(s, l) + Si(l) = 2SiO(g)$, $\Delta H = 605.441 kJ/mol$ (3)

$SiO(g) + SiC(s) = 2Si(l) + CO(g)$, $\Delta H = 166.714 kJ/mol$ (4)

$2SiO_2(s, l) + SiC(s) = 3SiO(g) + CO(g)$, $\Delta H = 1377.597 kJ/mol$ (5)

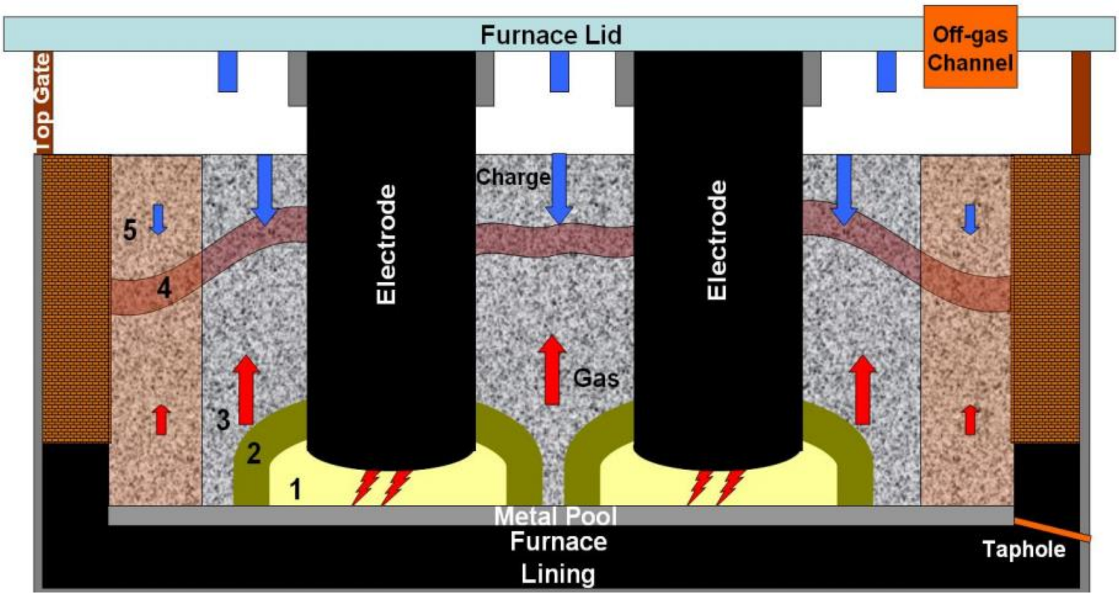

Figure 2 A cut through, graphical depiction of the submerged arc furnace used in high silicon alloys production. Different zones have been formed in the charge such as crater zone (1), crater wall (2), softening and melting zone (3), crust formation zone (4) and stagnant charge zone (5). (Kadkhodabeigi, 2011)

Since carbon has a high melting point, only its solid phase is participating in the reactions with the liquid and gas phases in the furnace.

The other raw material, quartz, has a lower melting point, and begins to soften in the middle of zone 3, see figure 2. It starts to melt at the boundary between zone 2 and 3. The now melted silica flows inwards to the crater, and reaction 3 can now occur. Chemical reaction 3 is the main former of SiO in the whole system, and high energy amounts are needed to have this reaction to proceed. This reaction is probably occurring in zone 1, strait under the electrode tip. The most important metal forming reaction is reaction 4. This is also a highly endothermic reaction consuming a high amount of energy. This reaction also needs a high partial pressure of SiO gas to proceed. Zone 2 in figure 2 is the most likely place for this reaction to occur. The excess gases produced here (SiO and CO) in the lower parts of the furnace will now travel upwards in the furnace. On their way up, these gasses will react with the charge materials in the outer parts of the furnace. One of the most important reactions occurring is the formation of SiC by reaction 6 (Schei et al. [1998]):

$$SiO(g) + 2C(s) = SiC(s) + CO(g), \Delta H = -77.592 kJ/mol \quad (6)$$

This reaction will probably occur in zone 3, and plays an important role in the silicon yield to the furnace. Another reaction that is important for the silicon yield is 7 (Schei et al. [1998]).

$$2SiO(g) = Si(l) + SiO_2(s, l), \Delta H = -306.92 kJ/mol \quad (7)$$

This is the condensation of SiO gas, occurring in zone 4 in the upper part of the furnace. This reaction occurs when the temperature of the charge high in the furnace is low enough and becomes lower than the condensation temperature. The product of this reaction is found as a thick layer of a brown substance within the charge in the upper parts of the furnace.

3.3.1 Cavities

In excavations of furnaces cavities around the electrode tips have frequently been observed. Such cavities in the furnace was establish by Zherdev et al. [1968] by using probes inserted into the charge. Otani et al. [1968] used some visual peep pipes, that was inserted towards the cavities in both the charge of a laboratory furnace and a small industrial furnace. These experiments established the presence of cavities around the electrode tip, and saw electric arcs burning from the electrode tip to a metal pool under the cavity. They observed lumped materials floating in the metal pool, continuously appearing in spite of a rapid consumption due to the heat from the electric arc. Based on (Valderhaug [1992]), summed up by Mehdi Kadkhodabeigi (Kadkhodabeigi, 2011), the cavity has the following typical features:

1. The arcs burn between the electrode and the liquid metal bath.

2. After tapping of the furnace, the cavity bottom consisting of solid materials is observed, which disappears as the liquid metal is produced.

3. Just after stoking and charging of raw materials, tough materials, probably silica, sag down from the cavity roof and partly cover the liquid metal bath. This sagging soon decreases.

4. Next, a somewhat different sagging of tough materials with solid particles, occurs. These materials float at the liquid metal surface and are consumed continuously by the reactions.

5. As time goes by, the cavity size increases, mainly upwards, provided the furnace is operated at a correct stoichiometric balance. This is due to the continuous sagging of materials from the cavity roof.

Based on the temperature distribution inside the furnace, lumps of quarts starts to melt in the region above the crater. With liquid silica's high viscosity around its melting point temperature, it will act like a glue for solid particles in the melt. This will create a dome shaped layer of silica melt and captured particles, making zone 2 in figure 2. This zone can be called the crater wall, because it lines the walls of the crater. As the process continues, silica melt and solid particles will be consumed by the chemical reactions occurring. Because of the low permeability of the crater wall the gas produced will go to the cavity, increasing the pressure, which ageing pushes the wall outwards. This combined with the lining of the wall being consumed by the reactions increases the cavity size. At a certain point the pressure inside the cavity becomes to high, and the cavity reaches its size limit. Stocking the furnace is a common procedure, which collapses the walls, and shrinks the size of the cavity.

3.3.2 Lining growth

During furnace excavations it has been showed that at the furnace bottom there is a porous layer of solid SiC particles. This layer being porous means that during operation of the furnace, these voids can be filled with liquid silicon. The shape, thickness and other physical properties of the layer is dependent on where in the furnace one looks.

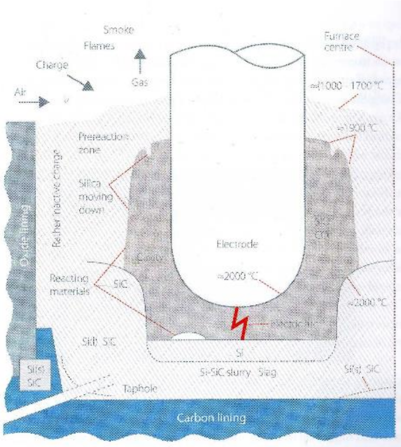

Figure 3 shows the zones, and formation of SiC deposits (Tangstad, 2013)

A furnace can accumulate SiC if the balance of the reactions or charge is not fulfilled. If the furnace is run with a excess of C in the charge, the surplus C will be deposited as SiC at the bottom. But when the charge is at balance, the SiC deposited can be consumed close to the electrode. The SiC deposited away from the electrode will not be able to react, so that in a rotating furnace there will over time be created a depression in the path of the electrodes. The walls of this circular trench is made by the SiC that has been deposited at times when the furnace has not been optimally run. (Schei et al. [1998]).

3.4 COMPOSITE ELECTRODE

The submerged-arc furnaces in Thamshavn use a type of electrode called the ELSA electrode. The electrodes are a modification of the more known Söderberg electrode. The principle of these electrodes is that they are continual. They are consumed at the bottom, and are at the same rate continually fed at the top. This ensures a continuous electrode (Johann-Chr. Leye, 2013).

The electrodes can also move up and down independently of each other. This feature allows the operator to modify the effect the height of the electrodes has on the process one by one.

The feeding of the electrodes are done by adding more of the different electrode materials at the top of the electrode as it gets pushed down to have a constant distance to the bottom of the furnace.

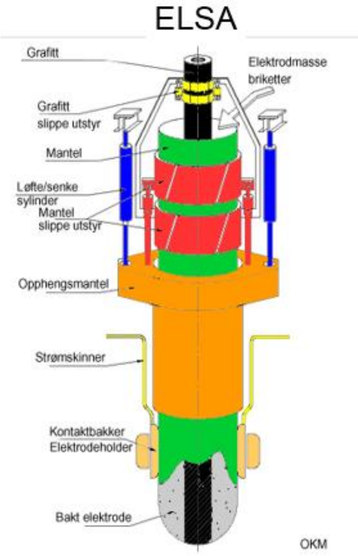

Figure 4 ELSA electrode (Elkem)

The electrodes consist of three main parts. The casing, the electrode paste and a graphite core. The different parts needs different ways to be added to the electrode.

3.4.1 Steel casing

The casings is made of steel, and its shape determine the shape of the electrode. These casings are shaped as a hollow circle and come in two half circles that is welded together with each other and the previous casings that was added. They have a diameter of about 170 cm, and each casing is about 70 cm tall.

3.4.2 Graphite core

In the centre of the electrode there is a massive graphite core. These graphite rods come as 3 meter long rods and have threads in both ends, so when a new rod is added it is simply screwed on. The diameter of one of these rods is about 70 cm whitch now leaves a void between the graphite core in the middle and the steel casings on the outer ring of the electrode. This void is filled with an electrode paste.

3.4.3 Electrode paste

The electrode paste used in Thamshavn comes in the form of briquettes, but electrode paste can come in different shapes and qualities. The paste mainly consists of carbon, but it also contain some binders (Sanghavi and Srivastava, 2010). This paste will fill the void between the graphite core and the outer steel casing. The paste will melt together and travel down with the rest of the electrode to the baking zone.

Figure 5 Electrode paste, in the form of briquettes (Elkem)

3.4.4 The baking zone

As the electrode travels down towards the furnace, the electrode will gradually get warmer and when the paste reaches temperatures above 100 °C it will start to melt together. The heat supplied to the electrode comes from a combination of the off-heat from the furnace and the electrical resistance from the current flowing in the electrode. When the electrode reaches temperatures around 1000 °C, it will enter what is called the baking zone. Here the electrode paste will start to solidify, and when the temperature increases even more the electrode eventually is fully baked, and becomes one solid electrode. (Schei et al., 1998)

3.4.5 Electrode tip position

At Elkem Thamshavn there is a system that indicates the electrode tip position for each electrode. The system is based on the hydraulic weight of each electrodes and an assumed shape of the electrode. The system then calculates the length based on the assumptions.

3.5 THE POT

The pot or the furnace body is a complex structure, even if its task is relatively basic. It is supposed to keep all the raw materials in place and provide an enclosed space so they can react. It also needs to be able to be opened, so one can get the fully reacted material out. The furnace body therefor needs to endure high temperatures, and a corrosive atmosphere for a long period, typically 10 to 20 years before it is rebuild. The pot is also continually rotating, and needs to be able to rotate both clockwise and counter-clockwise.

3.5.1 The lining

Since the lining has to endure such harsh conditions it has a very complex structure. The lining consists of five different layers. Figure 6 shows a cross-section of the constructed lining, with its five layers:

- Structural steel
- Morram
- Vic-60
- SiC-Paste
- K-Paste

All the properties for the materials are shown in table 1 below.

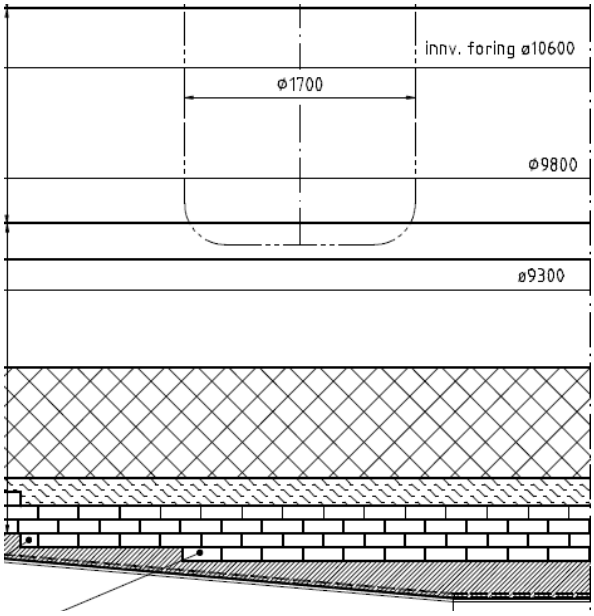

Figure 6 schematic of the lining (Elkem, 2012).

The outer layer, the structural steel layer, is like a steel shell that provides the furnace with a tough exterior and keeps the inner layers in place. It is also on this layer the different aids for operation of the furnace is installed. For example the necessary apparatus to keep the furnace rotating.

Next layer is a layer of a type of paste called Morram (Morganite Crucible Ltd). These bricks give the lining both structure and isolation.

The third layer, of Vic-60 layer is an isolating layer, and is the second thickest layer in the lining. This layer has the lowest thermal conductivity, and is therefore the biggest insulator in the lining.

Next there is a layer of silicon carbides. Since this layer is made of silicon carbide, it has the possibility of being manipulated, becoming thicker or thinner due to reactions in the furnace and lining.

Finally, the inner lining consists of a carbon paste, which is a layer that can withstand the high temperatures. As the silicon carbide layer, this layer can be controlled to grow or be eaten by changing how the furnace runs.

Table 1 Shows the specifics to the different layers in the lining (Garcia, 2015)

Material	*Heat capacity J/(kg*K)*	*Density (kg/m³)*	*Thermal conductivity w/(m*K)*	*Thickness (m)*
Structural steel	475	7850	44.5	0.025
Morram	1500	1500	12	0.1
Vic-60	1160	2500	2.2	0.4
SiC-Paste	980	2400	8	0.2
K-Paste	1900	1460	20	0.82

The different lining material physical properties presented in table 1 includes some uncertainties – and may change over the lifetime of the lining.

3.5.2 Thermocouple

Underneath the steel shell there different thermocouples are installed. These are in place so that it is possible to measure the temperatures in the bottom of the furnace, and are of great help. The thermocouples are placed in different circles underneath the pot, the side and tap holes of the furnace. Figure 7 shows a ring two of thermocouples, which is thermocouples 8 to 19, and are the ones this paper will focus on.

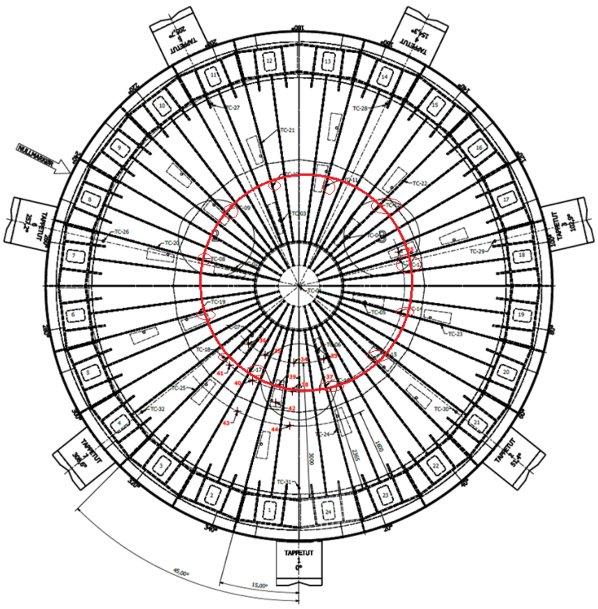

Figure 7 The furnace pot seen from above, with ring two of thermocouples marked with a red circle (Elkem)

3.6 HEAT TRANSFER

Heat transfer occurs because of a temperature-difference as a driving force and heat flows from the high- to the low-temperature region (Geankoplis and Geankoplis, 2003). There are three different basic mechanisms of heat transfer, conduction, convection and radiation.

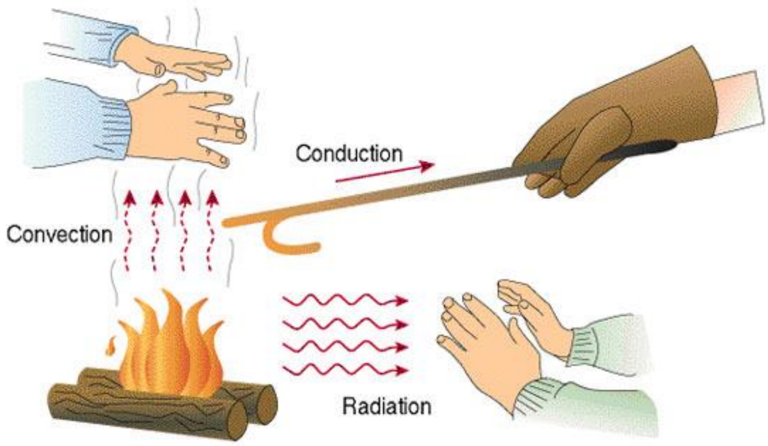

Figure 8 description of heat transfer (Secondary Science 4 all. 2015)

3.6.1 Conduction

"*In conduction, heat can be conducted through solids, liquids and gases. The heat is conducted by the transfer of the energy of motion between adjacent molecules"- (Geankoplis and Geankoplis, 2003) pp. 236*

The lining of a submerged-arc furnace is a good example of conduction heat transfer. The lining has a clear temperature gradient, with a high temperature inside the furnace, and the relative low temperature on the outside.

The equation COMSOL ® uses for heat-transfer trough solids is (8).

$$\rho C_p \, \partial T/\partial t + \rho \, C_p \, \mathbf{u} \cdot \nabla T = \nabla \cdot (k^* \, \nabla T) + Q \qquad (8)$$

In this equation, ρ stands density for the material, C_p for heat capacity at constant pressure and k for thermal conductivity for the material. T, t and Q are variables for temperature, time and heat transferred. Since this equation takes the gradient (∇) temperature, the equation can be used in three dimensions, x, y and z. Allowing it to be used to calculate the heat flowing through a solid, say the lining of a silicon furnace.

3.6.1.1 Heat transfer through solids

Thermal conductivity of homogeneous solids has a wide spectre. The difference between metallic solids and insulating non-metallic can be very high. The thermal conductivity (k) for copper (k=388) and rock wool (k=0,029) *(Geankoplis and Geankoplis, 2003)*, which is a big difference.

Energy or heat are conducted through solids by two mechanisms. One mechanism is present in all solids, heat is transferred through a solid by the transmission of energy vibrating between adjacent atoms. The second mechanism applies mostly to metallic solids. Here, free electrons in the material conduct heat, much like how electric energy is conducted. Lacking this last mechanism makes a solid more insulating, but what makes insulators like rock wool so effective is their porous structure. Rock wool have a lot of air trapped in void spaces, making its thermal conductivity close to that of air.

3.6.2 Convection

Heat transfer by convection implies that the heat is transferred by bulk transport and the mixing of macroscopic elements of a warm portion with a cold portion. Convection is also often refer to energy exchange between a solid surface and a fluid or a gas. This can again be split in two different groups, forced convection and free convection. Where forced convection could be a fan blowing cold air on the bottom surface of the furnace, and free convection being hot metal circulating inside the furnace over the colder inner lining.

An equation used to calculate the heat transfer between air and a substance is (9). This equation is from COMSOL ® and can be used to calculate the cooling rate air has on the bottom of the furnace lining.

$$-n \cdot (-k\nabla T) = h \cdot (T_{ext} - T) \qquad (9)$$

Here k and h are constants, standing for the thermal conductivity for the material and the heat transfer coefficient. T is a variable standing for temperature.

3.6.3 Radiation

Heat transfer in the form of radiation differs from the conduction and convection in the way that radiation do not need a physical medium in order to transfer heat. Radiation transfers heat by electromagnetic waves, in the same way electromagnetic light waves transfers light. The same laws for light governs the radiation transfer of heat. Examples of radiation is the sun heating the earth, and a heating lamp warming smokers outside a restaurant.

4 EXPERIMENTAL

4.1 COMSOL ®

The experiments ware done in the form of modelling. The programed used for these models was COMSOL ®, a multi physics modelling software. COMSOL Multiphysics® is a complex modelling software that has a wide range of different physics modules. In these experiments only the heat transfer module was used.

4.2 DESIGN

4.2.1 Drawing

First step was to draw the lining the heat was traveling through. This was done by creating a set of rectangles in a 2D axis-symmetric model. Each of the rectangles was set to be one of the materials used to build the lining. The original blueprint of the lining was used, resulting in 5 layers, and after some simulations it was decided to add a 6^{th} layer to compensate for the lack of isolation in the lining compared to the results from the actual furnace.

The 2D axis's-symmetric drawing had a radius of 2,5 m, which means the model will look like a cylinder cut out of the lining, going from top to the bottom, with a radius of 2,5 m.

Below, the six layers are listed with their respective specifications. The six layers in order from the bottom to the top are:

Table 2 Shows the specifics to the different layers in the lining, included the theoretical isolating layer

Material	*Heat capacity J/(kg*K)*	*Density (kg/m³)*	*Thermal conductivity w/(m*K)*	*Thickness (m)*
Structural steel	475	7850	44.5	0.025
Theoretical isolating layer	15000	5000	0.02	0.001
Morram	1500	1500	12	0.1
Vic-60	1160	2500	2.2	0.4
SiC-Paste	980	2400	8	0.2
K-Paste	1900	1460	20	0.82

4.2.2 Thermocouples

To get data out of the model, and to have a more complete picture of the heat travel, it was added 10 points in the lining that should symbolise thermocouples. In the program, they work as thermocouples as well, with the possibility to extract the temperature for each point and display them in graphs over time.

The thermocouples are located at the border of every layer, and in the middle of the thick layers. The different installed thermocouples have been named Model_TCx_x, where TCx is the location of the thermocouple it is supposed to be, for instance TC18. The last number is the distance in meters from the furnace lining. Making Model_TC18_0 the model version of the real TC 18. The coordinates of the thermocouple points are:

1. Model_TCx_1.546
2. Model_TCx_1.131
3. Model_TCx_0.726
4. Model_TCx_0.626
5. Model_TCx_0.526
6. Model_TCx_0.326
7. Model_TCx_0.126
8. Model_TCx_0.026
9. Model_TCx_0.025
10. Model_TCx_0

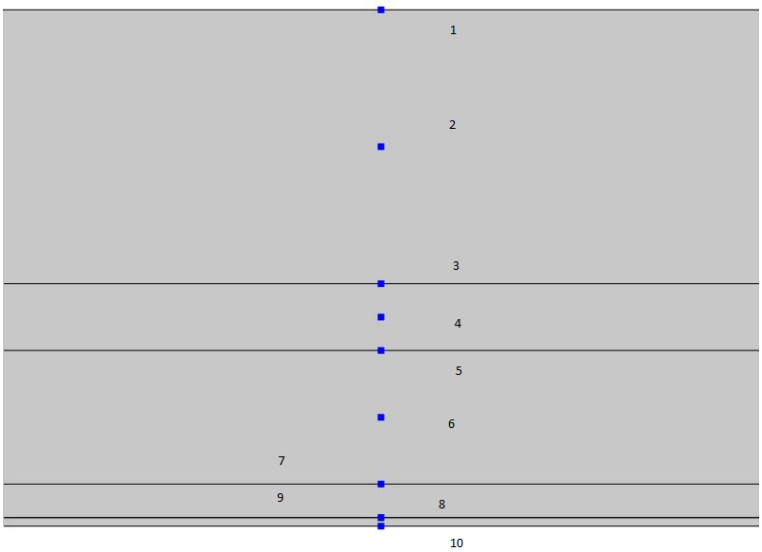

Figure 9 shows a picture of the lining drawn in COMSOL, with the 10 thermocouples

4.2.3 Isolating layer

As mentioned above, it was added a thin isolating layer to try to get closer to the real temperatures that are experienced at the real furnace. This layer was set to be 1 cm thick and have the following specifications:

*Heat capacity: 15000 J/(kg*K)*

Density: 5000 kg/ m^3

*Thermal conductivity: 0,02 W/(m*K)*

The different parameters for this layer were obtained by using Vic-60 as a reference and then by trial and error to get the same temperature for Model_TC9_0 as TC9 at 1800 °C inside the furnace. TC9 is on average 180 °C. The layer will be different for the different thermocouples due to variations in the furnace lining. On TC18 the lining appears even more isolating since the average temperature is lower, about 165 °C.

This layer was placed above the last layer made of structural steel, and it is expected to raise the temperature in the layers further up in the lining, since this layer will isolate both the heat from escaping and the cooling from below.

4.2.4 Energy

To have the model running it also needs to have an input of energy symbolising the furnace heat, and a cooling input symbolising the air-cooling at the bottom.

The way this was done for the energy going in was by applying a temperature at the top of the drawing. Saying that the border down to the start of the lining should be x K. This start temperature could then be made as a simple fixed temperature, or it could become an expression giving it variations. To model the different cases these in temperatures did become expressions with step functions, giving the expressions jumps from for example 2073 K to 2273 K and down to 1973 K.

The cooling was done by adding a function in COMSOL called heat flux. This flux is a convective heat flux, $q_0=h(T_{ext}-T)$ with a $h=35$ W/(m^2*K) and a T_{ext}= 15 [degC]+15. This function was added on the border of the bottom of the lining.

4.3 SIMULATIONS

The simulations were done in different ways. The parameters available are the length of the simulation and the length of each step. The final 4 simulations are showed both in results and the appendix.

In case one and 2, modelling incidents occurring at TC18 and TC9 in the real furnace are shown, with and without the isolating layer. The length of the simulation was 600 hours with a step size of 1 hour.

4.4 DATA

The data extracted from the simulations was made into graphs, displaying various thermocouples in the model lining over time. The main graphs displayed later under in the results are listed below with a short summary on how they where made.

4.4.1 TCx vs. Model_TCx_0

These graph shows the real temperature from a thermocouple from the bottom of the furnace, extracted trough the database at Elkem Thamshavn for a given time where there is a spike occurring. Then this plot is compared with the results from the simulation, and the temperature at Model_TCx_0, hopefully giving a good match.

This is the step where the furnace temperatures were decided. By trial and error the furnace temperatures were adjusted to obtain a similar curve as the incident occurring in reality. When the graphs overlapped to a satisfactory degree the furnace temperature was set, and the extraction and creation of the rest of data and graphs began.

4.4.2 Model_TCx_0 to Model_TCx_1,545

In the end it was crated a lot of these graphs. This graph shows all of the thermocouples placed in the lining. But to show the variations to all the thermocouples at a more detailed level the thermocouples are showed three and three, two and two, or simply by them self.

4.4.3 Time dealy Model_TCx_0 to Model_TCx_1,545

The setup to these graphs are much the same as the graphs for Model_TCx_0 to Model_TCx_1,545. The difference here is that the data for these graphs have been modified to plot the difference in temperature from a set point. This set point was picked to be when the temperature for the thermocouples had stabilized. The graph will then be plotted by using this formula:

Model_TCx_x 201 hours - Model_TCx_x at 200 hours = plotted point

Model_TCx_x 202 hours - Model_TCx_x at 200 hours = next plotted point

And so on.

4.4.4 Extra

The graphs that go under extra is a combination of a couple of graphs covering the variation of furnace parameters. For instance electrode passing, electrode load and electrode point position. These graphs have all their data gathered from the Elkem Thamshavn database and are measurements from the furnace.

5 CASE ONE

5.1 TC18 IN SEPTEMBER

In September 2014 there was a spike in temperature for thermocouple 18. This incident will be called case one. Figure 10 below shows the temperature over time in the period. The temperature increased 20 °C, from an average of 164 °C to 184 °C. The thermocouple was passing under electrode 2 at the time of the temperature spike. In this chapter, the results from the simulations are listed in the form of graphs as explained in the experimental chapter.

Figure 10 shows the temperature over time for TC18

5.2 WITH ISOLATING LAYER

5.2.1 Summary

In this section, the data from the simulations with the isolating layer is showed.

The furnace temperature starts at 1627 °C and is raised 300 °C. This temperature is still not realistic for the real furnace. This is because the isolating layer is designed for case two, the same incident but accruing over TC9. Thermocouple TC9 has a higher average temperature, with its 180 °C, while TC18 has a lower, 160 °C.

It takes Model_TC18_0 about 18 hours to experience a 5 °C increase in temperature with the 300 °C increase in the furnace temperature.

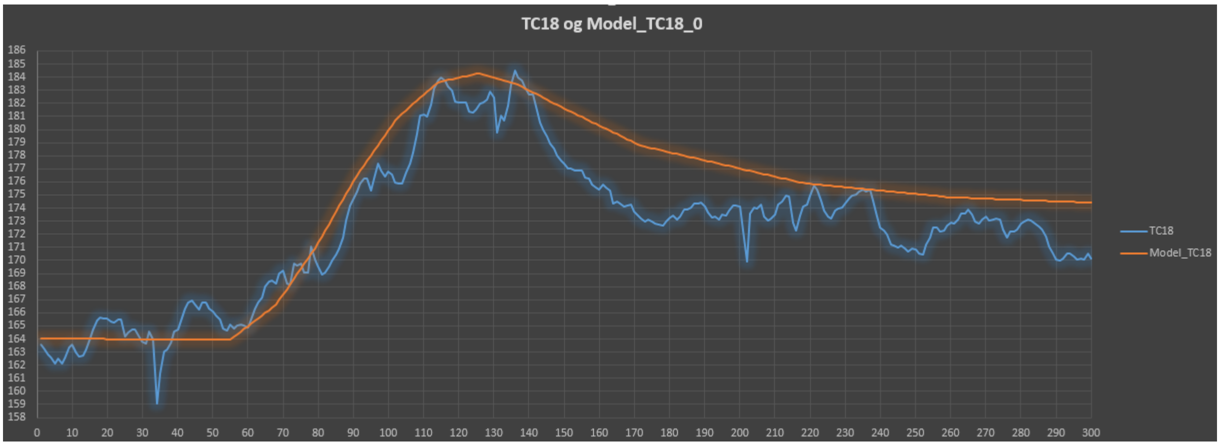

Figure 11 shows TC18 and Model_TC18_0, modelled with isolating layer

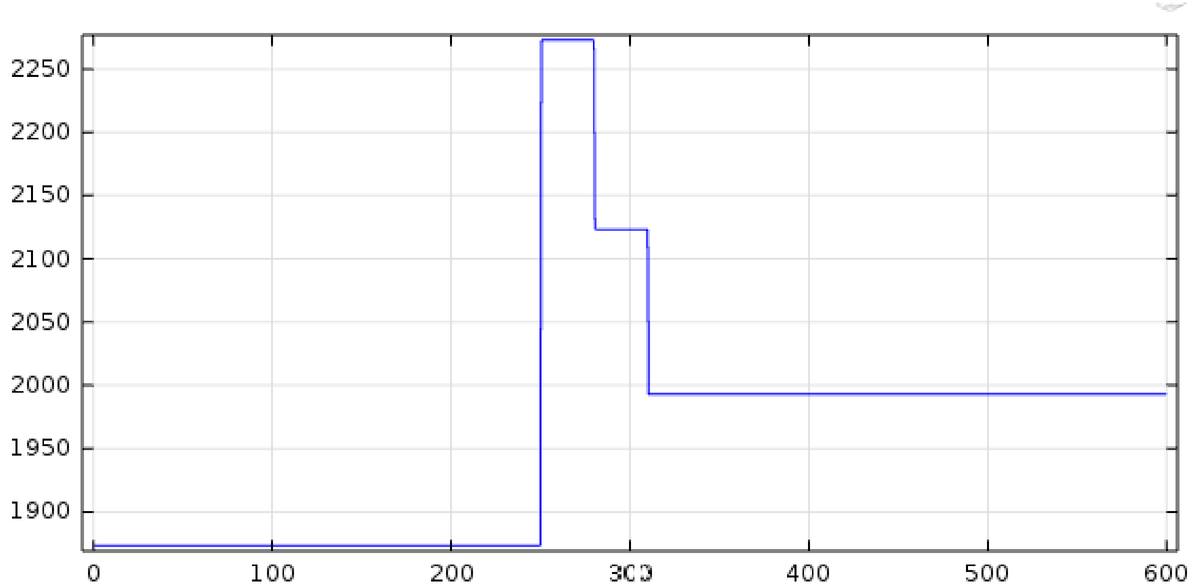

Figure 12 shows the furnace heat from COMSOL, with the isolating layer. Temperature showed in Kelvin.

5.2.2 Lining temperatures

The range of the lining temperatures goes from 1600 °C for Model_TCx_1,545 and down to 164 °C for Model_TCx_0. Figure 13 shows all the thermocouples installed in the model, it is clear that the layers isolate at different rates. Moreover, some of the thermocouples have been group up better show how the temperature changes over time. Figure 14 shows the top five thermocouples to the modelled lining. These five thermocouples standard difference is 300 °C, but as the furnace temperature change, it can be seen that the reaction time to the thermocouples come in to play, and the curves smooth out some. If one goes lower in the lining, and look at figure 15, we see that the isolating effect of the lining is higher. Here, the span between Model_TCx_0,325 and Model_TCx_0,125 is about 450 °C . Model_TCx_0,325 is placed in the middle of the Vic-60 layer, while Model_TCx_0,125 is placed on the border between the Vic-60 layer and Morram layer. In chapter 6.3.2 the temperature rages done with and without the isolating layer will be compared, since the isolating layer affects the temperature in these thermocouples. In Figure 16 thermocouple Model_TCx_0,026 is alone.

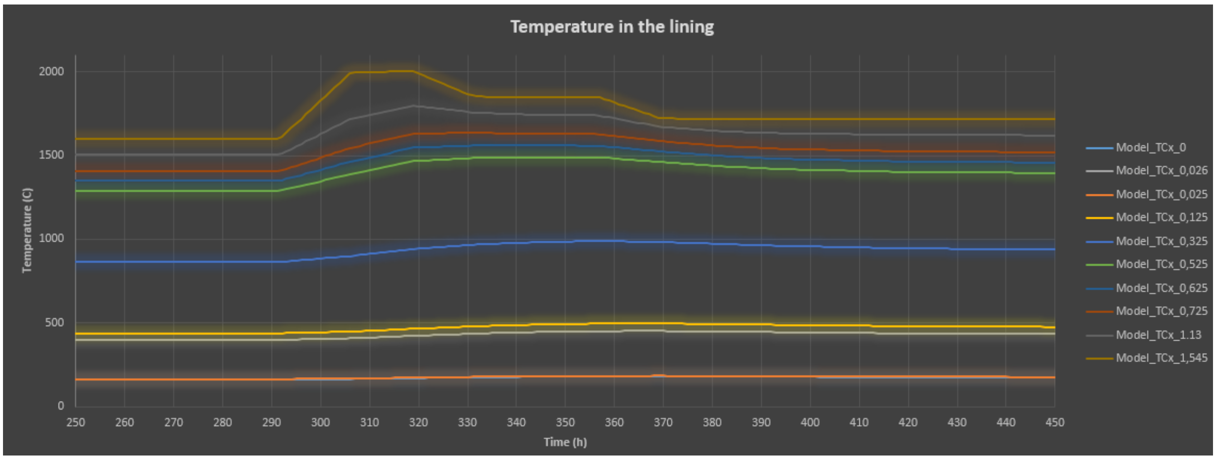

Figure 13 shows the lining temperature for Model_TC18_0 - Model_TC18_1.545 with the isolating layer

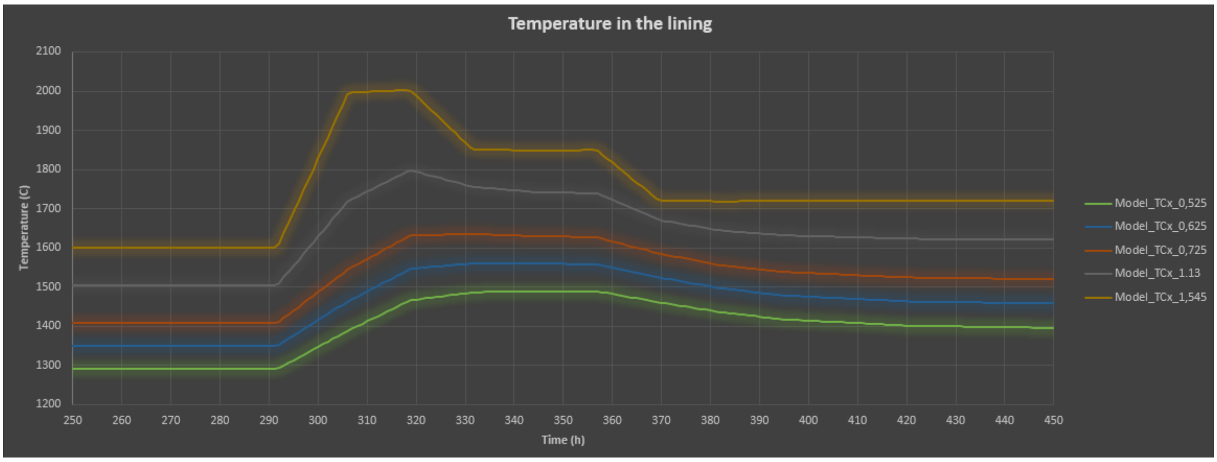

Figure 14 shows the lining temperature for Model_TC18_0.525 - Model_TC18_1.545 with the isolating layer

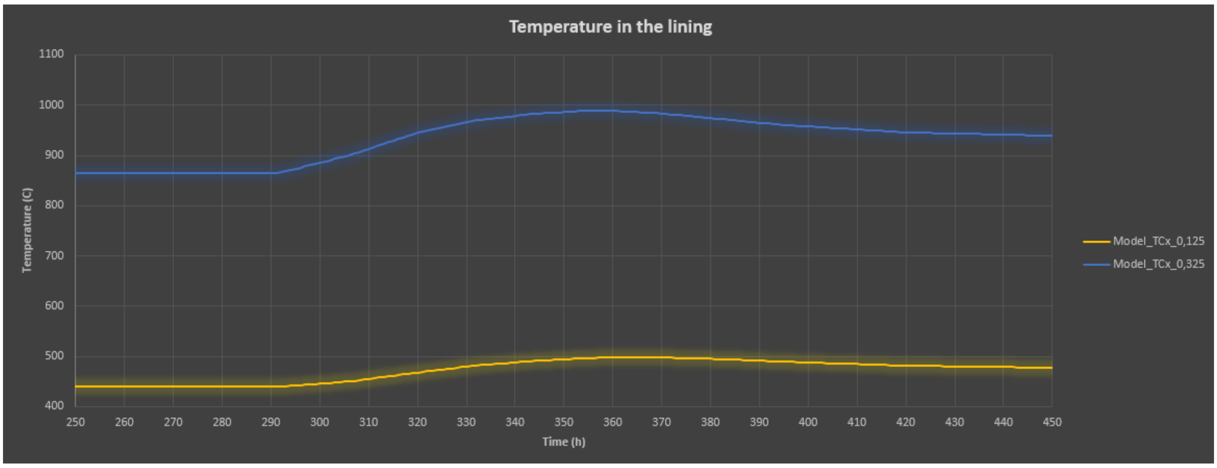

Figure 15 shows the lining temperature for Model_TC18_0.225 - Model_TC18_0.325 with the isolating layer

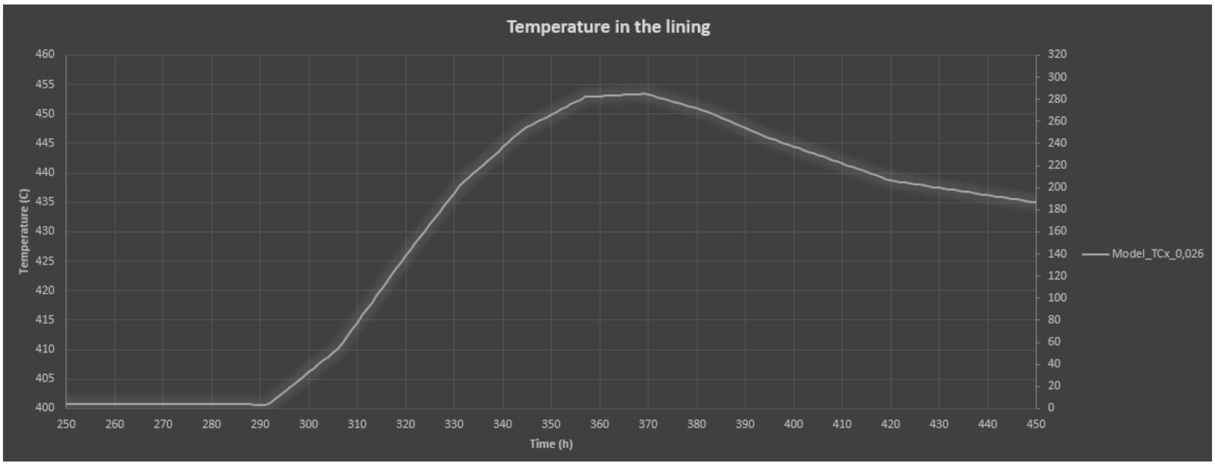

Figure 16 shows the lining temperature for Model_TC18_0.026 with the isolating layer

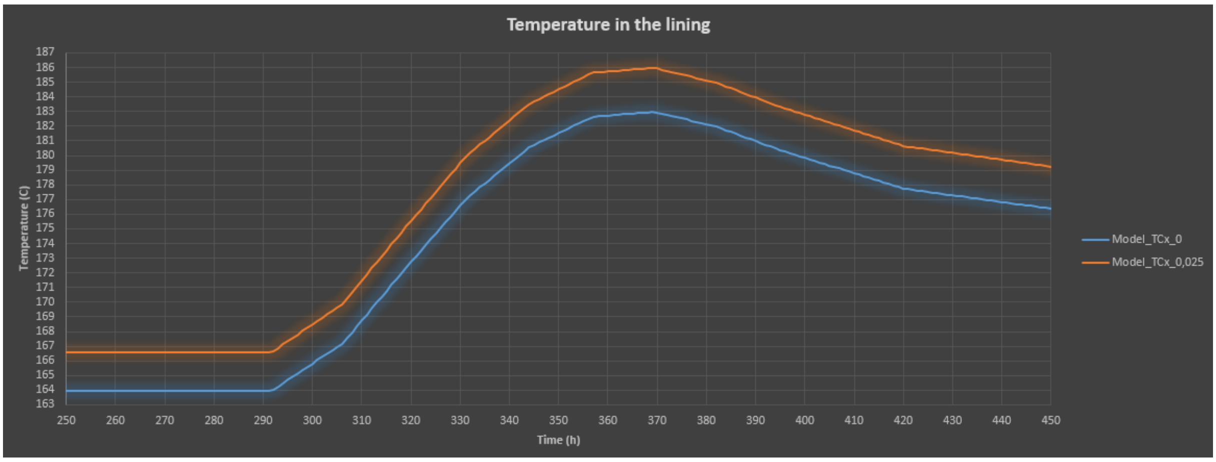

Figure 17 shows the lining temperature for Model_TC18_0 - Model_TC18_0.025 with the isolating layer

5.2.3 Reaction time in the lining

Below are the graphs that best displays the time delay or reaction time to the different thermocouples down into the lining. Figure 18 shows all the thermocouples in one graph, giving a good insight to the big delay that is occurring. Thermocouple Model_TCx_1,545 whitch is the furnace temperature has its max temperature at around 45 hours, with a steady rise from the start at 20 hours. While the bottom thermocouple Model_TCx_0 does not reach its max temperature before around 90. This means that the bottom thermocouple do not react fully to the incident occurring inside the furnace before almost two days has passed.

Figure 20 shows the bottom four thermocouples, and their reaction time. It can be seen that Model_TCx_0 needs 17 hours to experience a 5 °C rise. While only 12,5 cm further inside the lining, thermocouple Model_TCx_0,125 has a reaction time of five hours on the same five °C .

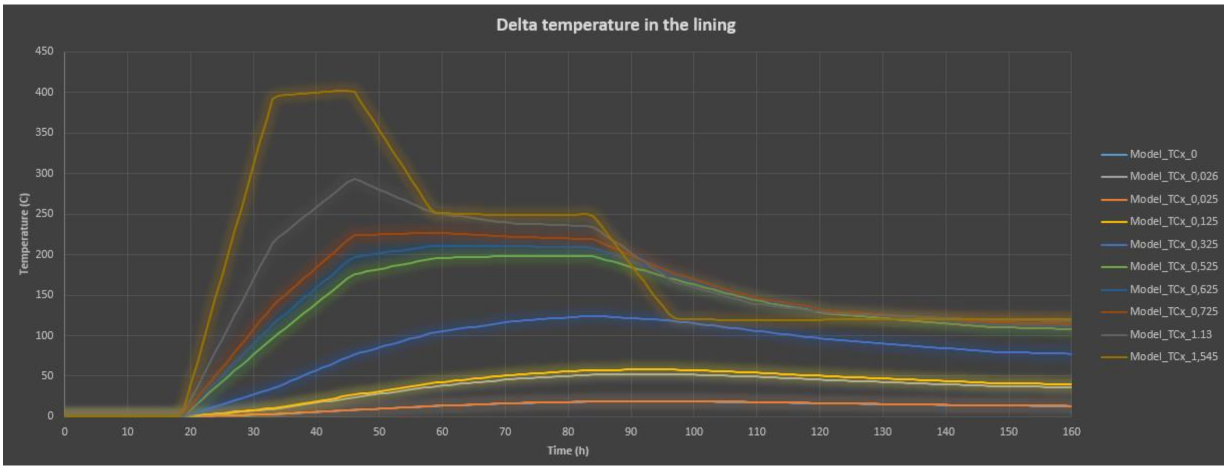

Figure 18 Shows delta temperature over time for Model_TC18_0 - Model_TC18_1,545 with the isolating layer

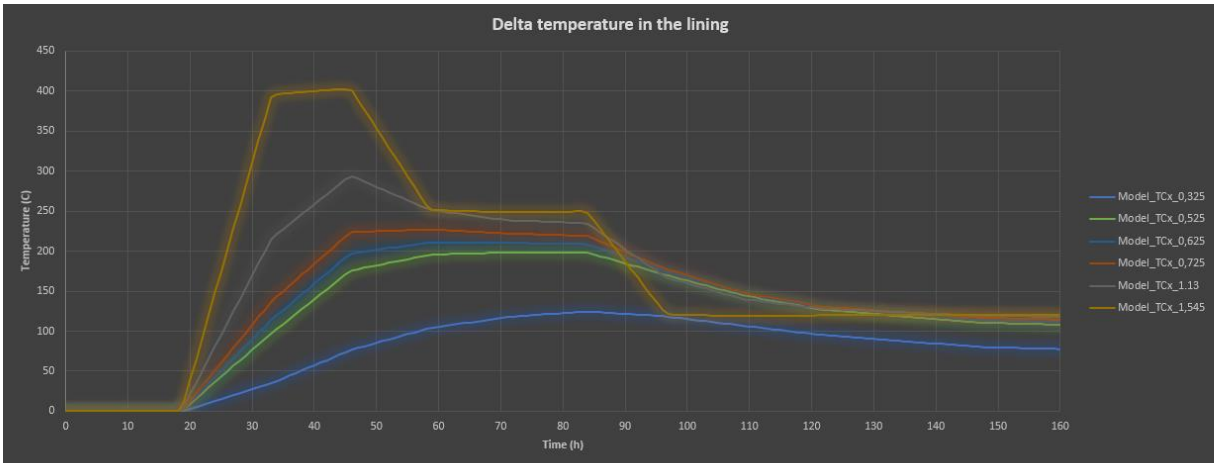

Figure 19 Shows delta temperature over time for Model_TC18_0.325 - Model_TC18_1,545 with the isolating layer

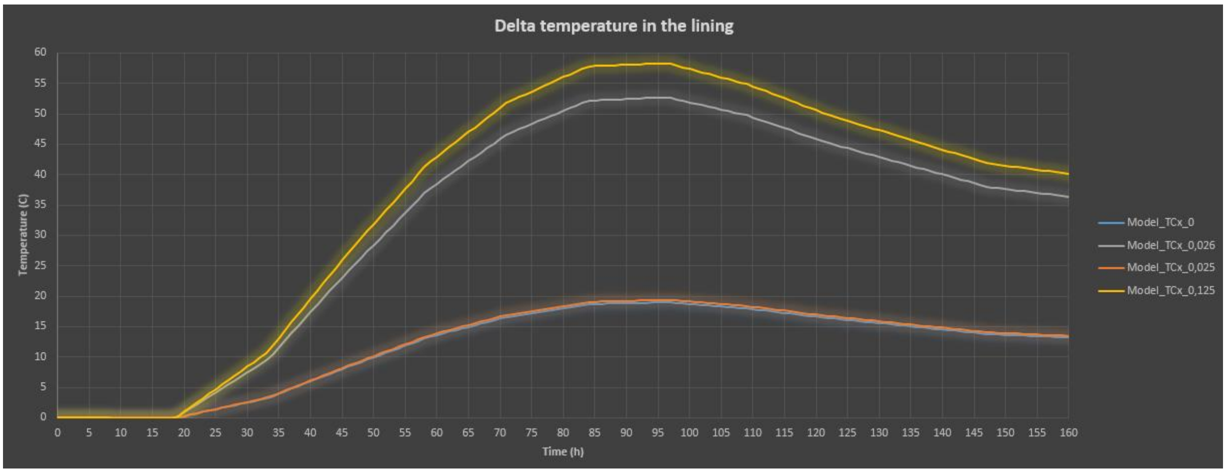

Figure 20 Shows delta temperature over time for Model_TC18_0 - Model_TC18_0,125with the isolating layer

5.3 WITHOUT ISOLATING LAYER

5.3.1 Summary

In this section the data from the model without the isolating layer is shown.

Here the furnace temperature is a very unrealistic 1400 °C, and the furnace temperature rise needed to recreate the incident is 240 °C.

The time it takes for Model_TC18_0 to experience a 5 °C raise is about 17 hours.

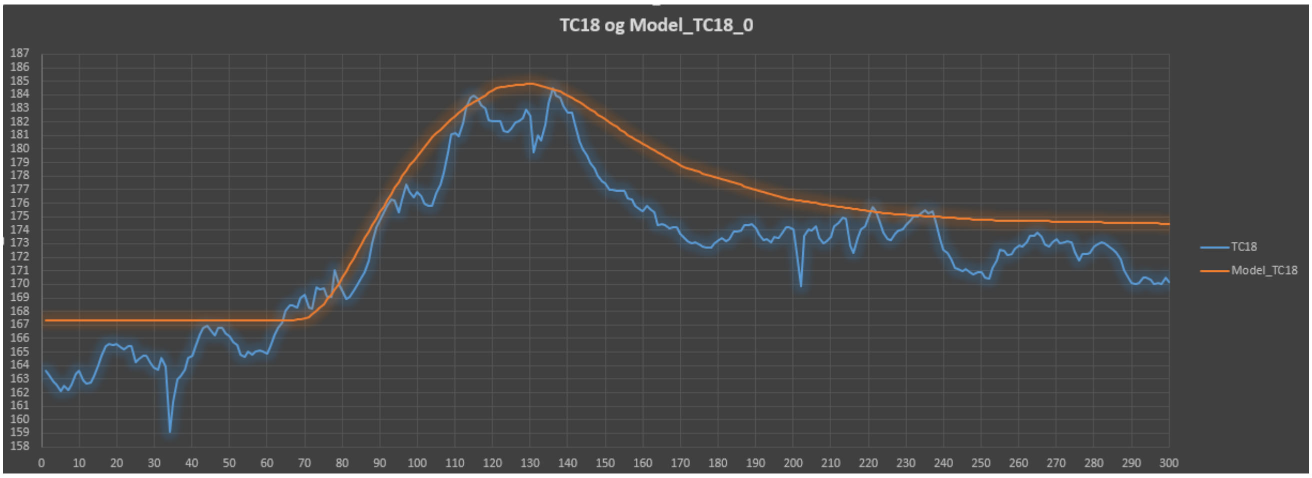

Figure 21 shows TC18 and Model_TC18_0

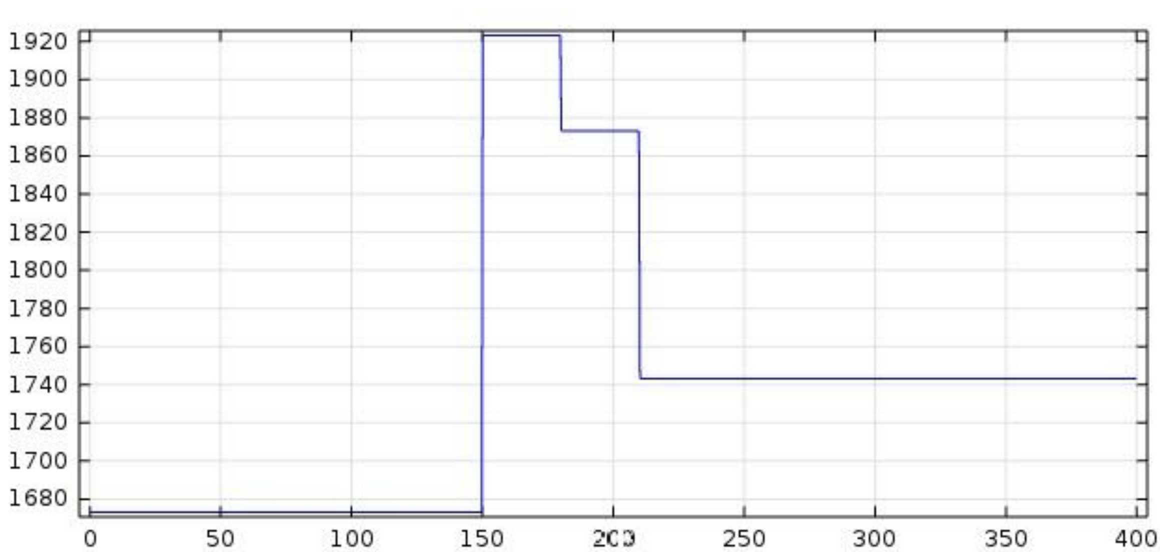

Figure 22 shows the furnace heat from COMSOL, without the isolating layer

5.3.2 Lining temperatures

The next five figures shows the temperature over time, same as in chapter 6.2.2, but this time without the isolating layer. It can be seen that in the simulations without the isolating layer the temperature range is from only 1400 °C for Model_TCx_1,545 down to 166 °C for Model_TCx_0, almost the same temperature as Model_TCx_0 for the simulation done with the isolating layer. These temperatures should be the same, since they are both models of the same case. However, with a difference of only 2 °C they are accepted as the same. Figure 23 is as its twin, the same graph in chapter 6.2.2, split to show the variations in temperature with more detail. There are here however four figures instead of five, due to that the temperature range is less, and easier to display.

In this simulation, one can now see the effect of the isolating layer. Figure 26 shows the bottom three thermocouples. As one can see they are now closer to each other in temperature. Meaning that the lack of the isolating layer makes the temperature range less, especially here in the lower part of the lining. The effect of the isolating layer is therefore exactly like it sound, it is isolating. It raises the temperature to the thermocouple above in the lining, while it shields thermocouples below.

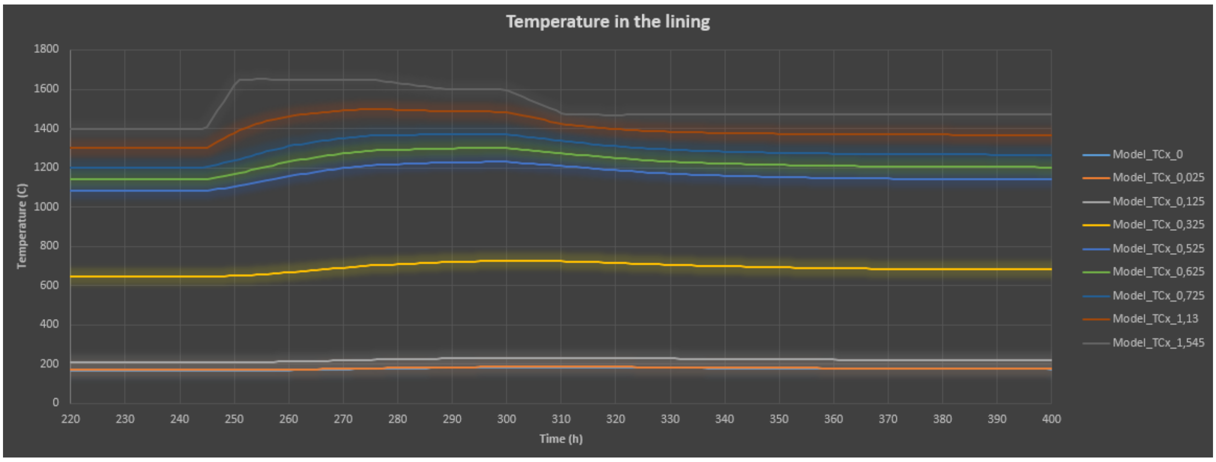

Figure 23 shows the lining temperature for Model_TC18_0 - Model_TC18_1.545

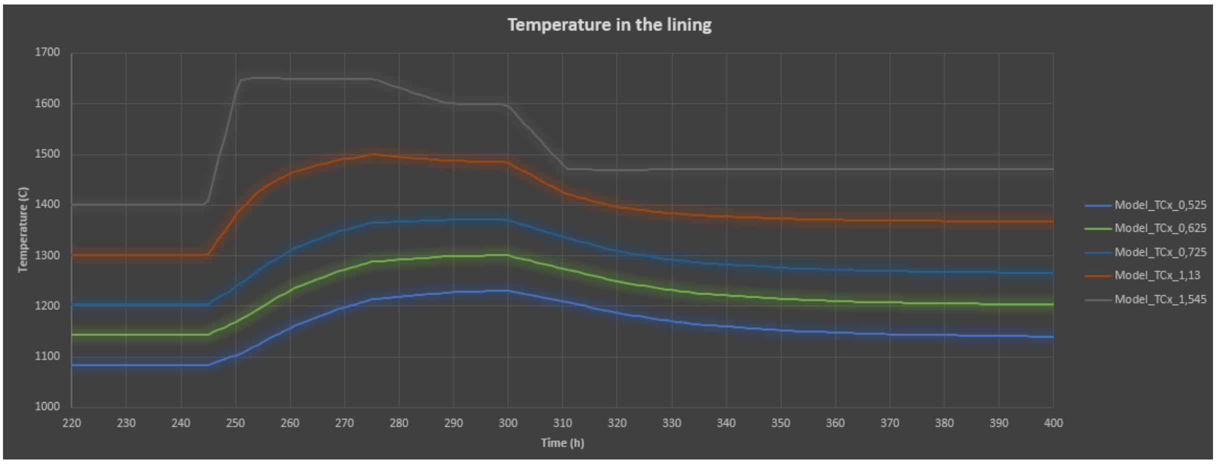

Figure 24 shows the lining temperature for Model_TC18_0.525 - Model_TC18_1.545

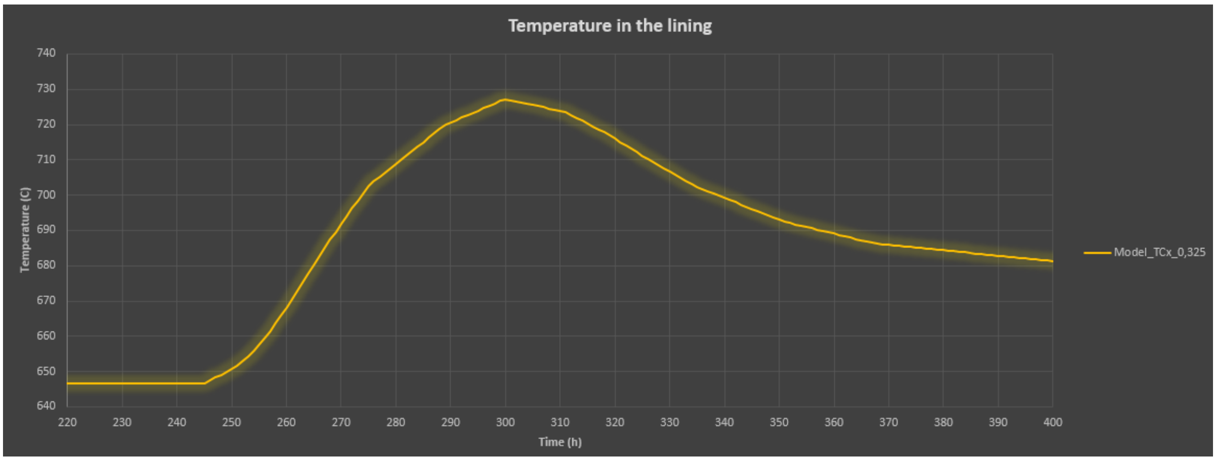

Figure 25 shows the lining temperature for Model_TC18_0.325

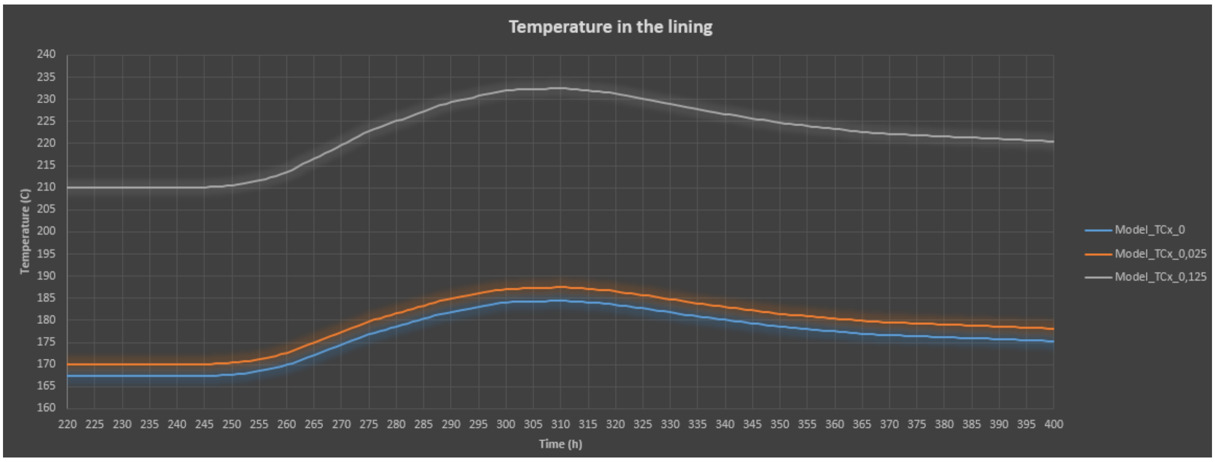

Figure 26 shows the lining temperature for Model_TC18_0 - Model_TC18_0.125

5.3.3 Reaction time in the lining

In figure 27 to 29, the reaction time to the simulation is showed. The results is similar to the results happening in 6.2.3, but since this simulation do not have the theoretical isolating layer the results are a bit different.

Model_TCx_1,545 reaches its max temperature in 5 hours, while Model_TCx_0 needs 66 hours to reach max temperature, and holds this temperature for only 5 hours, while Model_TCx_1,545 holds its max temperature for 25 hours. This is of course the intension to the isolating effect from the lining. However, the result is a slow reaction time for the bottom thermocouple.

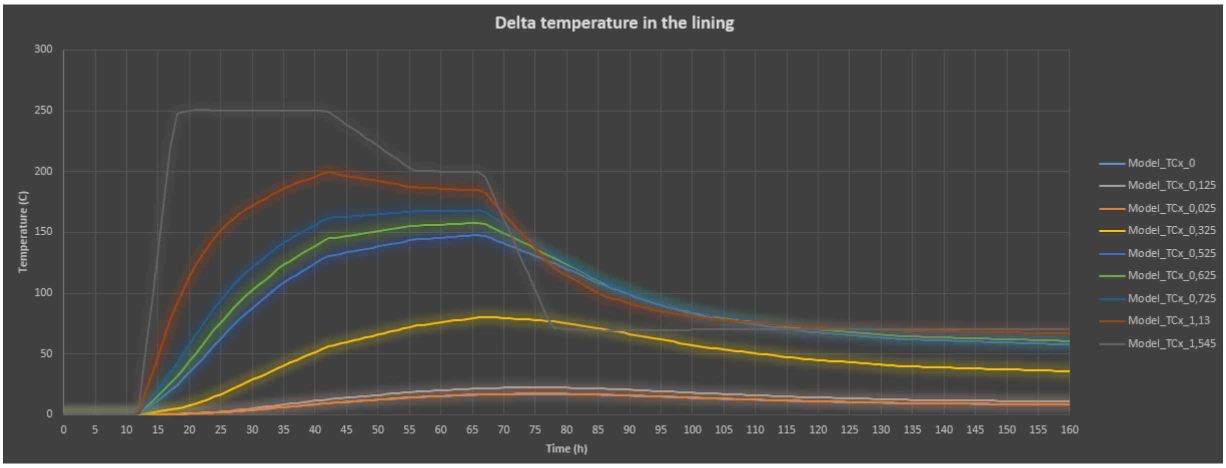

Figure 27 Shows delta temperature over time for Model_TC18_0 - Model_TC18_1,545

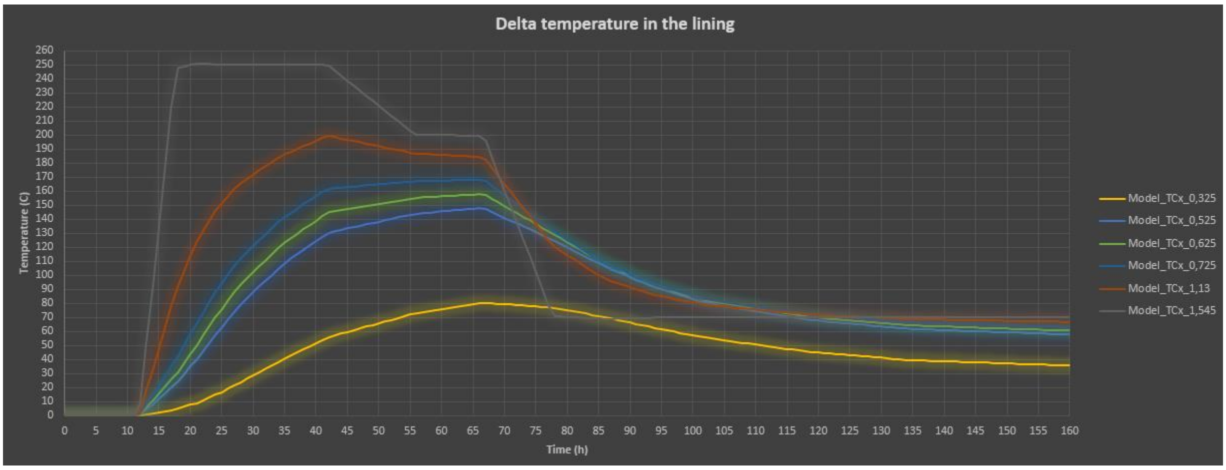

Figure 28 Shows delta temperature over time for Model_TC18_0.325 - Model_TC18_1,545

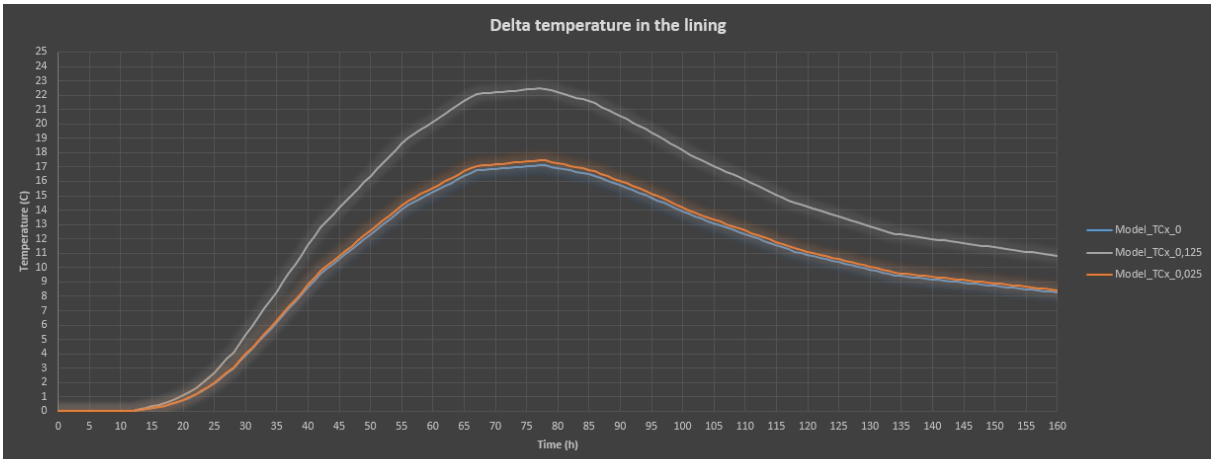

Figure 29 Shows delta temperature over time for Model_TC18_0 - Model_TC18_0.025

5.4 EXTRA

Below here figure 30 and 31 shows other parameters occurring in the furnace in the same period. Important parameters like the electrode position compared to the position of the thermocouple and the electrode tip position are displayed in figure 31. It can be seen that the temperature increase is happening when the thermocouple is passing electrode number two, and that the electrode tip position is very low when the electrode has passed thermocouple 18.

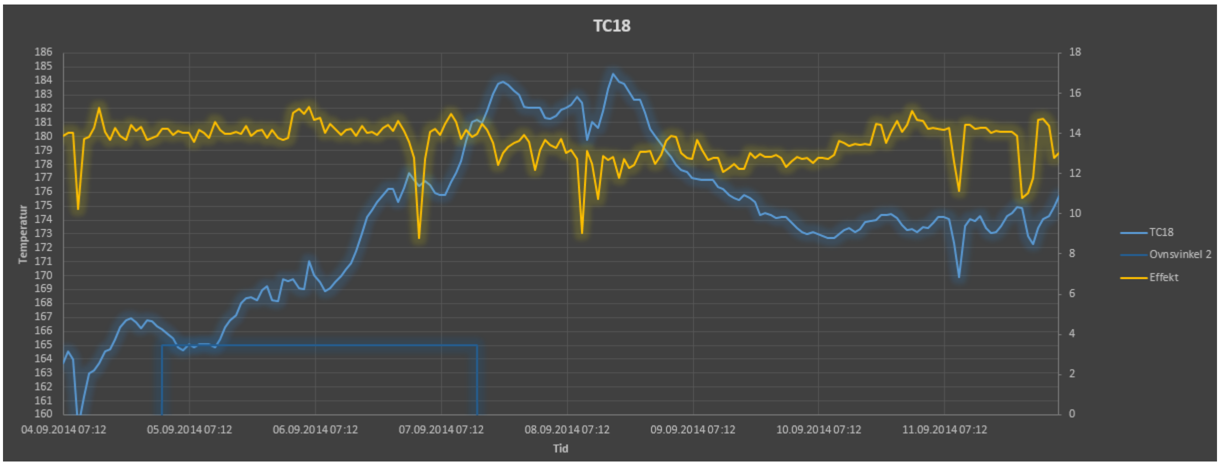

Figure 30 Shows the electrode position, furnace load and TC18 for the furnace

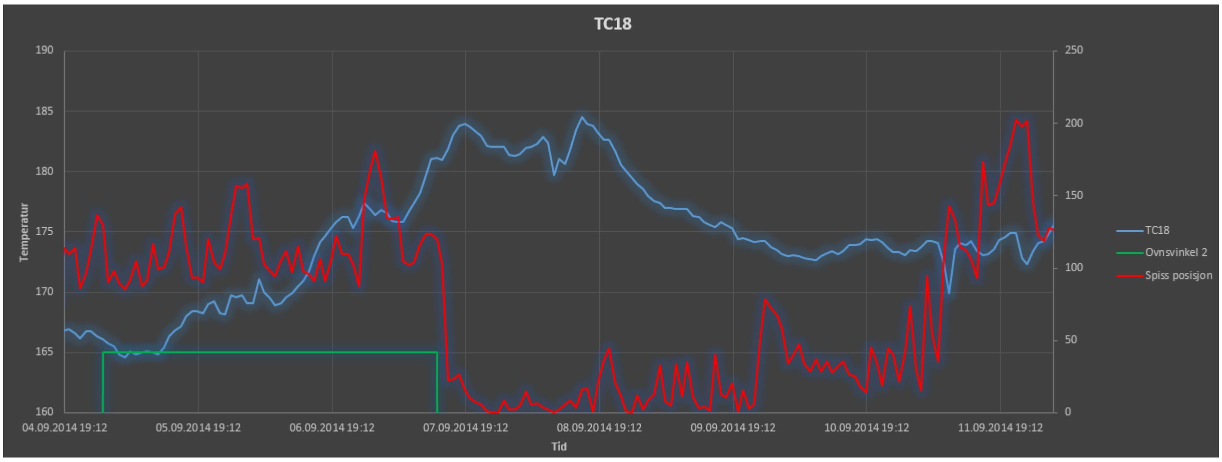

Figure 31 Shows the electrode tip position, electrode poisition and TC18

6 CASE TWO

6.1 TC9 IN SEPTEMBER

Case two is from September 2014 as well as case one. This spike occurred on TC9, and this incident will be called case two. Figure 32 shows the temperature to thermocouple 9 over time in the period of the incident. A clear rise in temperature is occurring, and the temperature goes up 17 °C from 180 °C to 197 °C. If one compare this to case one, and thermocouple 18, it can be seen that the average temperature here is about 20 °C higher. But still the thermocouple is experiencing a spike in temperature of about the same magnitude as thermocouple 18. At the time of the spike thermocouple 9 is passing under electrode 1, as shown in figures 55.

In this chapter the results from the simulations of case two are listed in the form of graphs as explained in the experimental chapter.

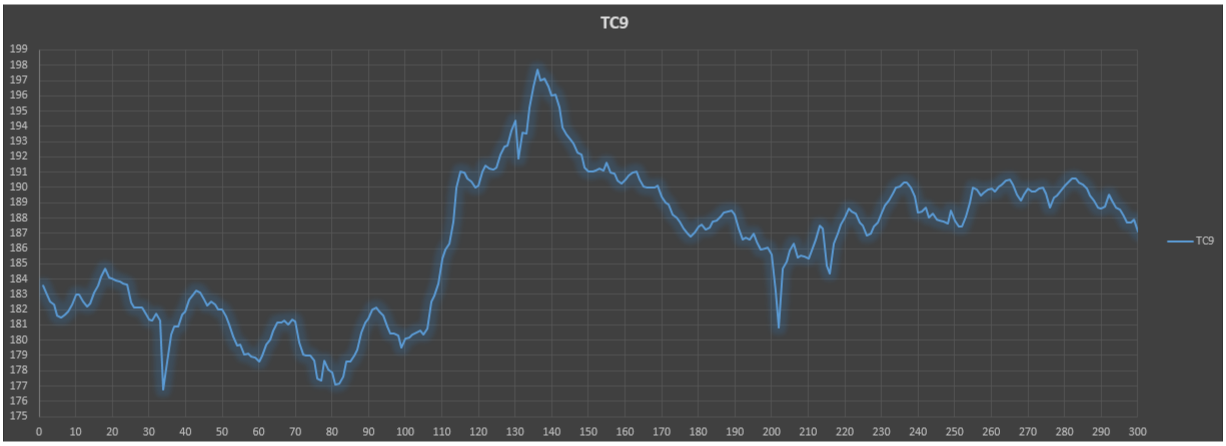

Figure 32 shows the temperature for TC9 over time

6.2 WITH ISOLATING LAYER

6.2.1 Summary

In this section the results from the simulation of the furnace with the isolating layer is showen.

The furnace holds a steady 2000 K or 1727 °C, and to fit the model to the curve of the real data a temperature increase of 450 is needed for the furnace temperature.

It takes Model_TC9_0 about 25 hours to show a 5 °C increase in temperature.

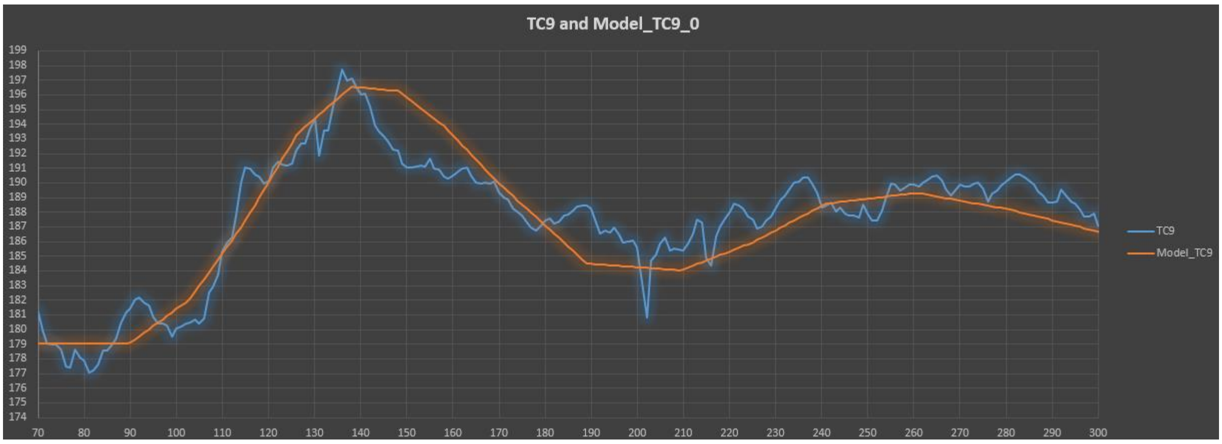

Figure 33 shows TC9 and Model_TC9_0

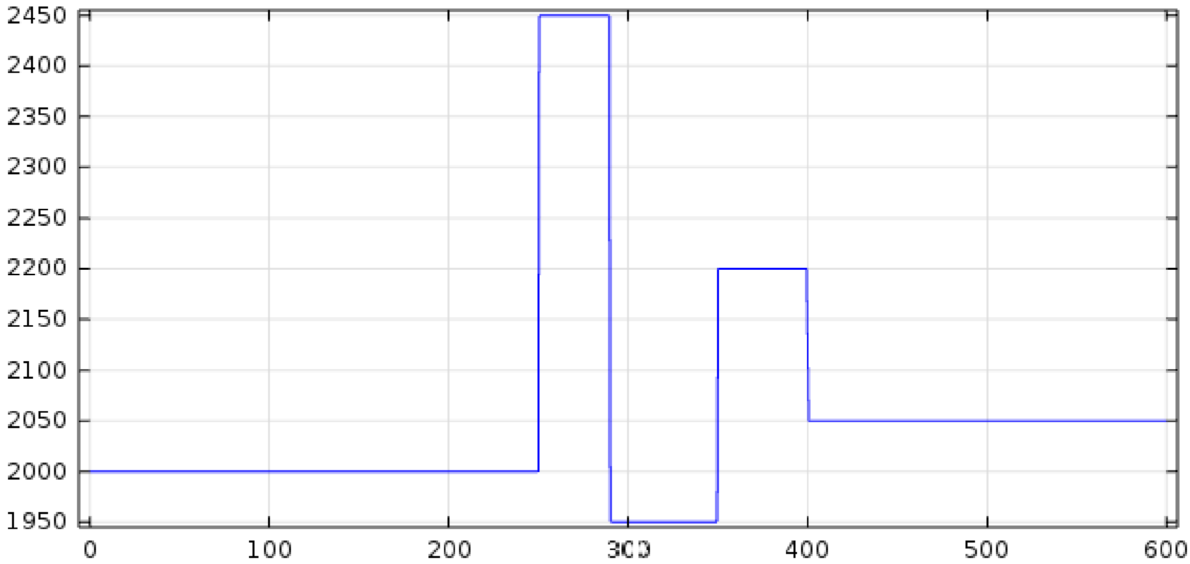

Figure 34 shows the furnace heat from COMSOL, without the isolating layer

6.2.2 Lining temperatures

Figure 35 to 39 shows the lining temperatures for the simulation with the isolating layer for case two. They are structured the same way as in case one. The range of the lining temperatures goes from the start temperature of 1727 °C for thermocouple Model_TCx_1,545 and down to 179 °C for the bottom thermocouple Model_TCx_0. If one compare this temperature to the temperatures shown in figure 3, it can be argued that this is a close to realistic temperature for the top lining to have. Figure 35 is split up in four more detailed graphs, showing the 10 different thermocouples downward in the lining. Again, it can be seen in figure 36 the first meter of the lining do not have a big isolating effect. Moreover, in figure 39 that the difference in temperature between the bottom side and the top side of the structural steel layer is only 3 °C.

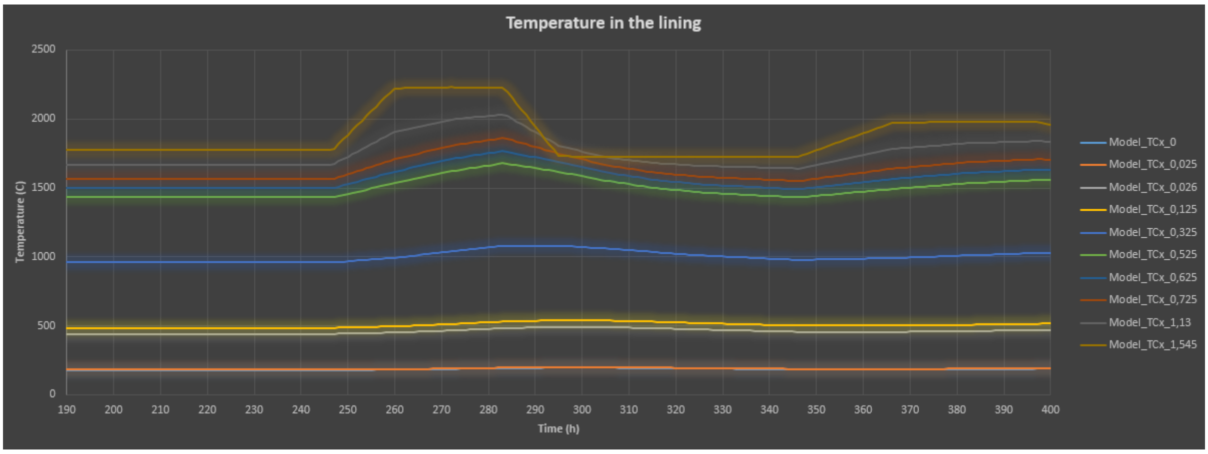

Figure 35 shows the lining temperature for Model_TC9_0 - Model_TC9_1.545

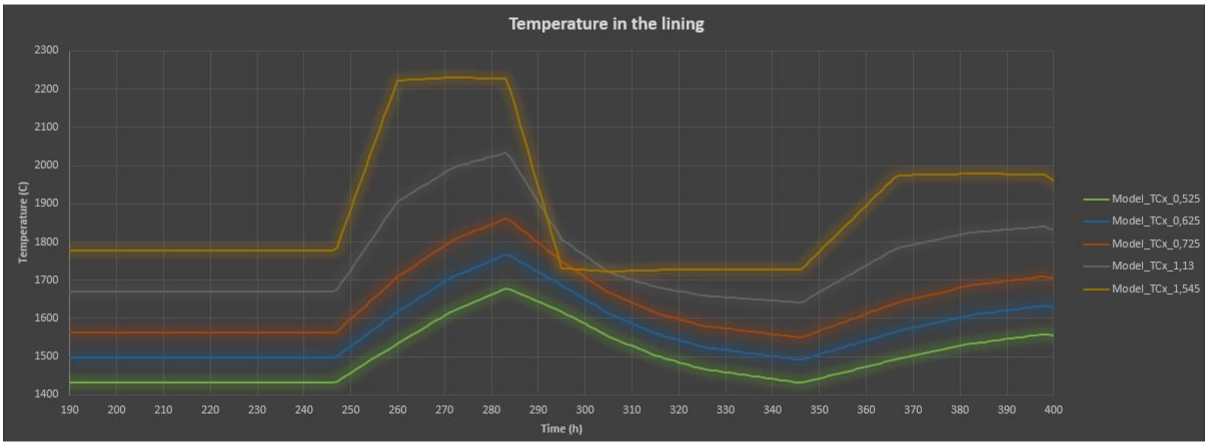

Figure 36 shows the lining temperature for Model_TC9_0.525 - Model_TC9_1.545

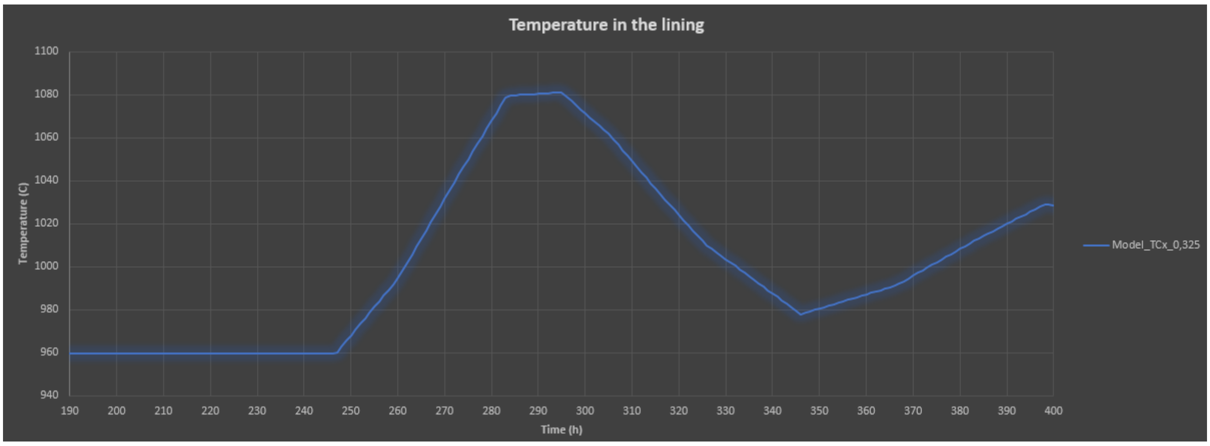

Figure 37 shows the lining temperature for Model_TC9_0.325

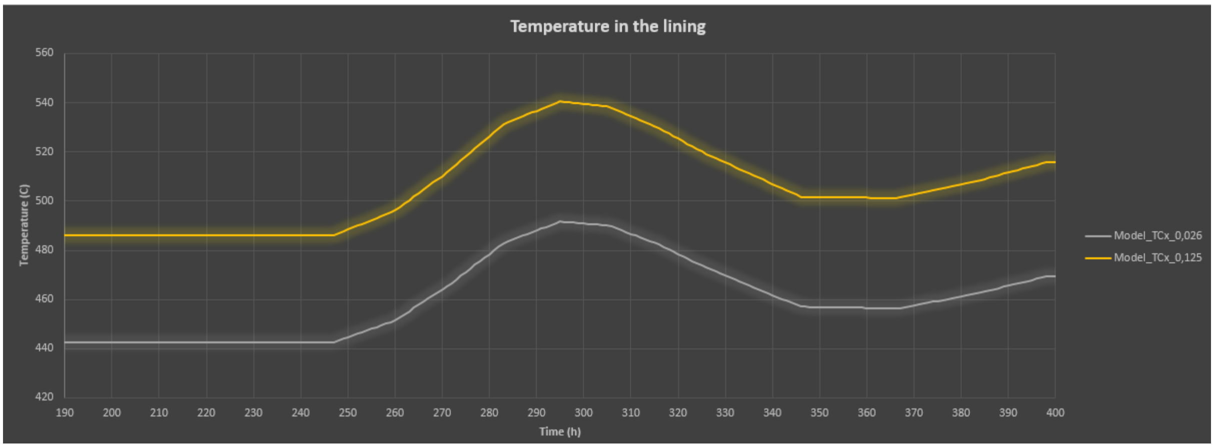

Figure 38 shows the lining temperature for Model_TC9_0.026 - Model_TC18_0.125

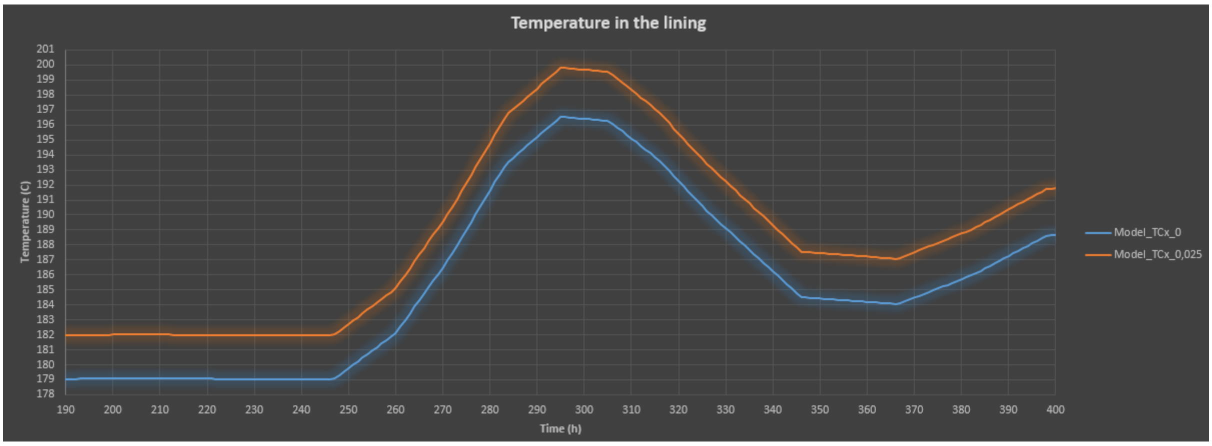

Figure 39 shows the lining for Model_TC9_0 and Model_TC9_0.025

6.2.3 Reaction time in the lining

Here it can be seen the delta temperature graphs for case two with the isolating layer. Figure 40 shows how the reaction to the thermocouples when the furnace temperature drops after an initial spike. It can be seen that the drop is registered very fast, but the thermocouples downwards in the lining holds the temperature longer, and have a less steep curve than the thermocouples higher up. As mentioned in 7.2.2 the difference between Model_TCx_0 and Model_TCx_0.025 is very low, and that is very clear to see here in figure 43.

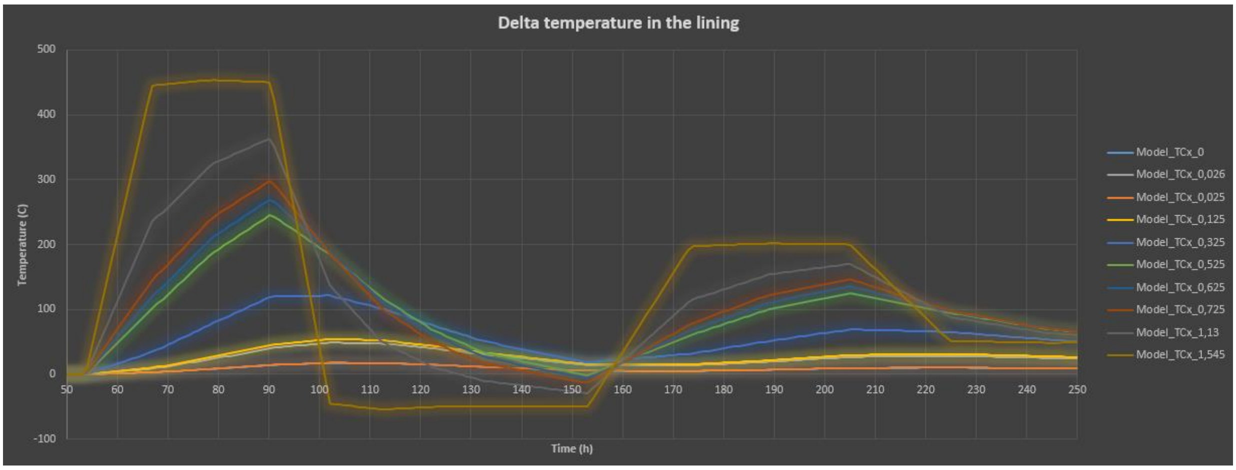

Figure 40 Shows delta temperature over time for Model_TC9_0 - Model_TC9_1,545

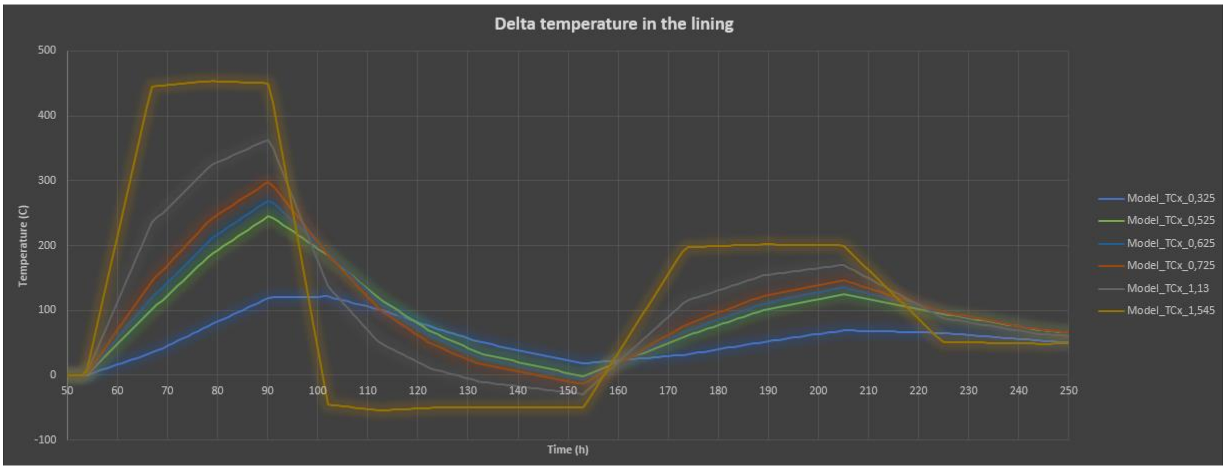

Figure 41 Shows delta temperature over time for Model_TC9_0.325 - Model_TC9_1,545

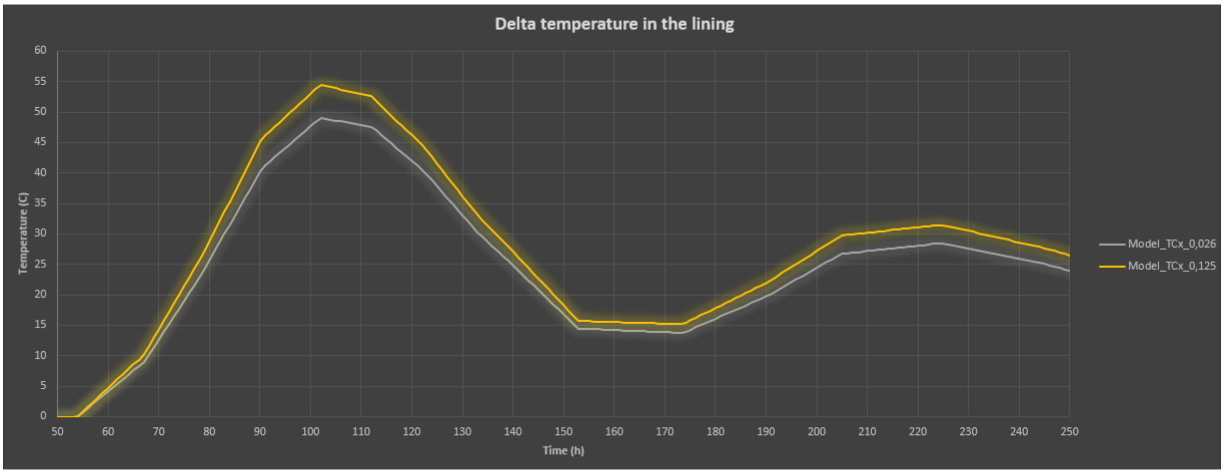

Figure 42 Shows delta temperature over time for Model_TC9_0.026 - Model_TC9_0.125

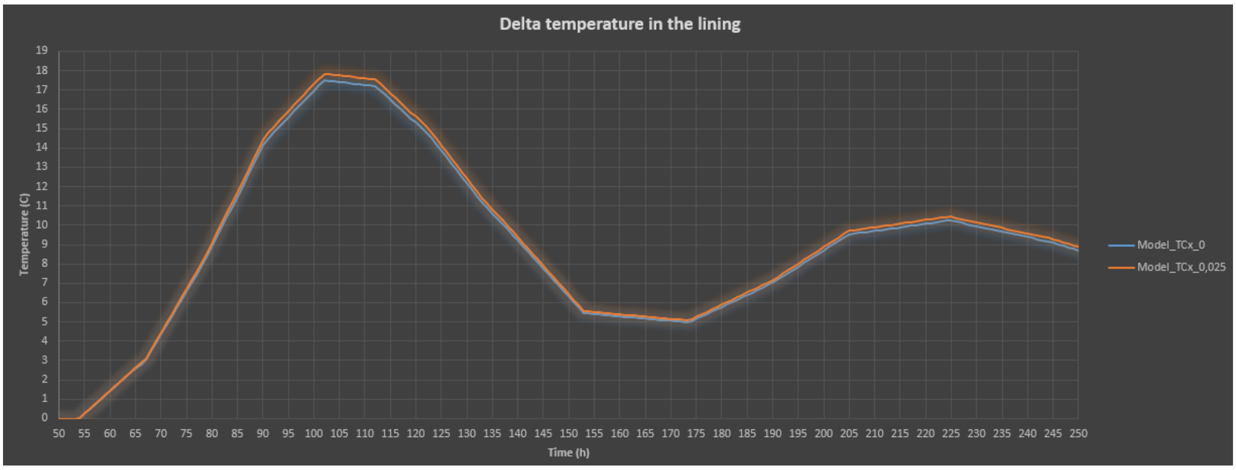

Figure 43 Shows delta temperature over time for Model_TC9_0 and Model_TC9_0.025

6.3 WITHOUT THE ISOLATING LAYER

6.3.1 Summary

In this section the results from the simulation of the furnace without the isolating layer is shown.

The furnace holds a steady 1800K or 1527 °C, and to fit the model to the curve of the real data a temperature increase of 250 °C is needed for the furnace temperature.

It takes Model_TC9_0 about 28 hours to show a 5 °C increase.

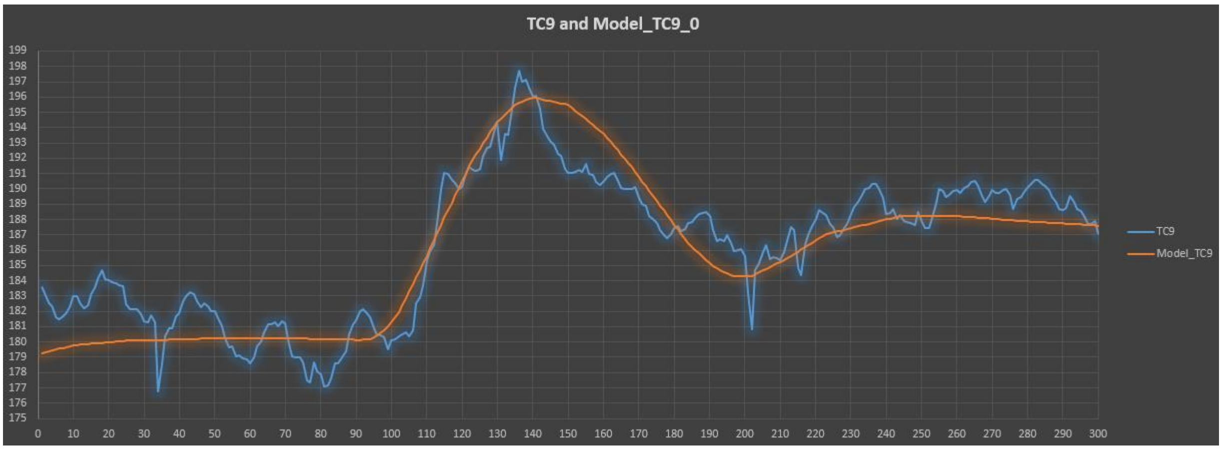

Figure 44 shows TC9 and Model_TC9_0, modelled without the isolating layer

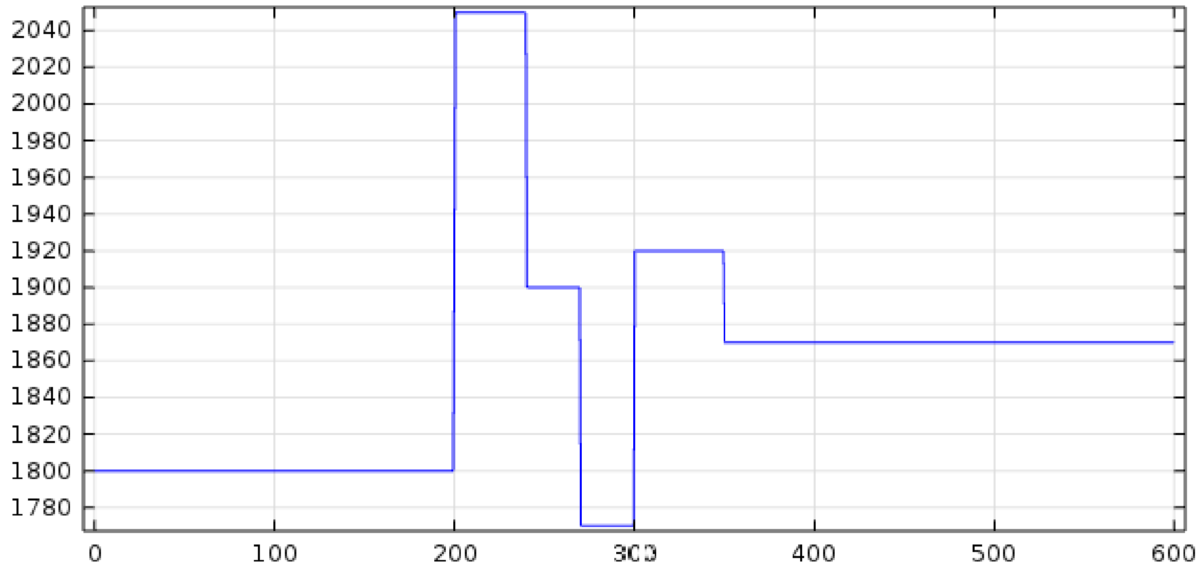

Figure 45 shows the furnace heat from COMSOL, without the isolating layer

6.3.2 Lining temperatures

Figure 46 to 50 shows the temperature profile to case two without the isolating layer. In figure 47 one can see that the grey Model_TCx_1,1545 line has more variations than in the other simulations done in both case one and in case two with the isolating layer. Compared to figure 36, it can be seen that the line for Model_TCx_1,545 in this case does not cross any other lines, as it does in figure 36. This is because it is needed smaller temperature variations now that the isolating layer is not a part of the simulation. In this way these simulations without the isolating layer is more realistic.

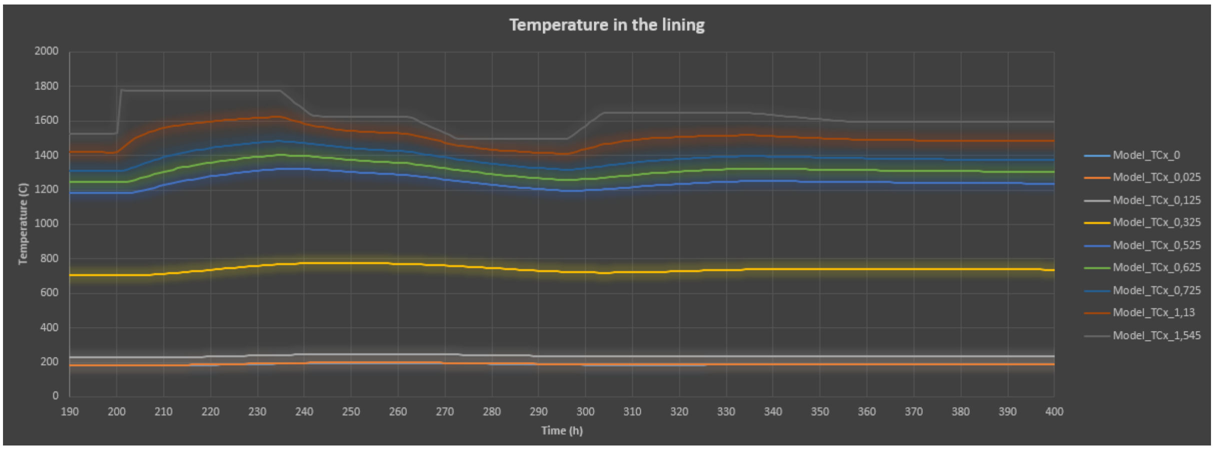

Figure 46 shows the lining temperature for Model_TC9_0 - Model_TC9_1.545 without the isolating layer

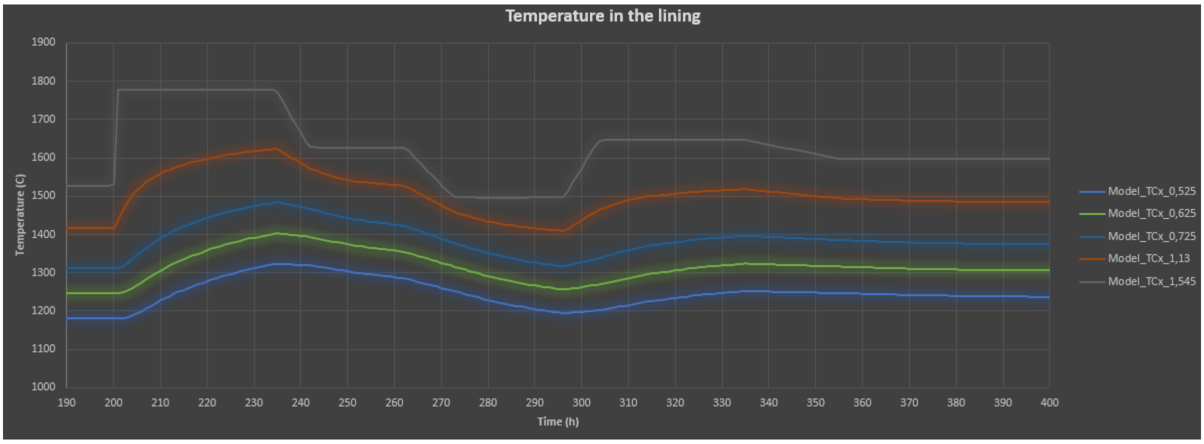

Figure 47 shows the lining temperature for Model_TC9_0.525 - Model_TC9_1.545 without the isolating layer

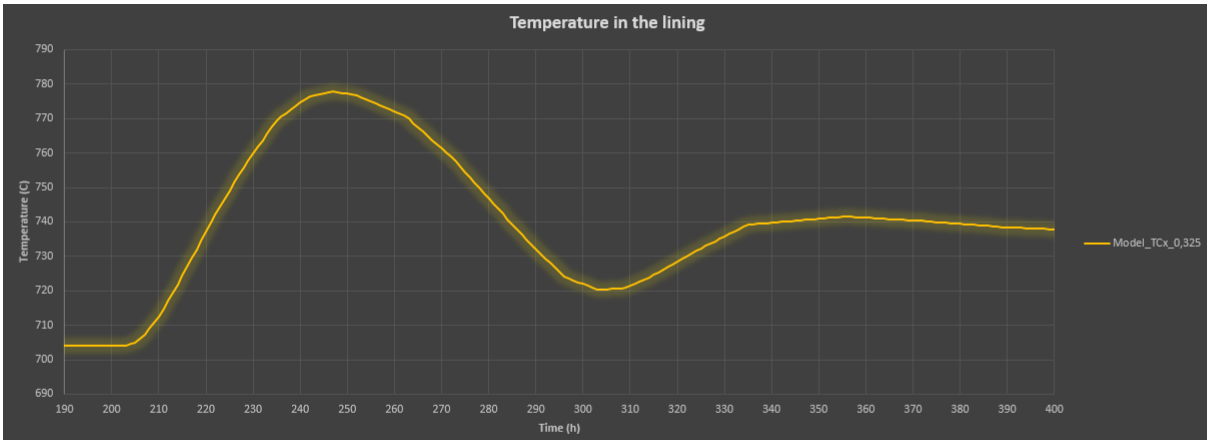

Figure 48 shows the lining temperature for Model_TC9_0.325 without the isolating layer

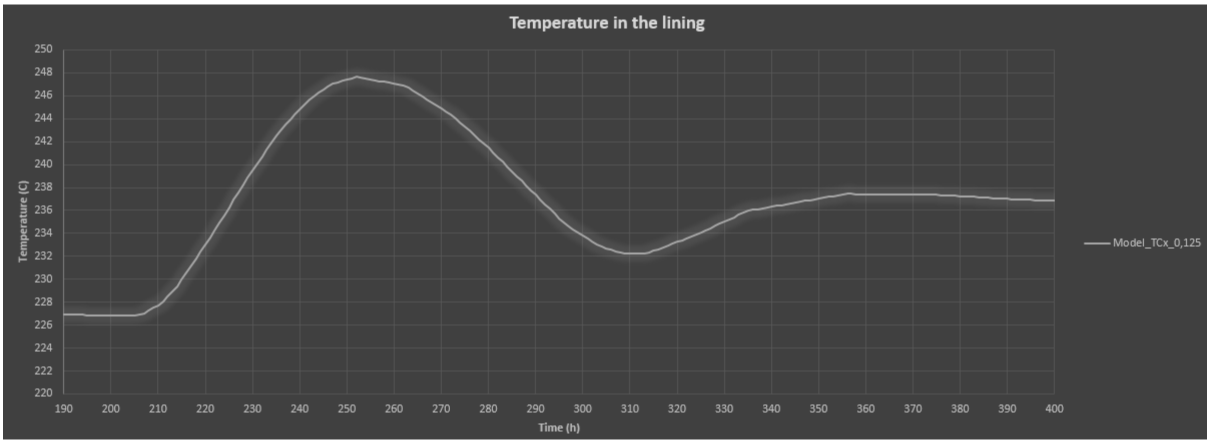

Figure 49 shows the lining temperature for Model_TC9_0.125 without the isolating layer

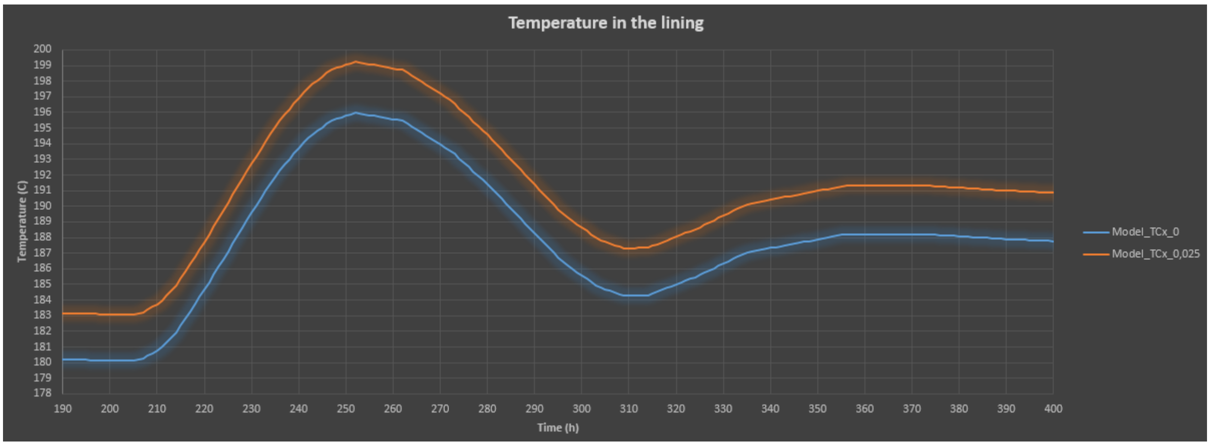

Figure 50 shows the lining temperature for Model_TC9_0 - Model_TC9_0.025 without the isolating layer

6.3.3 Reaction time in the lining

Below are the graphs showing the temperature variations to the simulation done without the isolating layer is shown. Below In figure 52 it can be seen that the temperature increase to Model_TCx_1,1545 is 250 °C for the first 2 hours, before it goes in steps down to -30 °C of its start temperature. The temperature variations to Model_TCx_0 are in figure 54 easy to read. They peak at almost 16 °C after about 48 hours after Model_TCx_1,545 reaches its maximum temperature, and about 18 hours after the temperature spike has passed at Model_TCx_1,545.

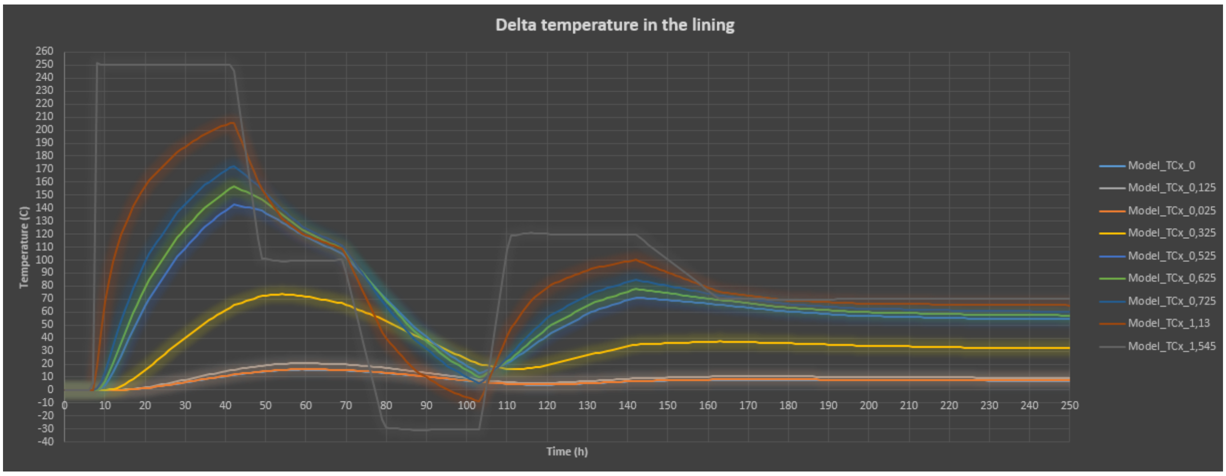

Figure 51 Shows delta temperature over time for Model_TC9_0 - Model_TC9_1,545 without the isolating layer

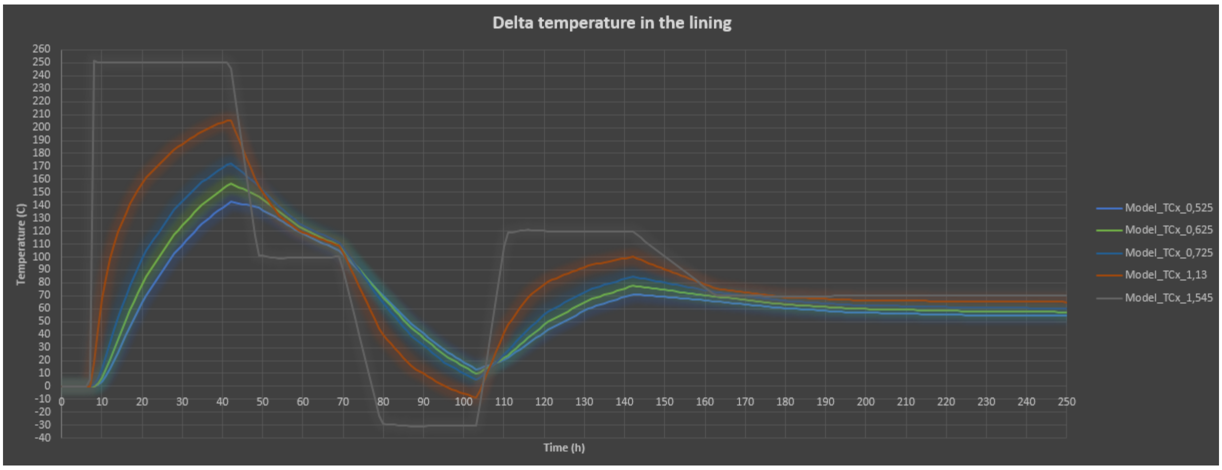

Figure 52 Shows delta temperature over time for Model_TC9_0.525 - Model_TC9_1,545 without the isolating layer

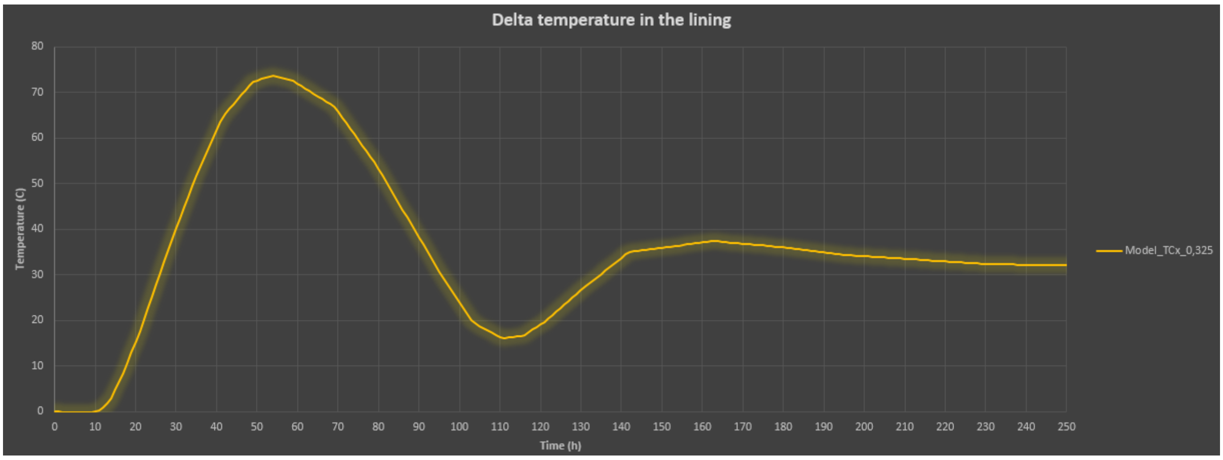

Figure 53shows delta temperature over time for Model_TC9_0,325 without the isolating layer

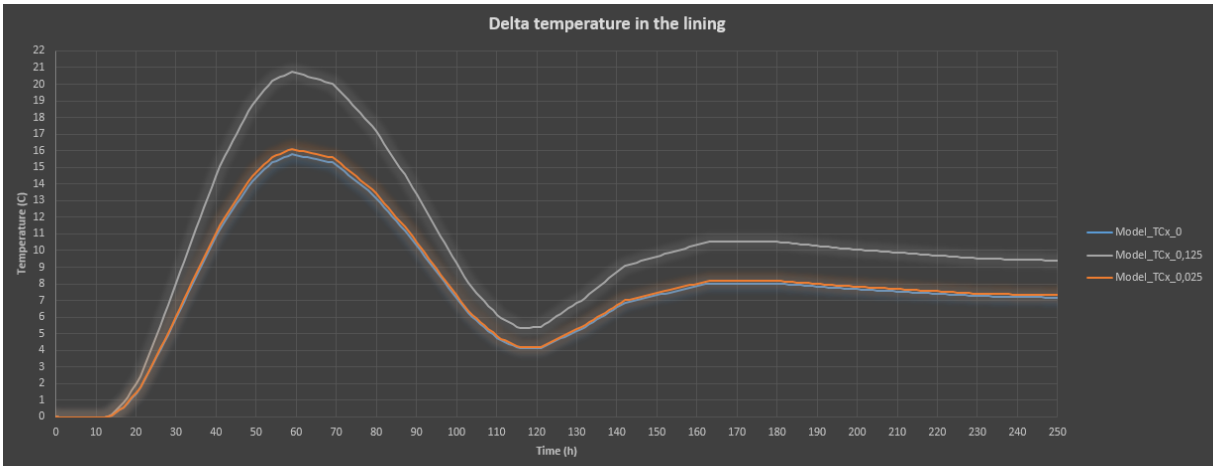

Figure 54 Shows delta temperature over time for Model_TC9_0 - Model_TC9_0,125 without the isolating layer

6.4 Extra

In figure 55 and 56 below, the other furnace parameters are displayed. As in case one it can be seen the important parameters as electrode position relative to thermocouple 19, the electrode tip position, and the load of the single electrode at the given time. In addition figure 56 shows that the temperature raises just when it is passing electrode 1, and in figure 56 it can be seen that at the time thermocouple 19 is passing the electrode the electrode tip position is pulsing up and down. Right after the passing the electrode travels down in the furnace, and stays low for around two days.

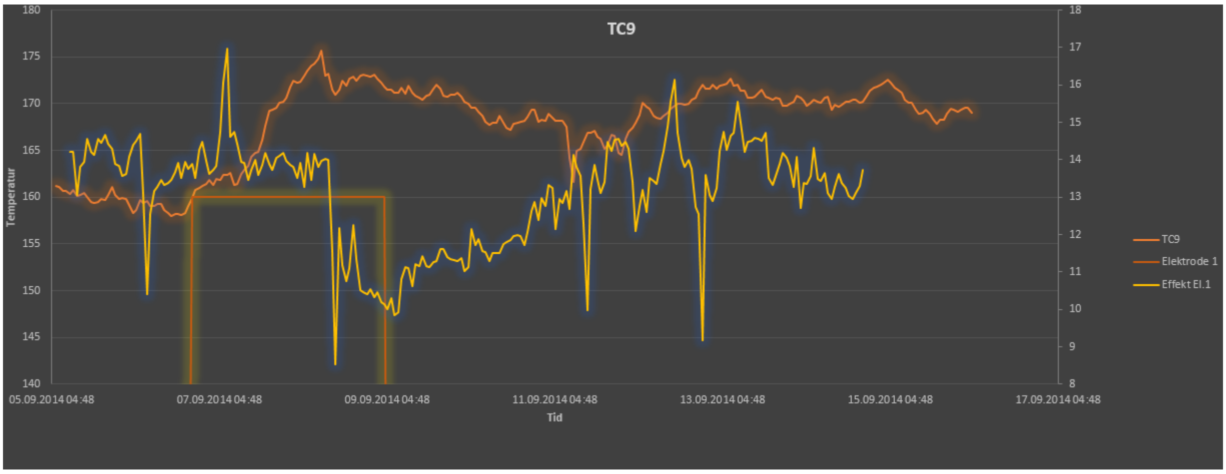

Figure 55 Shows the electrode position, furnace load and TC9 for the furnace

Figure 56 shows the electrode point position, electrode passing (position) and TC9

7 TIME DELAY

From the reaction time graphs, it has been created tables. These tables will better show how the heat travels through the lining. In addition, by discussing these tables one can come to better solutions as to where a thermocouple should be placed in the lining to give a short as possible reaction time, making the data from the thermocouples a better tool in monitoring the furnace, and how it should be operated.

7.1 RESPONSE TIME

The response time in the two cases is listed below in two tables. The response time are calculated from the graphs shown in 5.2.3, 5.3.3, 6.2.3 and 6.3.3. To calculate the response time, the time from the start of the temperature increase is registered and the time when the thermocouples experience a 5 °C increase is registered. Then the start time is subtracted from the time when the thermocouple reached the 5 °C mark. An example of this is for Model_TCx_0 for case one with the isolating layer.

Start of the temperature increase: 18,45 h

Model_TCx_0 reaches 5 °C increase: 37,6 h

Reaction time: 37,6 – 18,45 = 19,15 h

This is done for all the thermocouples in both cases, with and without the isolating layer.

7.1.1 Case one

Table 3 lists the different thermocouples response time in case one with the isolating layer

Postion	Thermocouple temperature range (°C)	Delay (h) With isolating layer	Comments
Model_TCx_1.546	1600 - 2000	0	
Model_TCx_1.131	1505 - 1794	0,38	
Model_TCx_0.726	1408 - 1632	0,67	
Model_TCx_0.626	1349 - 1560	0,78	
Model_TCx_0.526	1291 - 1488	0,9	
Model_TCx_0.326	865 - 990	2,25	
Model_TCx_0.126	440 - 497	4,9	
Model_TCx_0.026	400 - 453	7,8	
Model_TCx_0.025	166 - 185	18,75	
Model_TCx_0	164 - 183	19,15	

Table 4 lists the different thermocouples response time in case one without the isolating layer

Postion	Thermocouple temperature range (°C)	Delay (h) Without isolating layer	Comments
Model_TCx_1.545	1400 - 1650	0	
Model_TCx_1.130	1300 - 1500	0,54	
Model_TCx_0.725	1203 - 1370	0,95	
Model_TCx_0.625	1143 - 1301	1,22	
Model_TCx_0.525	1083 - 1230	1,52	
Model_TCx_0.325	646 - 736	6,32	
Model_TCx_0.125	210 - 232	17,92	
Model_TCx_0.025	170 - 187	22,62	
Model_TCx_0	167 - 184	23,02	

7.1.2 Case two

Table 5 lists the different thermocouples response time in case two with the isolating layer

Postion	Thermocouple temperature range (°C)	Delay (h) With isolating layer	Comments
Model_TCx_1.546	1773 - 2225	0	
Model_TCx_1.131	1670 - 2033	0,5	
Model_TCx_0.726	1563 - 1861	0,7	
Model_TCx_0.626	1498 - 1768	0,8	
Model_TCx_0.526	1433 - 1678	0,9	
Model_TCx_0.326	960 - 1080	2,2	
Model_TCx_0.126	486 - 540	6,8	
Model_TCx_0.026	442 - 491	7,7	
Model_TCx_0.025	182 - 200	17,6	
Model_TCx_0	179 - 196	18	

Table 6 lists the different thermocouples response time in case two without the isolating layer

Postion	Thermocouple temperature range (°C)	Delay (h) Without isolating layer	Comments
Model_TCx_1.545	1527 -1777	0	
Model_TCx_1.130	1418 - 1623	0,25	
Model_TCx_0.725	1312 - 1485	1,8	
Model_TCx_0.625	1246 - 1403	2,55	
Model_TCx_0.525	1181 - 1323	3,25	
Model_TCx_0.325	704 - 778	8,1	
Model_TCx_0.125	227 - 248	18,2	
Model_TCx_0.025	183 - 199	20,9	
Model_TCx_0	180 - 196	21,2	

7.2 THERMOCOUPLE PLACEMENT

From the tables one can clearly see that there is a long reaction time for the thermocouples at the bottom of the lining. In the simulations done with the isolating layer the reaction time is shortest 19,5 hours and 18 hours for case one and two. This is not so strange, seeing as these two simulations have a much higher temperature spike occurring on the top of the lining. Respectively 400 °C for case one and 450 °C for case two, while the simulations done without the isolating layer have a temperature spike of only 250 for both case one and two.

In all four tables there are two thermocouples that have the biggest difference in reaction time. The difference between Model_TCx_0,325 and Model_TCx_0,125 or between Model_TCx_0,126 and Model_TCx_0,125 in the simulations done with the isolating layer is all about 10 hours.

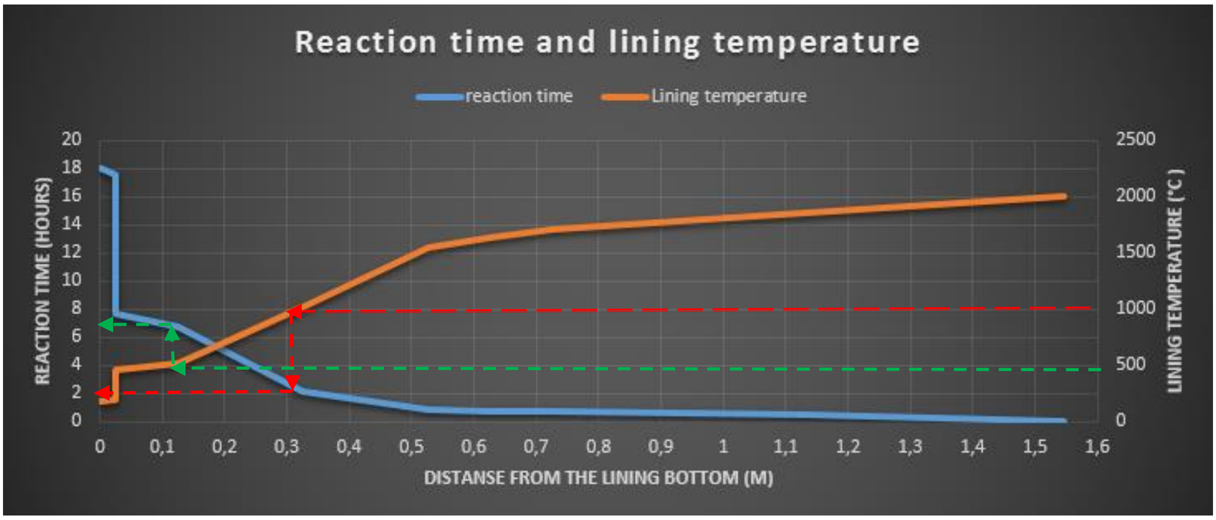

Figure 57 shows reaction time plotted with lining temperature

Figure 57 shows the reaction time and the temperature in the lining, relative to where in the a thermocouple is placed. This table is created from case two with the isolating layer, the most realistic simulation in consideration to furnace temperature. The red line in the graph points out that if a thermocouple can endure a temperature of 1000 °C, it will now have a reaction time of about 2 hours – i.e. this is the shortest time from an incident to alarm may be given. The green line does the same, but now for a thermocouple at 500 °C. Here the reaction time is about 7 hours. Both cases give an strong improvement from the current system that has a reaction time at about 18 hours. This graphs shows how long a thermocouple can be moved inside a furnace, and how much shorter reaction time one could experience by doing so.

Table 7 shows the reaction time and temperatures in the lining

Distance from the bottom of the furnace lining (m)	Reaction time (h)	Temperature (°C)	Comment
0	18	180	Current situation
0,1	7	500	Need thermocouples that has a 10-20 years life expectancy at 500 °C
0,325	2	1000	Need thermocouples that has a 10-20 years life expectancy at 1000 °C

Table 7 shows the possible reaction time one can obtain by moving the thermocouples, but also lists the challenges this new position gives the thermocouple.

The obstacles in moving a thermocouple is many, the biggest would be the change in atmosphere the thermocouple would experience. Now constantly being at a temperature much higher. The temperature for this layer varies a lot in the different simulations, but one can assume it to at times be as high as above 900 °C as the simulation with the isolating layer in case two suggests. Withstanding such high temperatures over time is a challenge, and seeing as another obstacle is the trouble of being able to replace or repair a thermocouple due to it being inside of the lining makes this a challenging improvement.

8 THEORIES FOR THE TEMPERATURE SPIKE

In both case one and two, the temperature increase is similar, a temperature rise of about 15–20 °C. The reason for this increase could be a number of reason, or the combinations of these theories. From the simulations we can see that a the energy required to induce these spikes is equivalent to a temperature rise of 400 – 450 °C in the simulations done with the isolating layer, and 250 °C in the simulations without the isolating layer. Below are a table that lists a number of possible reasons to the temperature spikes. These will also be discussed later.

Table 8 shows a summation of the different hypotheses for the temperature increase, with reasons and probability

Hypotheses for the temperature increase	Estimated necessary effect	Possible reasons	Comments	Probability
1. Increased temperature at the top of the lining	250 °C without the isolating layer. 450°C with the isolating layer.	Increased temp in cavity Electrode position. Low electrode tip position.	Problems with endothermic reactions in the crater? Some indication that electrode positioned above give higher temperature. Combined effect– higher temp and lower amount of the isolating layer	
2. Increased heat transfer to the lining		The porous SiC structure above the lining fills with Si metal. Or partially reacts, and therefore decreases.	The pressure in the cavity may increase when the electrode goes down. This increase in pressure may affect the heat transfer to the lining.	

3. Increased heat transfer in the lining		A layer of solid silicon in a wound in the lining melts and give increased heat transfer.	This is although possible, unlikely since it would be a reoccurring thing that easily could be traced. Since very few, or no similar cases are found on this particular thermocouple.	
4. Measurement uncertainties		Thermocouples or the computer system giving the wrong temperatures over time.	Always a possible factor. However, due to a consistent high temperature over time in several cases on many different thermocouples, not very likely.	
5. Cooling air temperature		The cooling air heated up somehow.	Not likely due to no consistent reaction on other thermocouples. In addition, to high values necessary not to be recognised. To be possible a measurement failure must also occur.	

8.1 INCREASED TEMPERATURE AT THE TOP OF THE LINING

As mentioned in the table 7 the reason for an increase in temperature at the top of the lining can be a number of reasons. Case one and two has some similarities occurring. In both cases, the thermocouple in question is passing strait under an electrode at the time of the temperature spike. If we look at figure 30 and 55, we see that at the time of the spike the thermocouples are below electrode 2 in case one, and electrode 1 in case two. Another parameter that is evident from figures 31 and 56 is that at the time the thermocouples are passing the electrodes the electrode tip position is low. Meaning that the distance between the tip of the electrode and the lining of the furnace is small. This will possibly intensify the energy concentration at the lining surface.

In addition to the electrode now having a smaller catchment area, the access to reaction materials to complete the endothermic reactions:

$SiO2(s, l) + Si(l) = 2SiO(g)$, $\Delta H = 605.441 kJ/mol$ (3)

$SiO(g) + SiC(s) = 2Si(l) + CO(g)$, $\Delta H = 166.714 kJ/mol$ (4)

Could decrease.

As stated before reaction 3 should be occurring strait underneath the electrode. If the balance of the energy input and the energy consumption from this reaction comes out of balance, we will have an amount of excess energy not being spent.

Under normal conditions these two reactions uses up almost all the energy being sent through the electrode. From figure 30 and 55 it can be seen that the electric load on the electrode in question in the two cases is steady at about 14 MW for case one and varies from 13 MW to 17 MW in case two. To make the calculations simper a steady value of 14 MW is assumed. Next assumption will be that 90 % of the energy going through the electrode is used to drive chemical reaction 3 and 4. Making the energy available for the reactions:

Energy available = 14 MW * 0,9 = 12,6 MW

This amount of energy means that if the energy balance between the two reactions are similar 50/50, the amount of raw materials reaction each second can be calculated by the ΔH value to reaction 3 and 4.

Energy to each chemical reaction: 12,6 MW / 2= 6,3 MW = 6300 kJ/s

Table 9 shows the calculations for reaction 3 and 4 on how much materials are consumed during normal operations

Reaction 3: $SiO2(s, l) + Si(l) = 2SiO(g)$ $\Delta H = 605.441 kJ/mol$ (3)	Reaction 4: $SiO(g) + SiC(s) = 2Si(l) + CO(g)$ $\Delta H = 166.714 kJ/mol$ (4)
6300 kJ/s / 605,441 kJ/mol = 10,4 mol/s	6300 kJ/s / 166,714 kJ/mol = 37,9 mol/s

If these assumptions are correct, it is now possible to calculate the difference for raw materials not present to induce a temperature spike.

If the temperature spike is a consequence of the misbalance of the equation alone the amount of energy to induce a temperature rise of 250 or 450 °C , as simulations done in case one and two states, can be calculated by the formula:

$$H = C_p * m * \Delta T$$

If we now assume that the temperature spike occurs in the top of the lining, like in the models created in COMSOL, only the data from the top layer of the lining is needed. The C_p to the K-paste we can find in table 1, an is said to be: 1900 J/kg*K.

To have an estimation of the mass of the K-paste layer affected, we can by attaining the density of the K-paste, and the volume of the affected area. A rough estimation would be to assume that the affected area is the same size as the shape of the electrode. At the top the electrodes have a diameter of 170 cm. The electrode goes through many transformations through its travel downwards in the furnace, and it is known that it will change its shape at the tip. However, since the affected area of the lining probably is a bit broader than the electrode, it is a plausible estimation. Since we need a volume to calculate the mass we must estimate a height for the affected layer, to make this as thin as possible we say h = 0,1 cm.

$\rho = 1460\ kg/m^3$ d = 170 cm => r = 1,70/2 = 0,85 m h = 0,001 m

$$V = \pi r^2 h$$

$$V = 3,14 * 0,85^2 * 0,001 = 0,002269\ m^3$$

The mass to the affected area becomes:

$$m = V * \rho = 0,002269 * 1460 = 3,31274\ kg$$

If we assume the affected area of the K-paste has a mass of 3,3 kg the resulting energy needed to heat the lining 250 or 450 °C will be:

Table 10 shows the calculations for the heat needed to induce a the different temperature spikes

For 450 °C	For 250 °C
H = 1900 J/kg*K * 3,3 kg * 450 K H = 2821,5 kJ or 2,82 MWs	H = 1900 J/kg*K * 3,3 kg *250 K H = 1567,5 kJ or 1,57 MWs

If the whole temperature spike is a consequence of reaction 3 not being in balance, the amount of raw materials missing is:

Table 11 shows the calculations for materials needed not to react to induce the temperature spike

For 450 °C	For 250 °C
2821,5 kJ / 605,441 kJ/mol = 4,66 mol	1567,5 kJ / 605,441 kJ/mol = 2,59 mol

The difference between the normal energy consumption of the furnace and the assumed energy consumption of the furnace is displayed here in table 12:

Table 12 shows the difference between the raw materials consumed, during normal operations and at the time of the temperature spike

Reaction 3	Normal amount energy spent	Energy spent with low electrode	Difference	Comment
450	10,4 mol/s	5,74 mol/s	-44,8%	Leaving 2821,5 kJ/s to heat the lining
250	10,4 mol/s	7,81 mol/s	-24,9%	Leaving 1567,5 kJ/s to heat the lining

If these estimations are correct or close to correct, a 44,8% or 24,9% difference in reaction materials is plausible, and the temperature spike could if not entirely alone, done by the difference in reaction material for chemical reaction 3.

8.2 INCREASED HEAT TRANSFER TO THE LINING

A possible reason to the experienced temperature rise in the bottom of the furnace can be that the energy from the electrode is transferred to the lining more efficiently than normal. The cause of this could be that the porous SiC structure above the lining experiences a different filling compared to what is usually experiences. Kadkhodabeigi's works states that the pressure in the cavity around the electrode varies in the range from 30 mBar to 200 mBar (Kadkhodabeigi, 2011). Even though his research focused on the tapping process to a submerged arc furnace it is evident that there are occurring many variations in the cavity. These variations could affect the total heat transfer coefficient to the space between the electrode and the lining.

8.3 INCREASED HEAT TRANSFER IN THE LINING

The lining of the furnace is in constant change. The original lining has experienced transformations, and over time, these can affect the heat transfer to the lining. If the temperature spikes in case one and two is the result of a change in the lining it would probably not be a change that has been occurring over time. The spike occurs to sudden to be the result of a transformation that has occurred over time. It may on the other hand be a result of a wound in the lining being reopened. If a finger of solidified silicon metal suddenly were melted, the heat would have an easier and shorter travel through the lining. For this to occur there must have been a wound present in the lining, that only show during extra stress. This explanation, although plausible is not likely due to the relatively quick temperature drop after the spike. What also makes this not a likely occurrence, is that fact that there then must be many wounds present in the lining. Here in this paper only two cases with these temperature spikes are discussed. But in studies done before by Strømmen, there where many such cases, and many of them on other thermocouples than TC9 and 18.

8.4 Measurement uncertainties

The measurement uncertainties are always a possible factor in all occasions where measuring equipment is used. In the case of the measured temperatures to the silicon furnace at Thamshavn where the data is extracted, the data from the thermocouples placed under the furnace is logged in a database, which then again is extracted to be displayed here in the form of graphs. The likely hood of there being an error at the thermocouples are very low, due to the fact that they display a steady temperature over time, and under and after the temperature spike has passed they return to their normal temperature. The fact that there are more than one thermocouple that show spikes at the same time, while other thermocouples remain steady is an indication that no error is occurring.

Other parameters have a higher likely hood of errors. The electrode tip position system is based on an estimation. Since the length of the electrode is estimated there is no possible way to actually know how long the electrode is at any given time. This gives some uncertainties to the number being correct, but since the electrode travels down so long, in case one ca 100 cm, and stays down, and case two have a pulsing up and down rhythm with a about 100 cm drop, up a 100 cm before going down again. Since these numbers are so big one can assume that if they are not completely correct the electrode in each case at least goes down, fitting the hypothesis.

8.5 Cooling air temperature

There is a theoretical possibility that the temperature spikes occurring in case one and two is a consequence of the cooling air temperature raising. One can imagine the air that is being pumped in from the outside has become heated. The hot air heats, or at least not cools the bottom of the furnace lining. This is of course possible, but in both case one and two the other thermocouples place around at the bottom of the lining do not experience the same spikes. Since all these thermocouples are cooled by the same air this theory must not be valid.

Another argument for that this is not happening is that the temperature of the cooling air is measured. And such a temperature spike that is required here would have been noticed if not an error occurred on the measuring equipment.

9 CONCLUSION

The current system for lining monitoring with thermocouples at the bottom has some disadvantages:

- Long delay time (approximately 18 hours) from an incident near the reaction zone to the temperature change can be monitored at the thermocouples.
- The passing of a thermocouple in the furnace body below an electrode may be registered as a temperature increase with the same delay time.
- Some increase in the lining temperature has been link to low electrode tip position.
- 2 cases have been studied in detail. Some hypotheses for the sudden temperature increase are presented. Probably the reason for the temperature is due to variation in the endothermic reaction or changes in the heat transfer from the reaction to the top of the lining.
- The reaction time for the lining may be improved by introducing thermocouples higher in the lining. A reduction from the existing 18 hours to 2 hours should be achievable.
- To have multiple thermocouples at the same horizontal position but at different vertical positions may also give some information regarding heat flow level and dynamics.

10 FURTHER WORK

For further work on this project, a more detailed study where more cases where modelled and simulated would be useful to get a more statistically significant result.

It would also be interesting to investigate the furnace lining further. And how it has changed during operation. An experiment where one could excavate a test furnace, or do tests on an already excavated furnace. To see how the different specifics for the different layers has changed. This would again make the simulations more accurate, and one could obtain a more realistic result.

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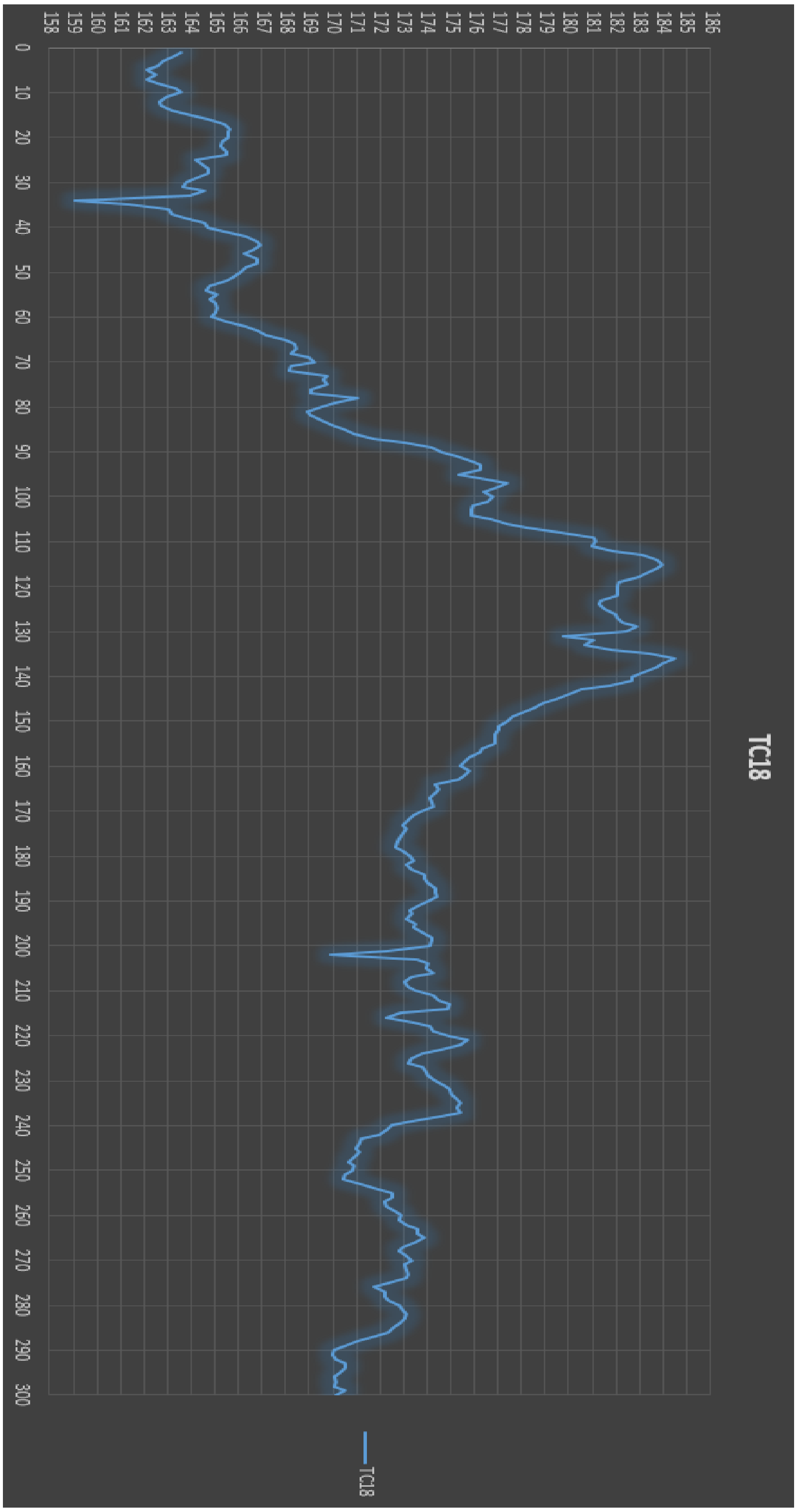
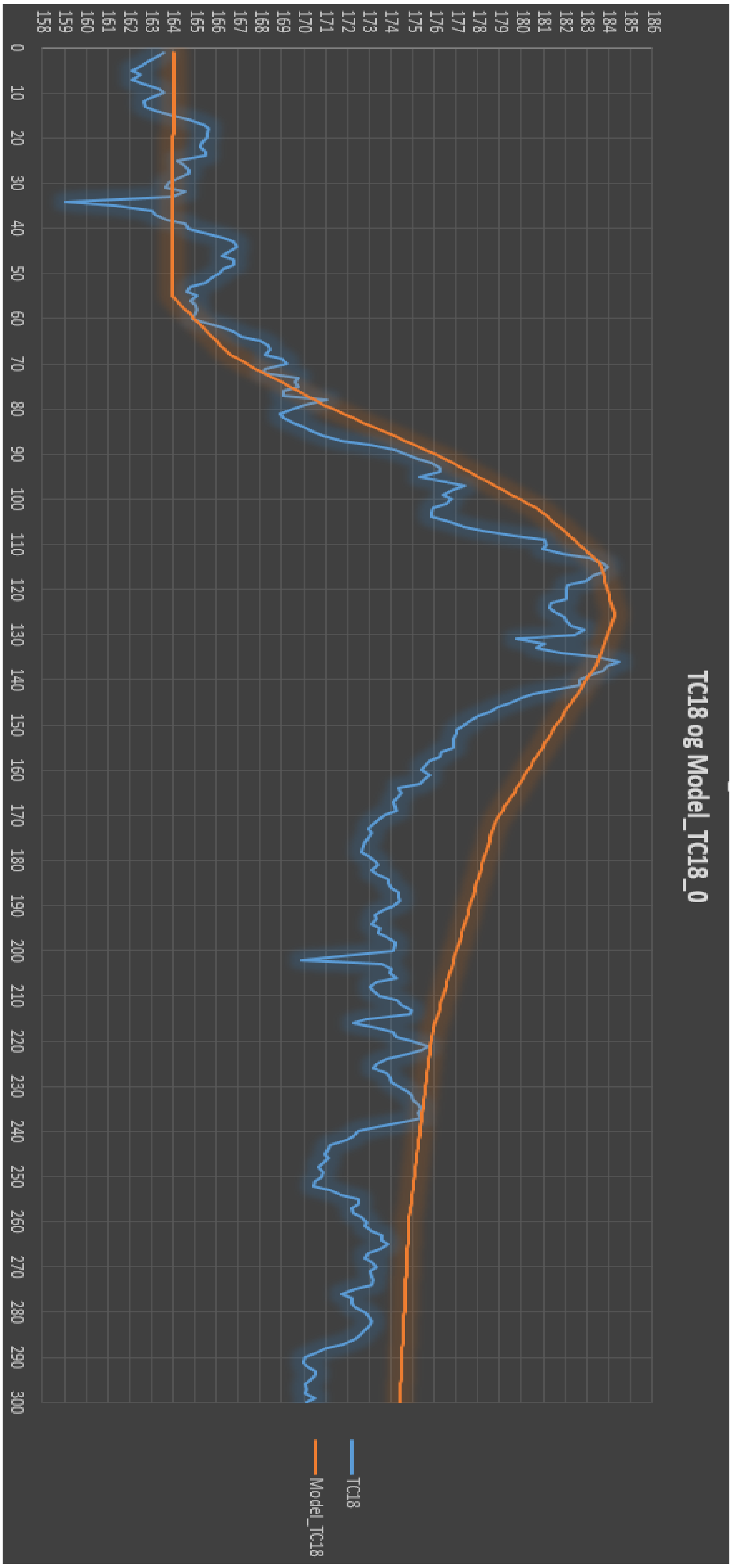
12 APENDIX

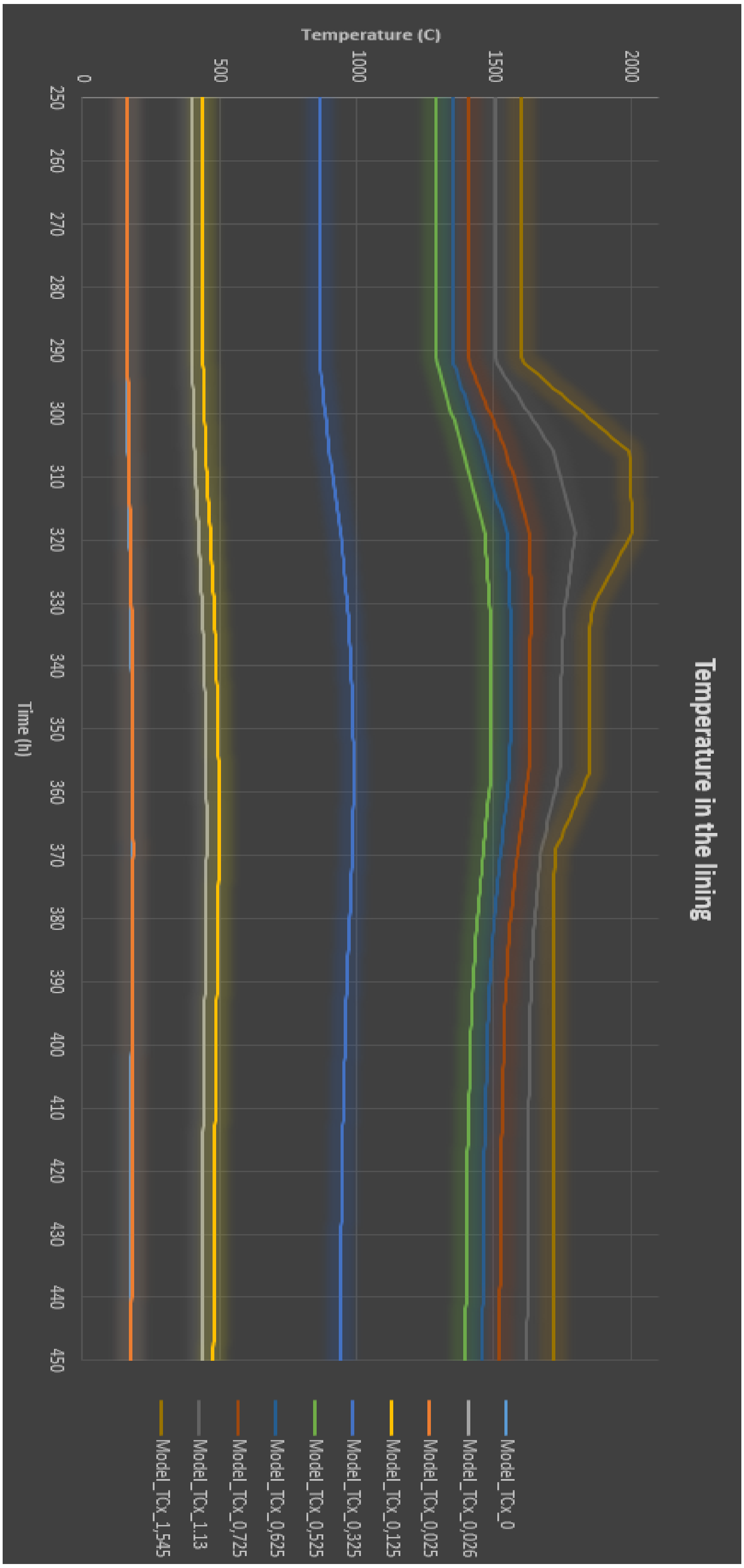
12.1 CASE 1 WITH THE ISOLATING LAYER



Figur 1 shows the temperature over time for TC18

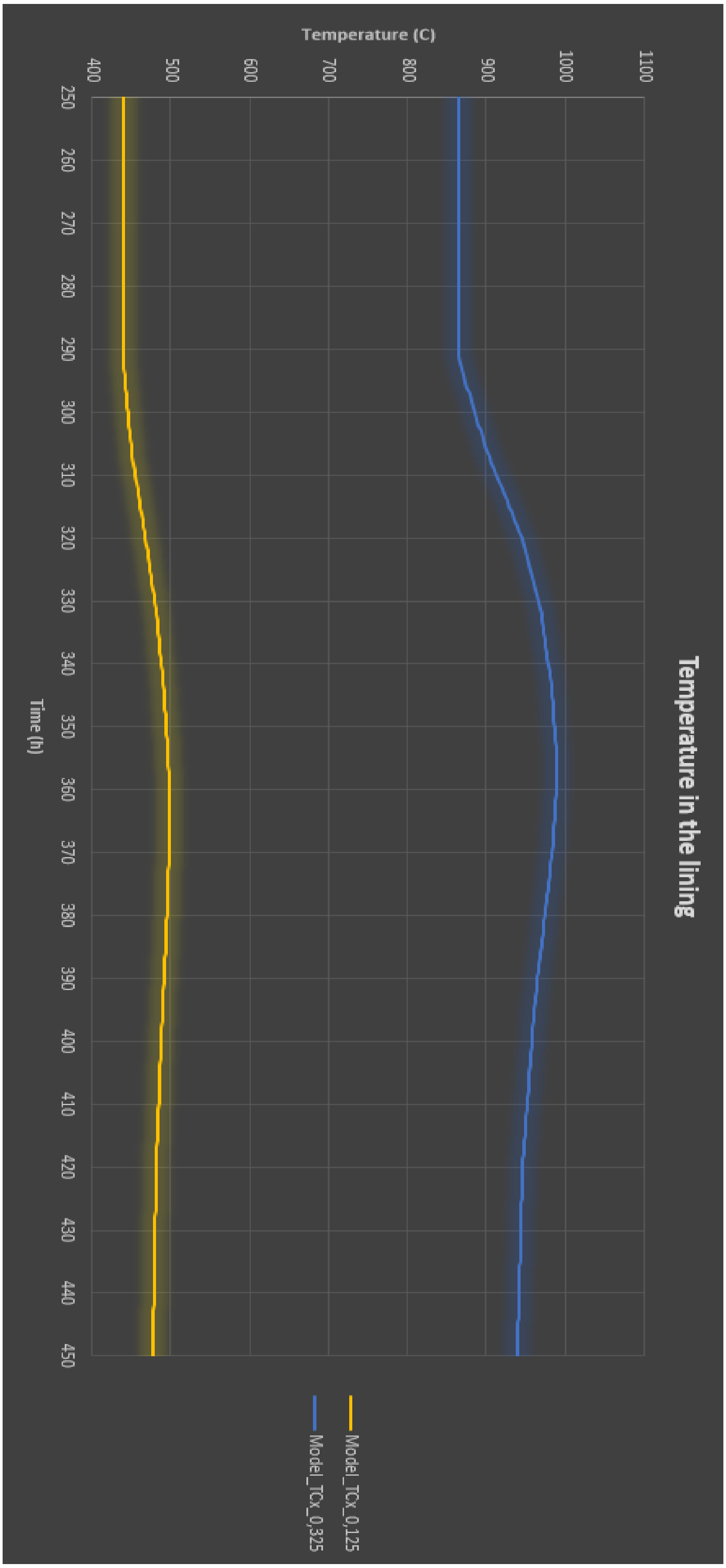


Figur 2 shows TC18 and Model_TC18_0, modelled with isolating layer

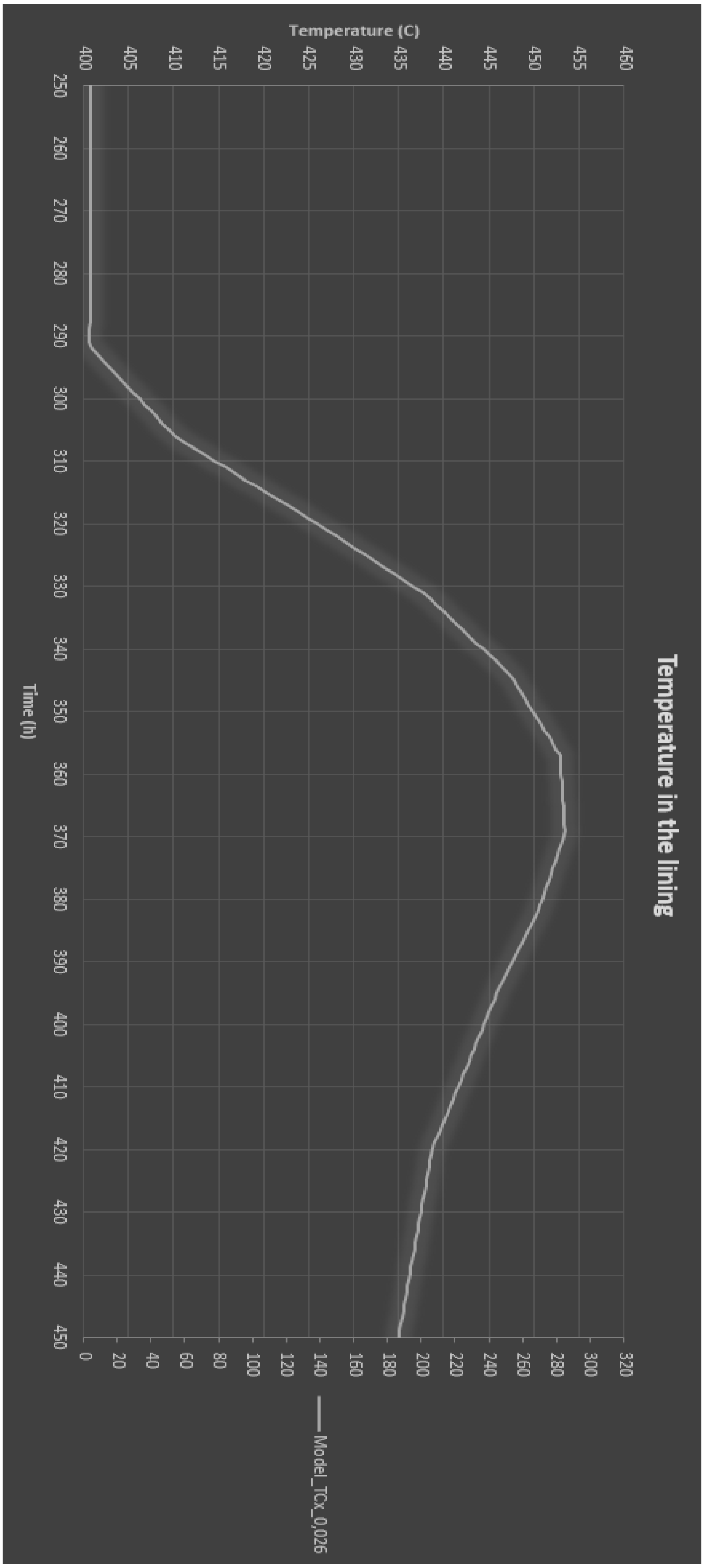


Figur 3 shows the lining temperature for Model_TC18_0 - Model_TC18_1.545 with the isolating layer

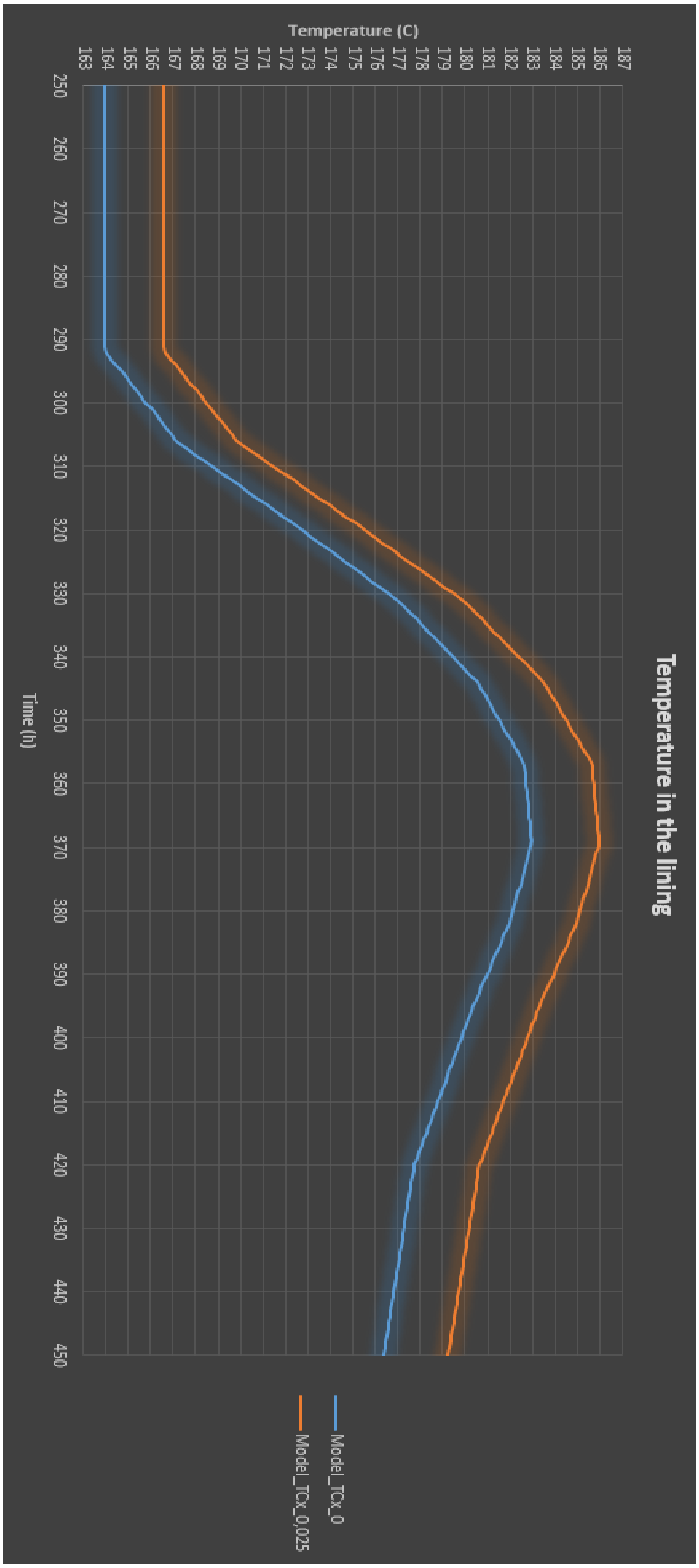
Figur 4 shows the lining temperature for Model_TC18_0.525 - Model_TC18_1.545 with the isolating layer



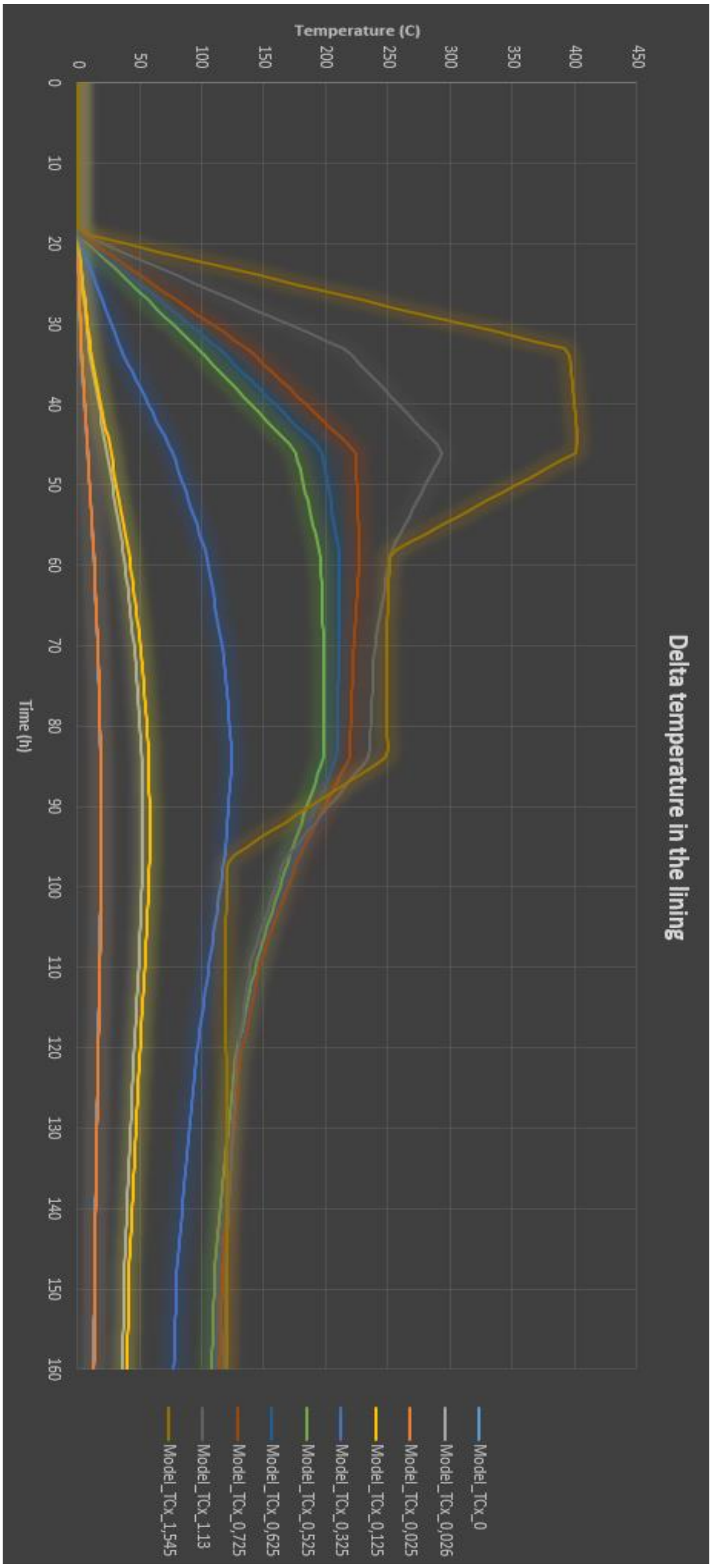
Figur 5 shows the lining temperature for Model_TC18_0.225 - Model_TC18_0.325 with the isolating layer



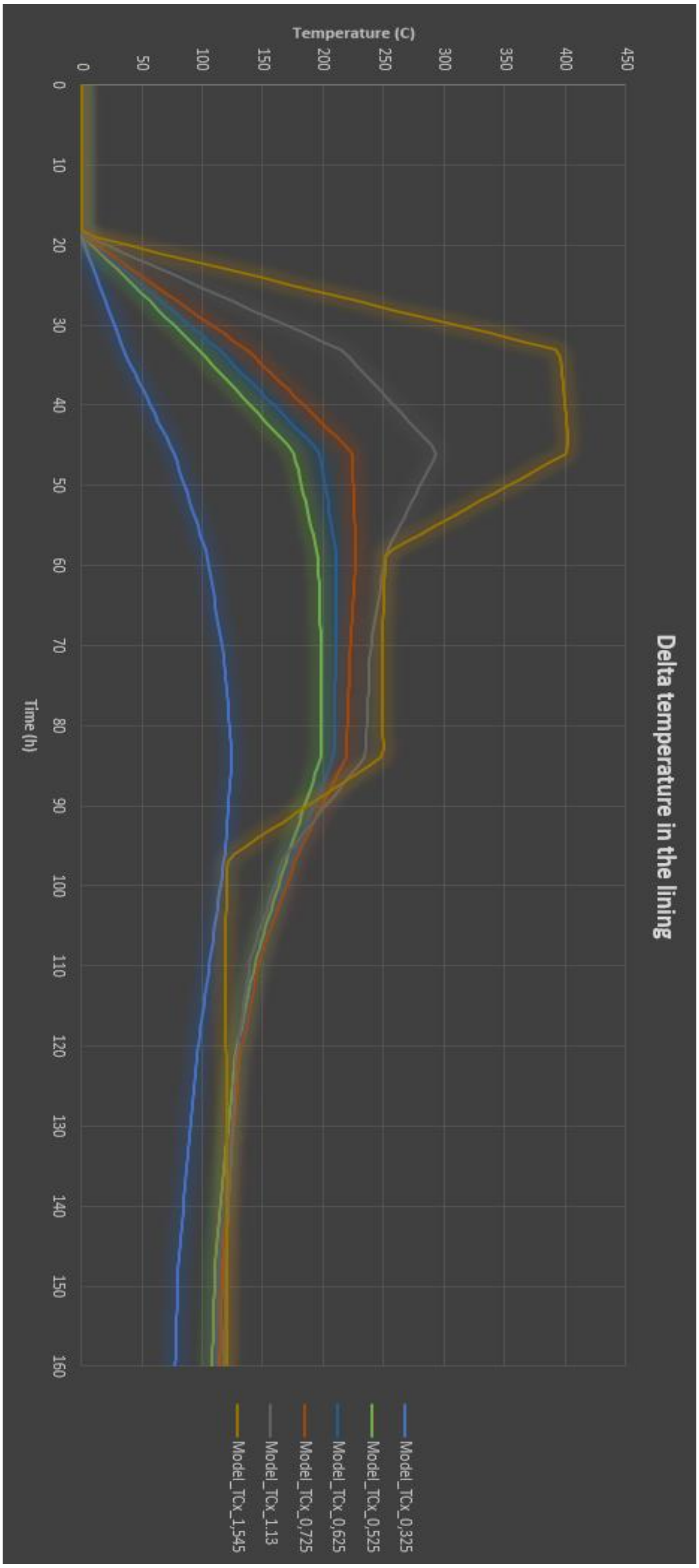
Figur 6 shows the lining temperature for Model_TC18_0.026 with the isolating layer



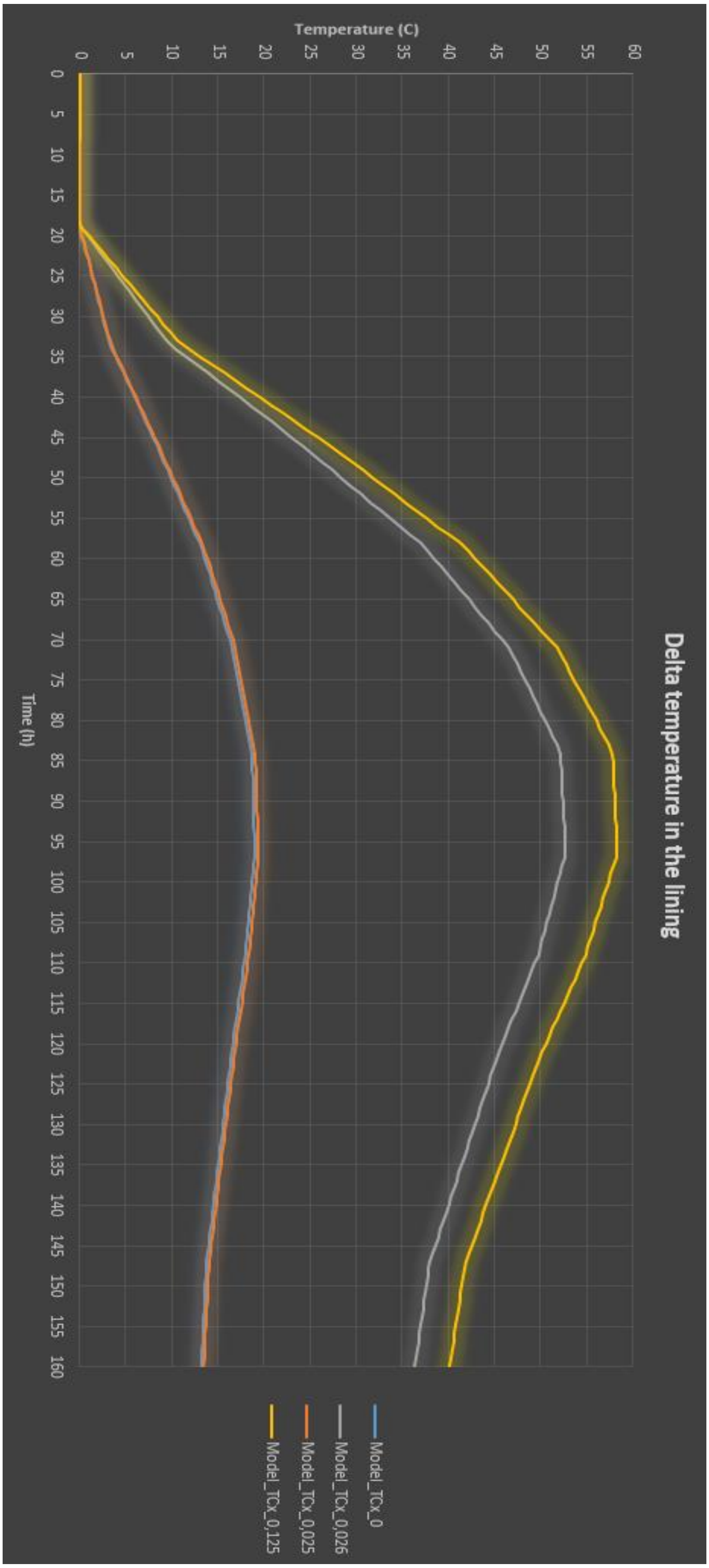
Figur 7 shows the lining temperature for Model_TC18_0 - Model_TC18_0.025 with the isolating layer



Figur 8 Shows delta temperature over time for Model_TC18_0 - Model_TC18_1,545 with the isolating layer

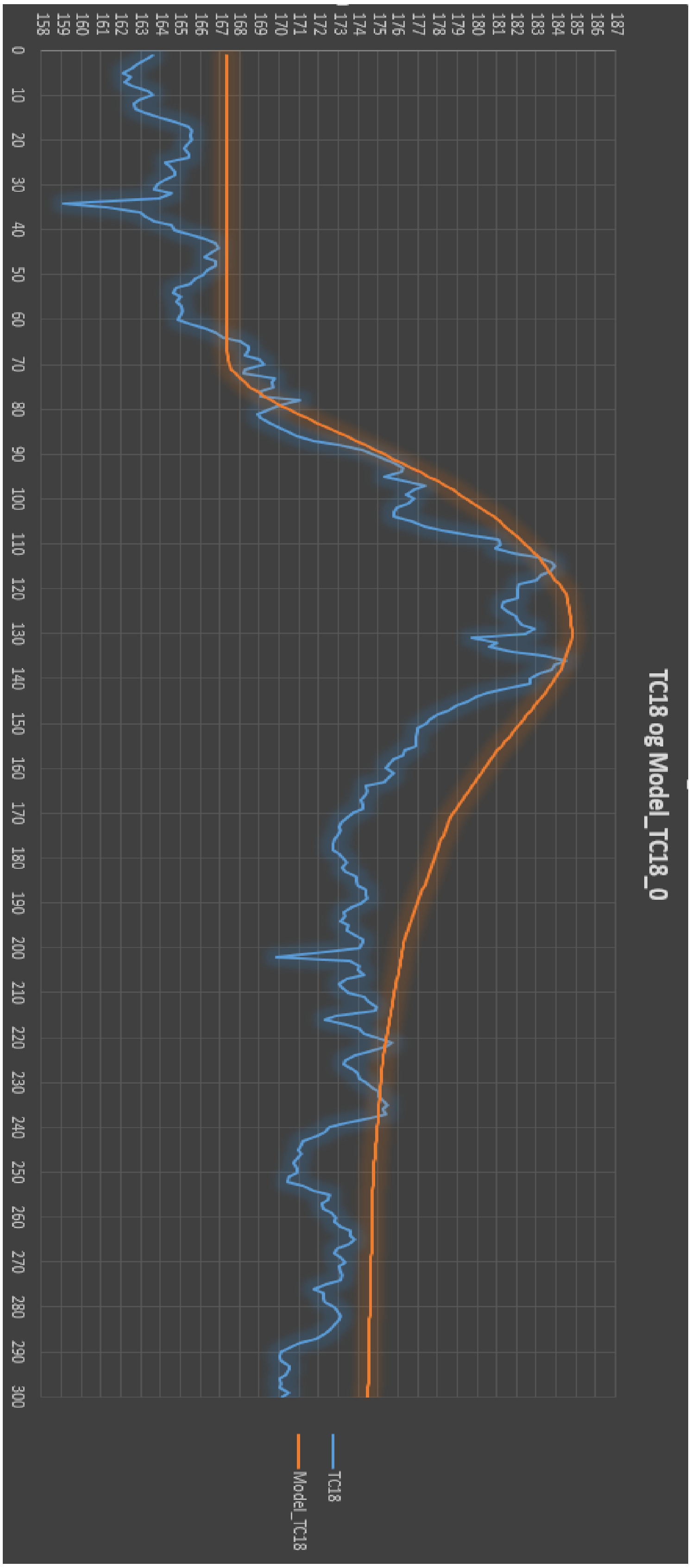


Figur 9 Shows delta temperature over time for Model_TC18_0.325 - Model_TC18_1,545 with the isolating layer

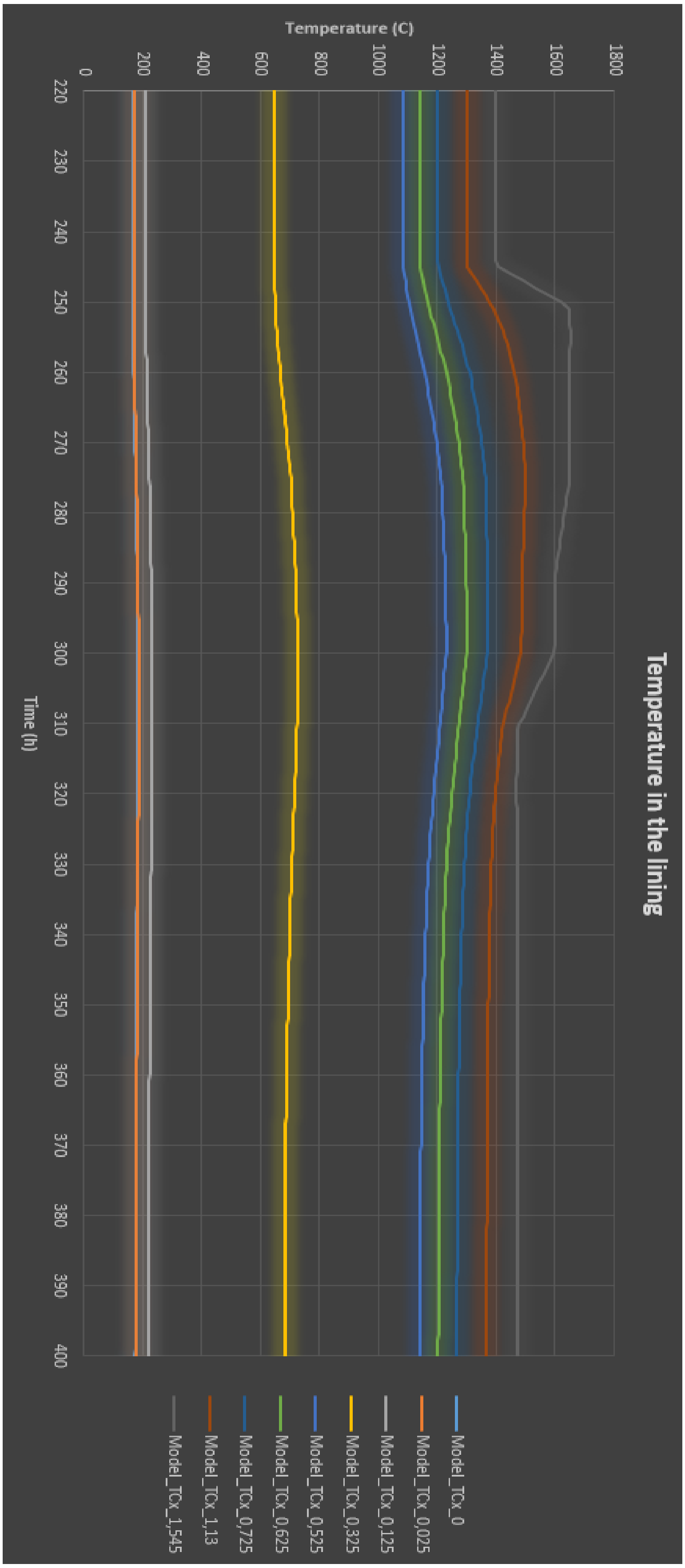


Figur 10 Shows delta temperature over time for Model_TC18_0 - Model_TC18_0,125with the isolating layer

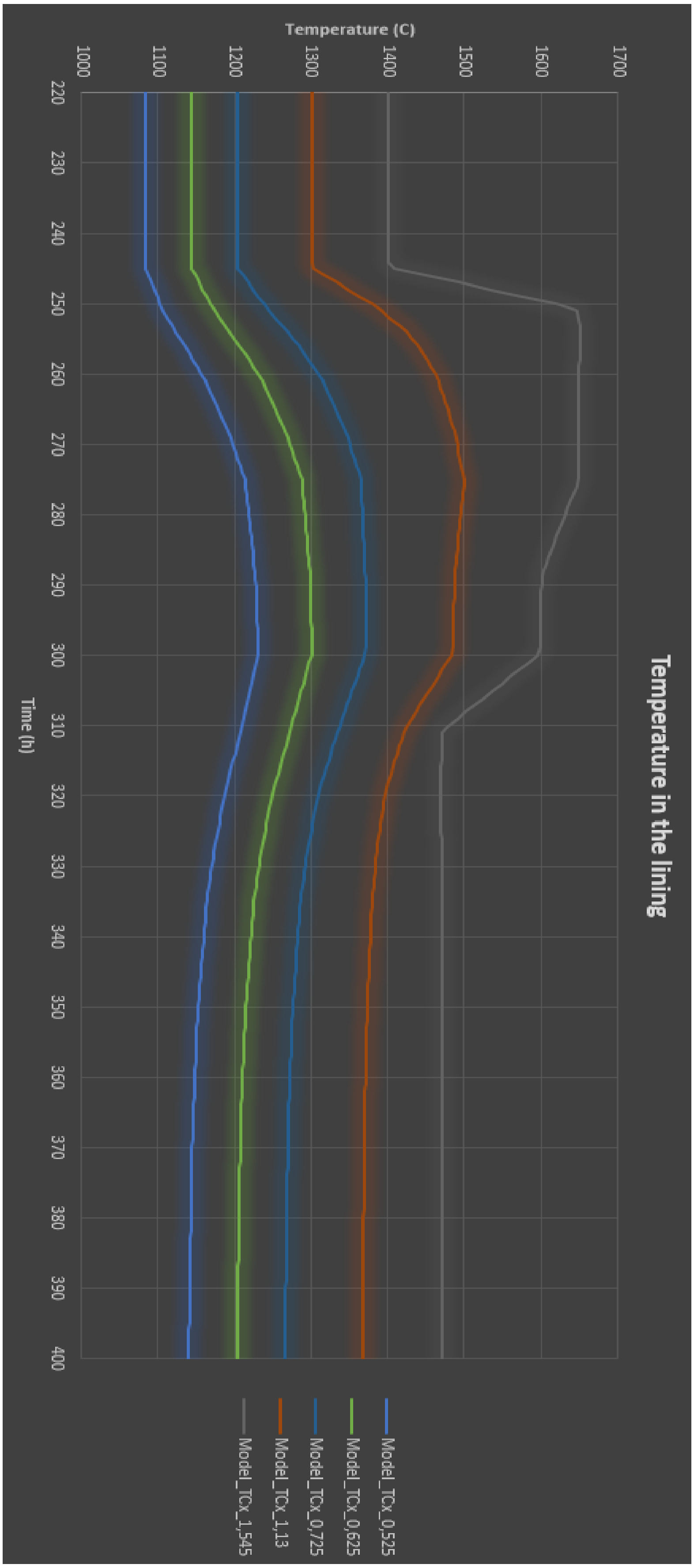
12.2 CASE 1 WITHOUT THE ISOLATING LAYER



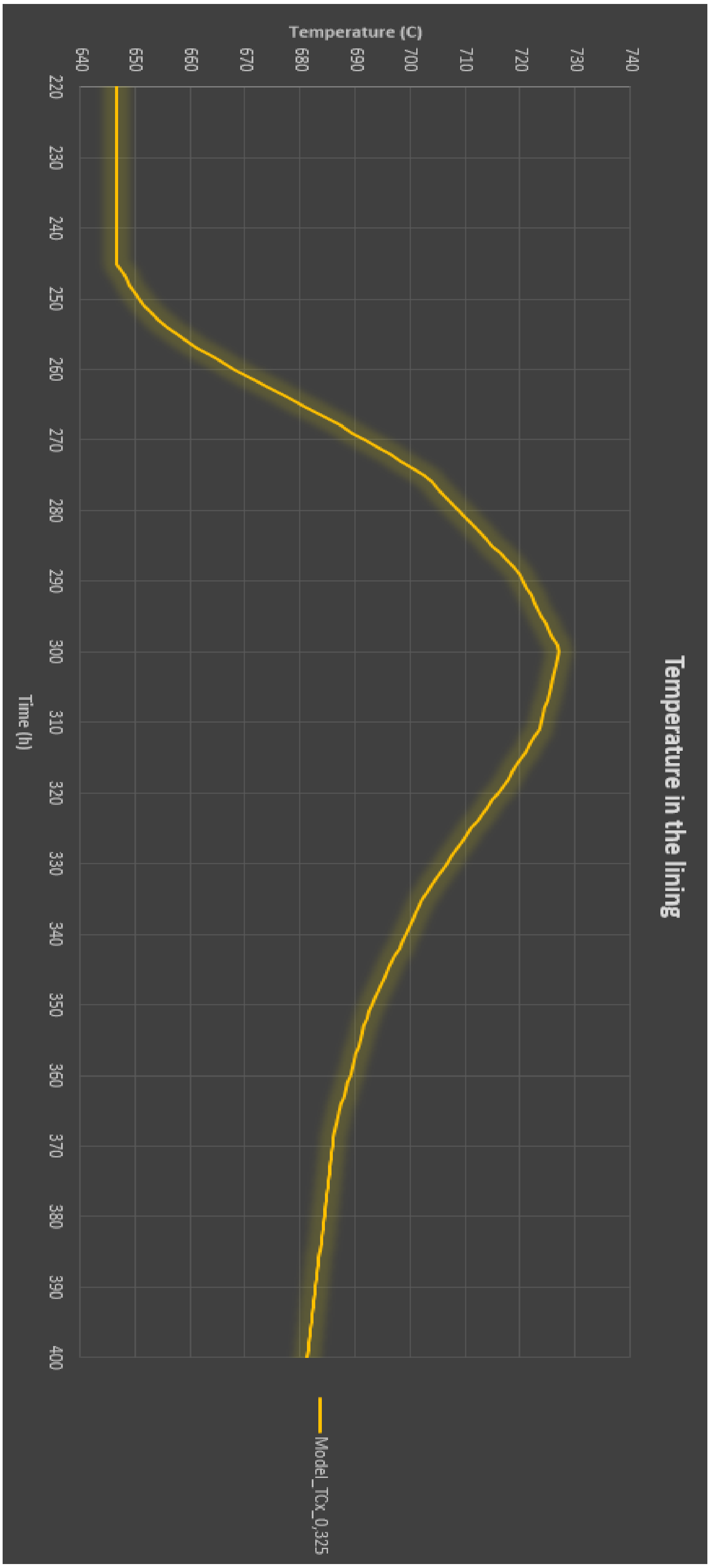
Figur 11 shows TC18 and Model_TC18_0



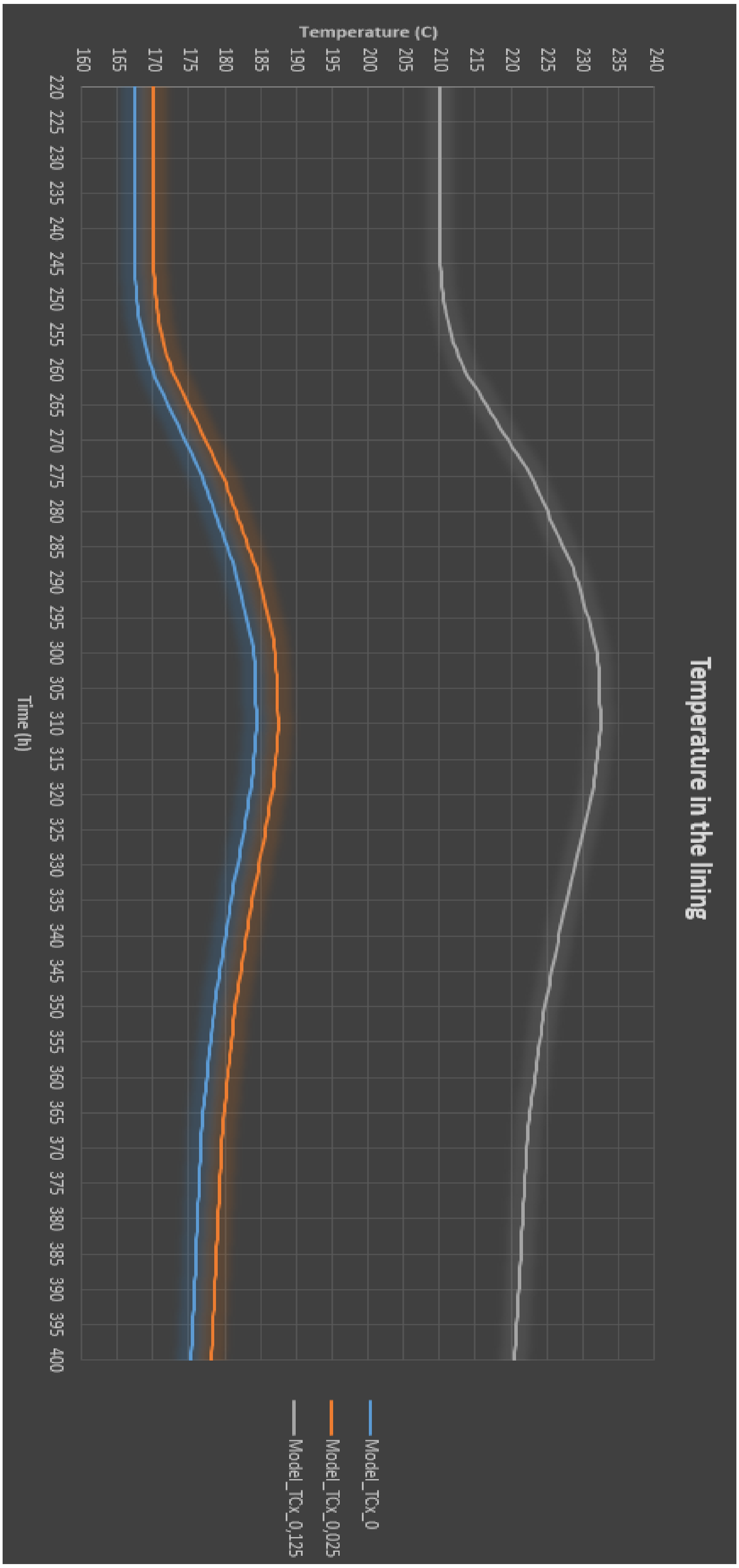
Figur 12 shows the lining temperature for Model_TC18_0 - Model_TC18_1.545



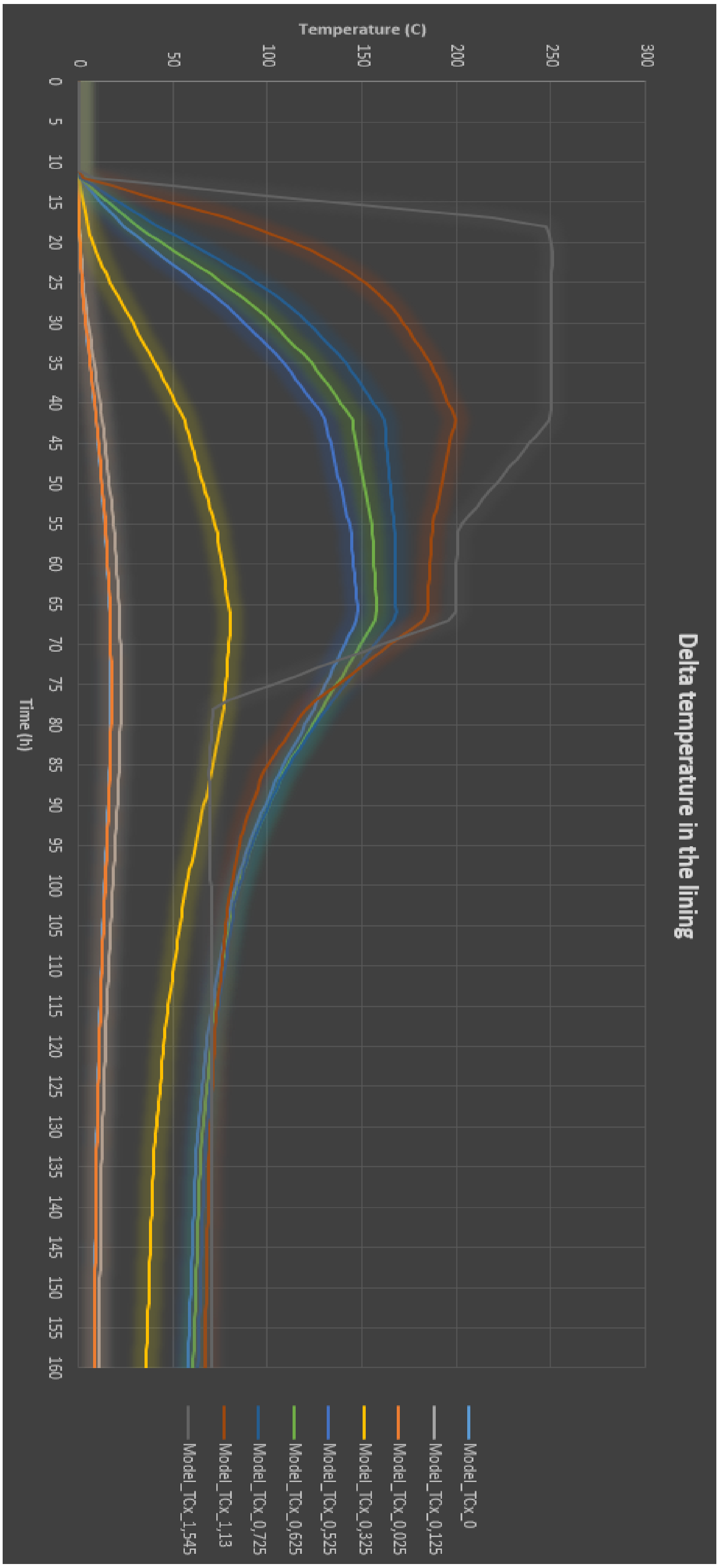
Figur 13 shows the lining temperature for Model_TC18_0.525 - Model_TC18_1.545



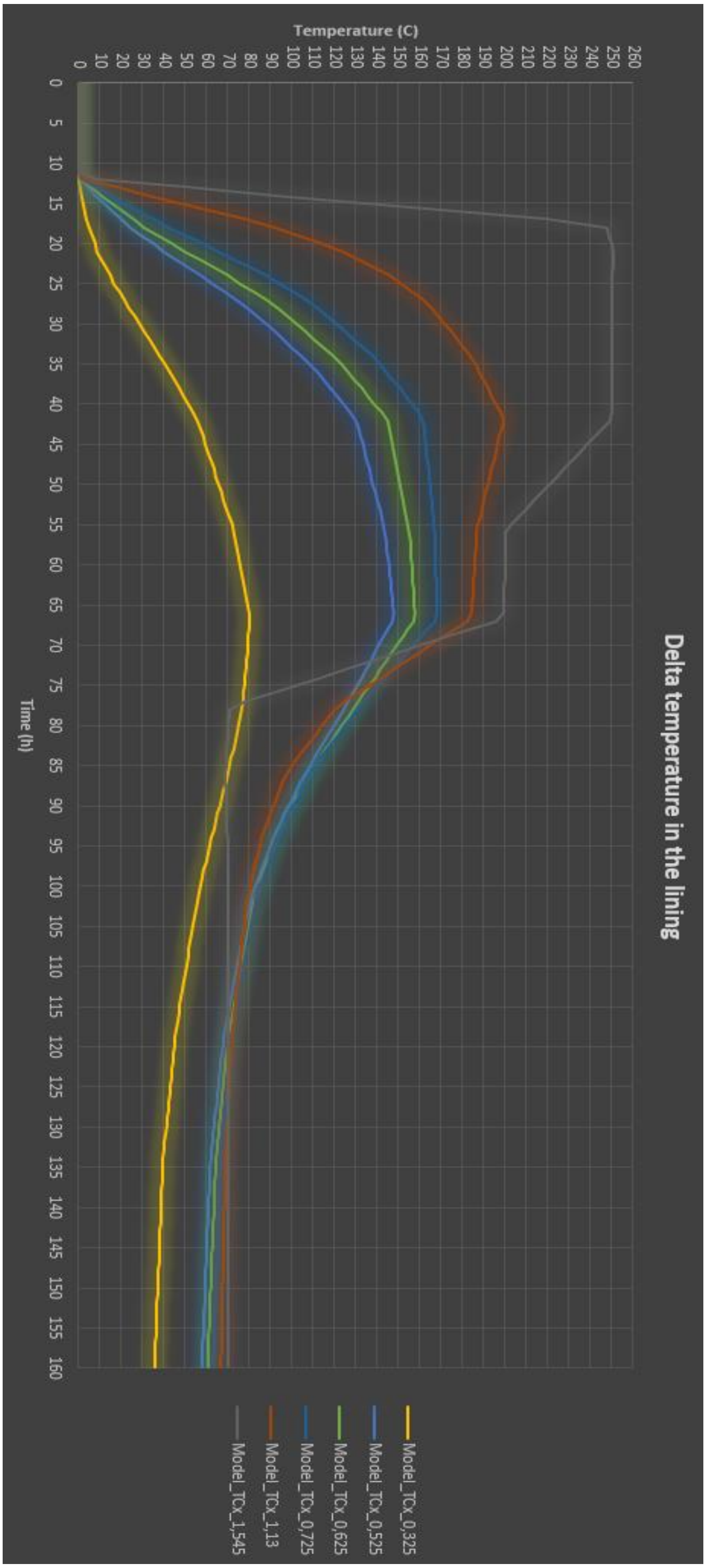
Figur 14 shows the lining temperature for Model_TC18_0.325



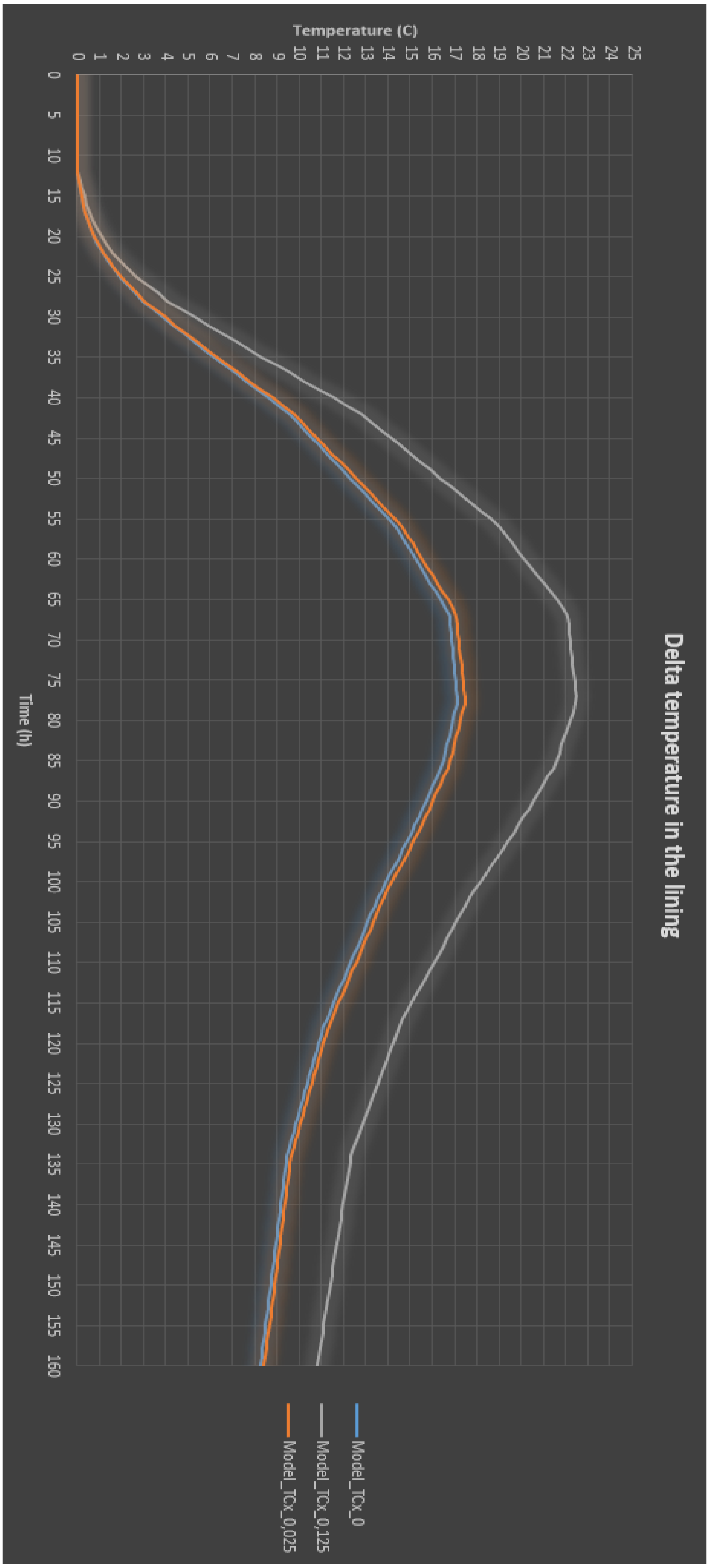
Figur 15 shows the lining temperature for Model_TC18_0 - Model_TC18_0.125



Figur 16 Shows delta temperature over time for Model_TC18_0 - Model_TC18_1,545

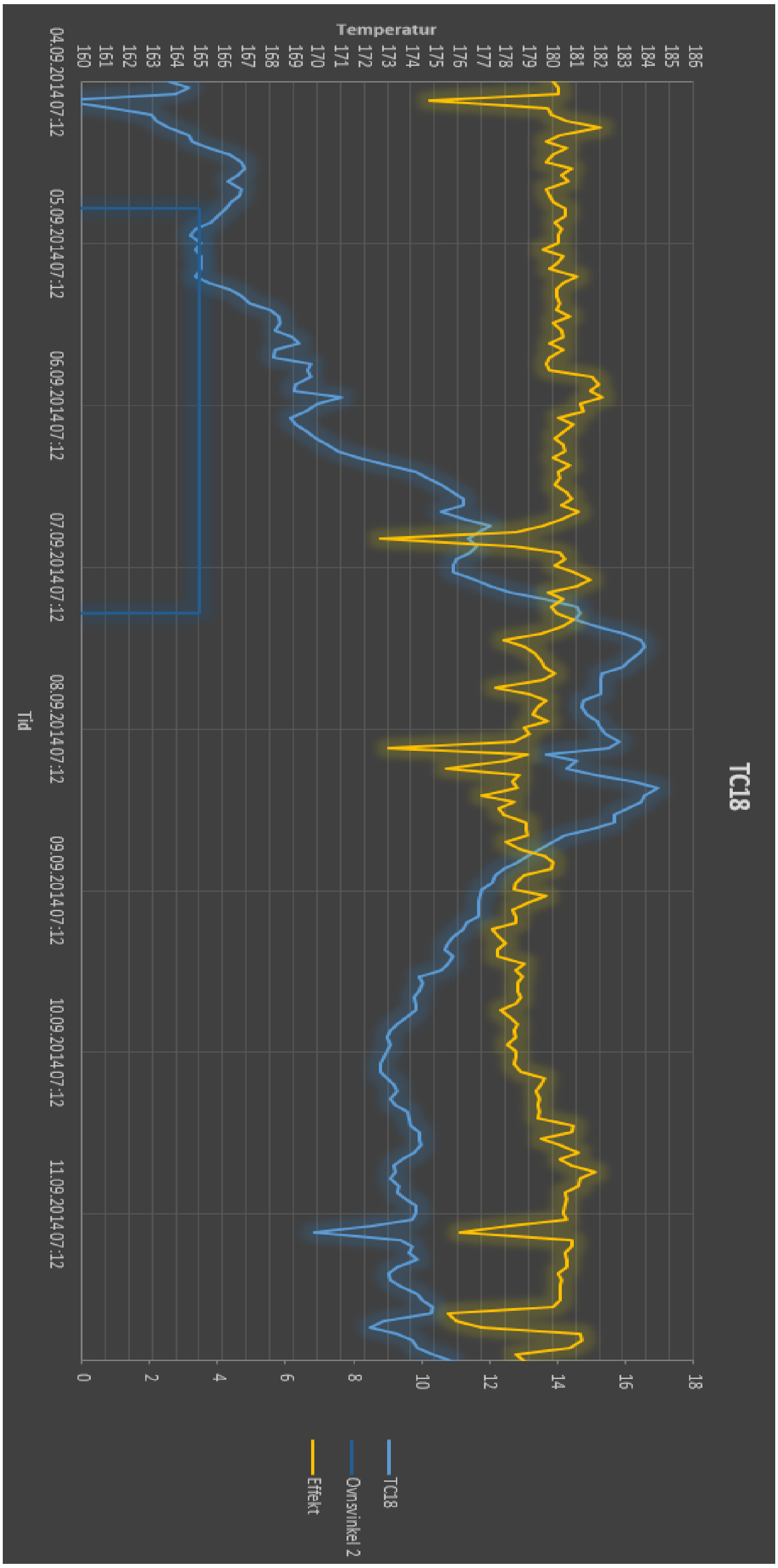


Figur 17 Shows delta temperature over time for Model_TC18_0.325 - Model_TC18_1,545

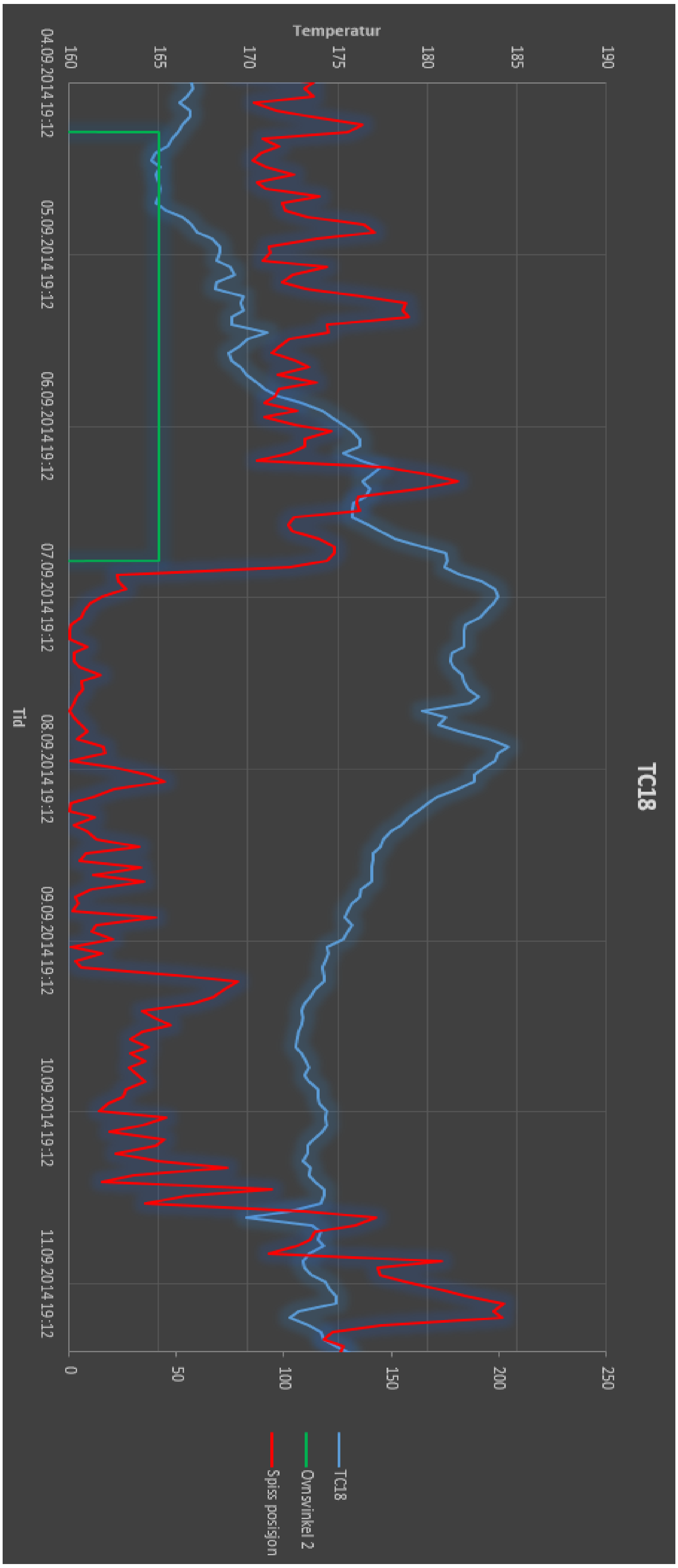


Figur 18 Shows delta temperature over time for Model_TC18_0 - Model_TC18_0.025

12.3 CASE 1 EXSTRA

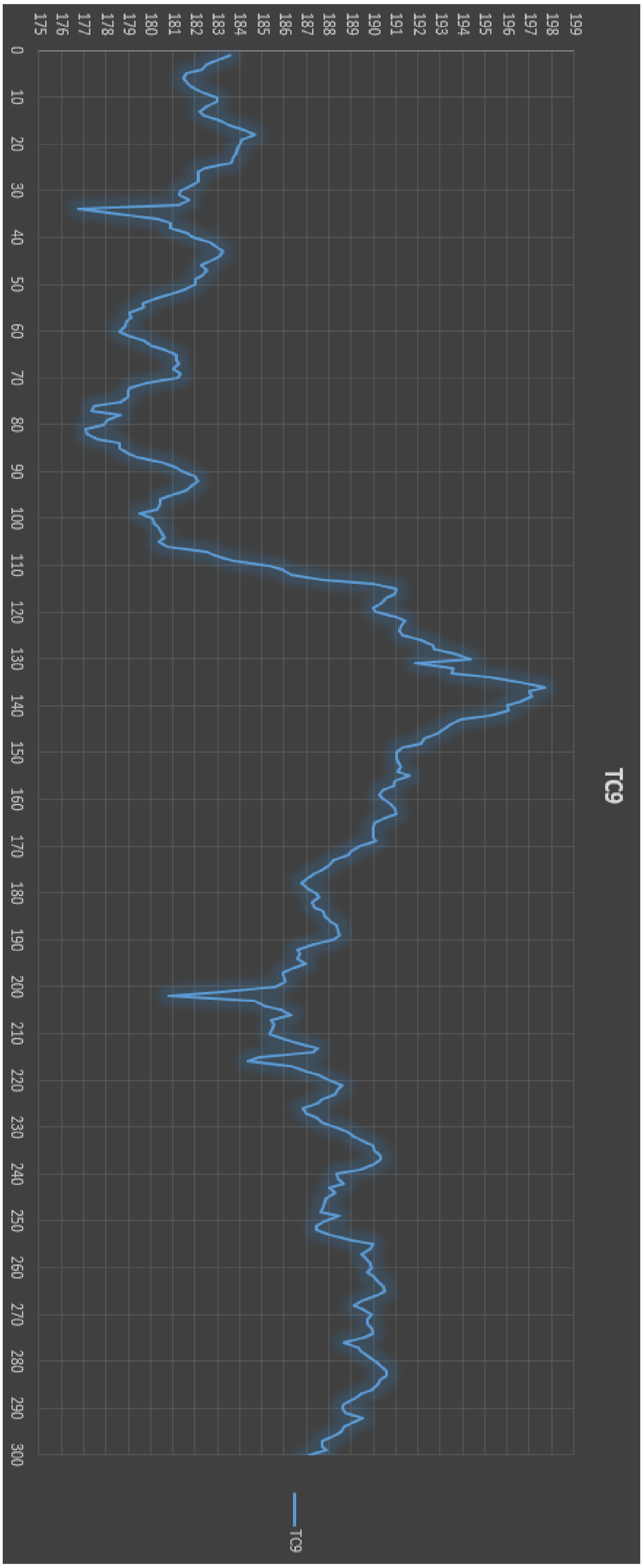


Figur 19 Shows the electrode position, furnace load and TC18 for the furnace



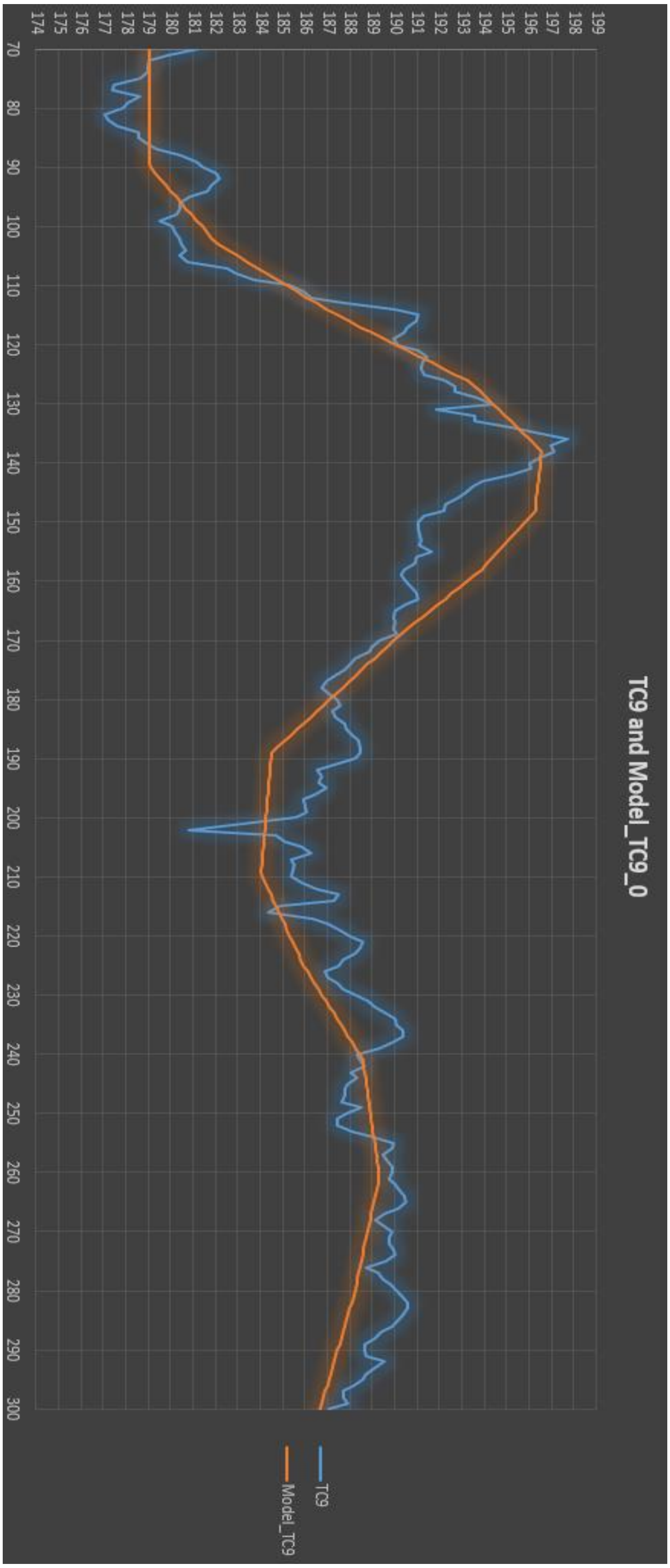
Figur 20 Shows the electrode tip position, electrode poisition and TC18

12.4 CASE 2

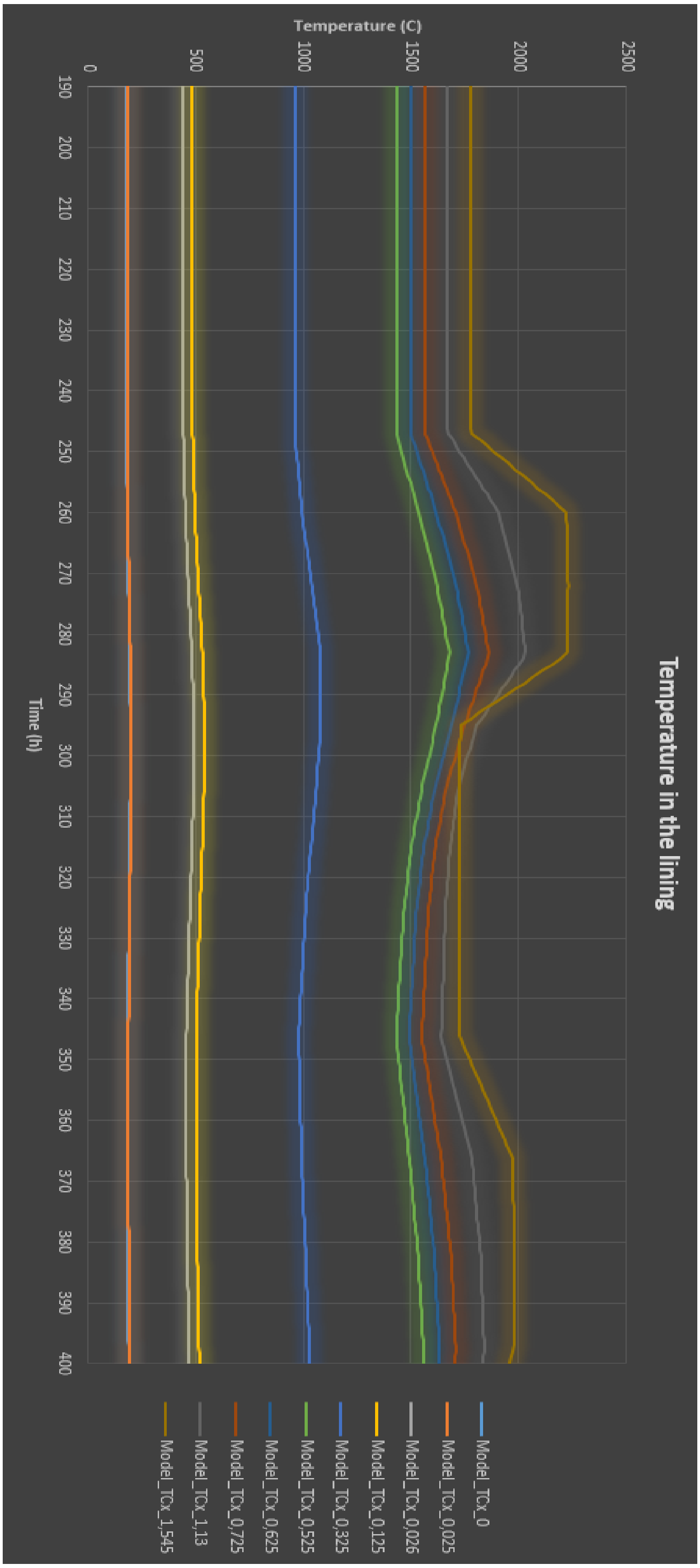


Figur 21 shows the temperature for TC9 over time

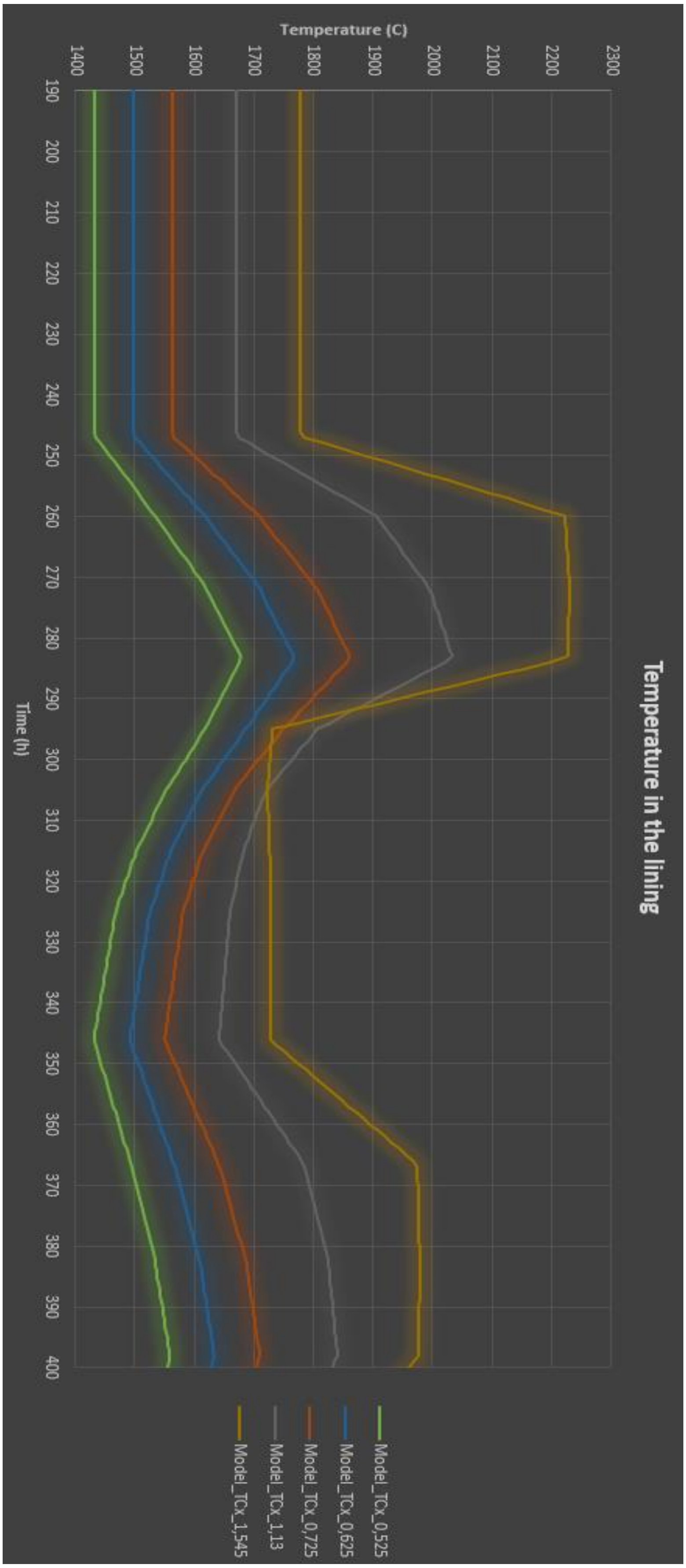
12.5 CASE 2 WITH THE ISOLATING LAYER



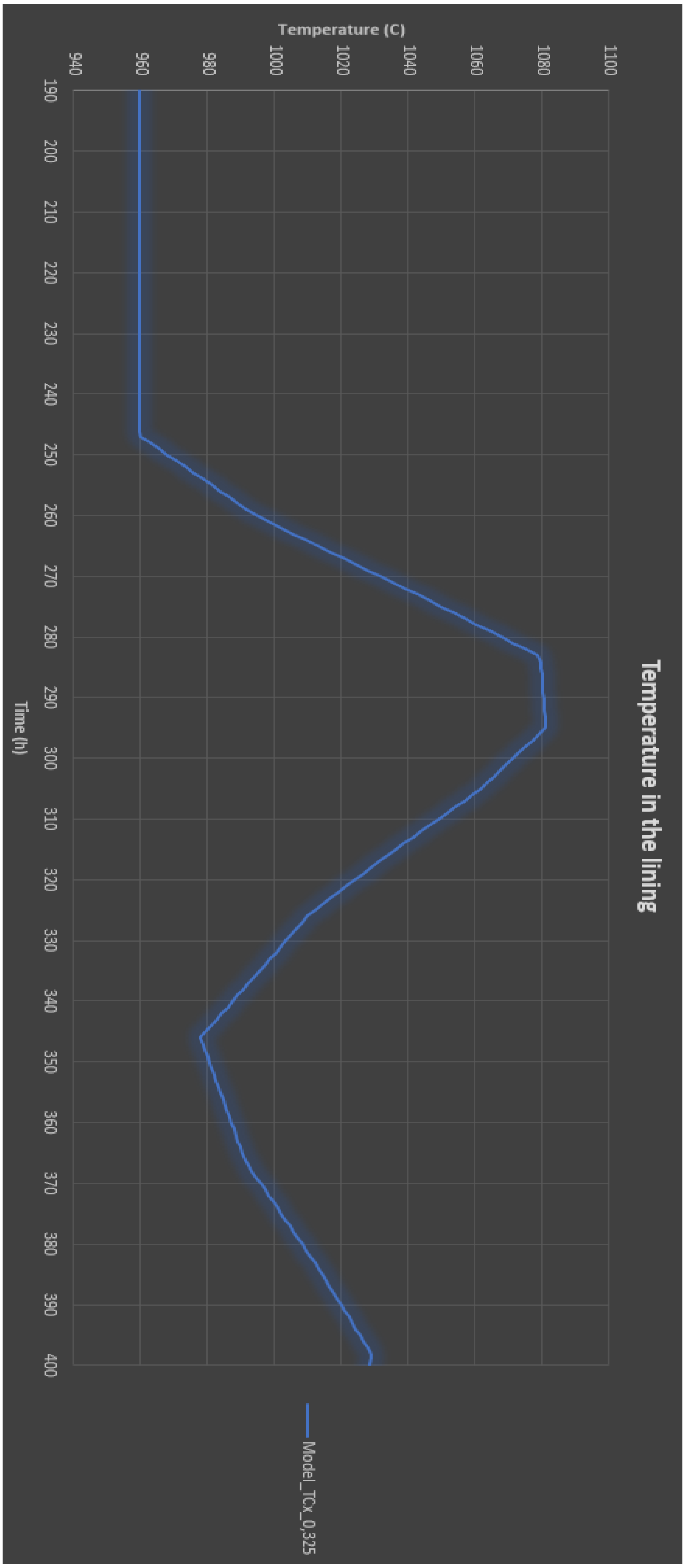
Figur 22 shows TC9 and Model_TC9_0



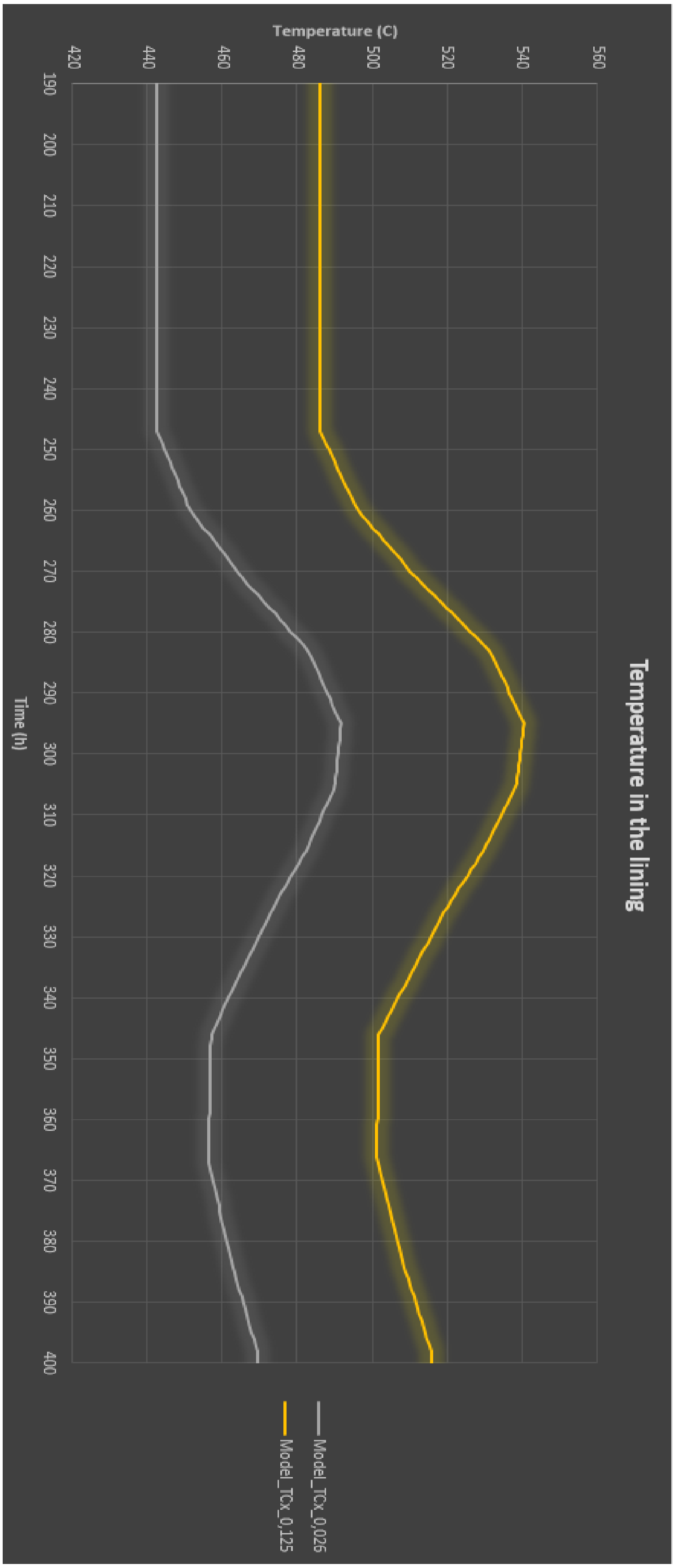
Figur 23 shows the lining temperature for Model_TC9_0 - Model_TC9_1.545



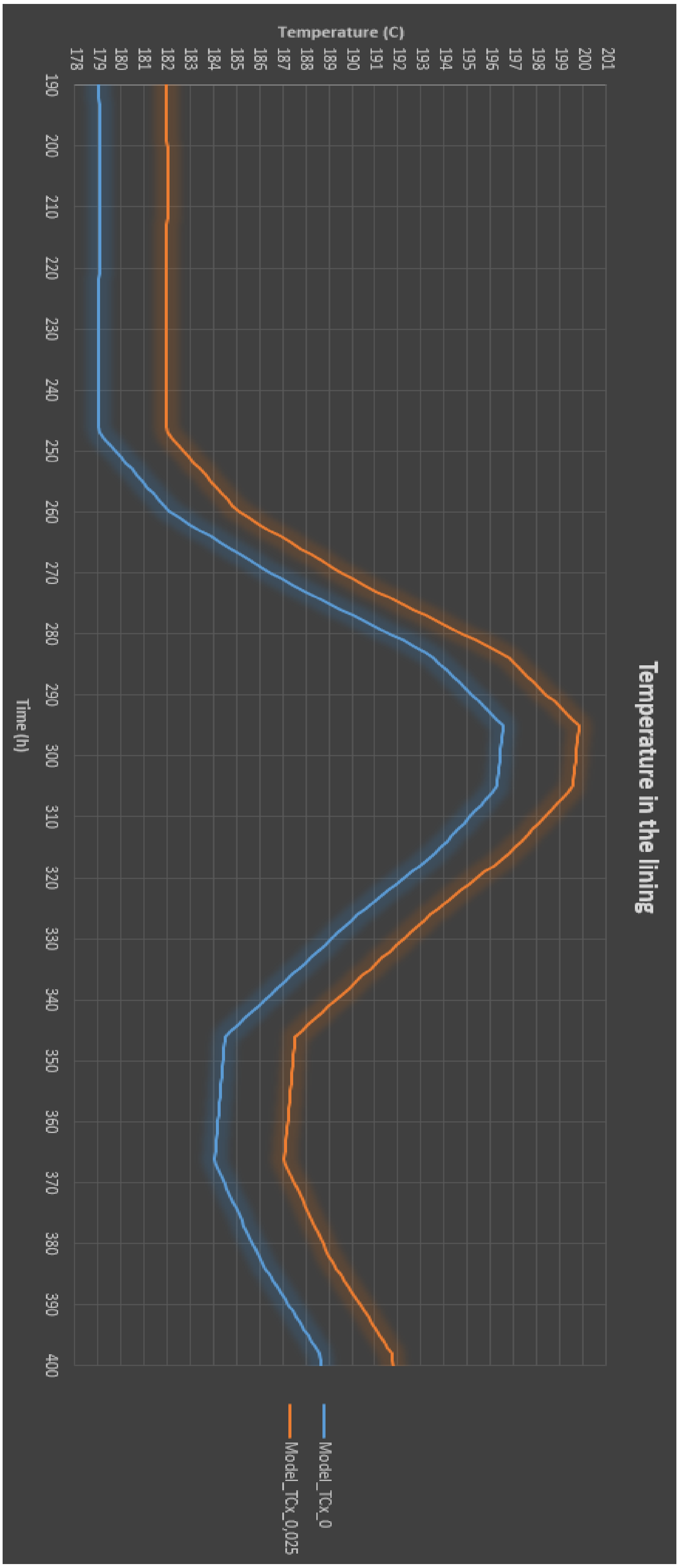
Figur 24 shows the lining temperature for Model_TC9_0.525 - Model_TC9_1.545



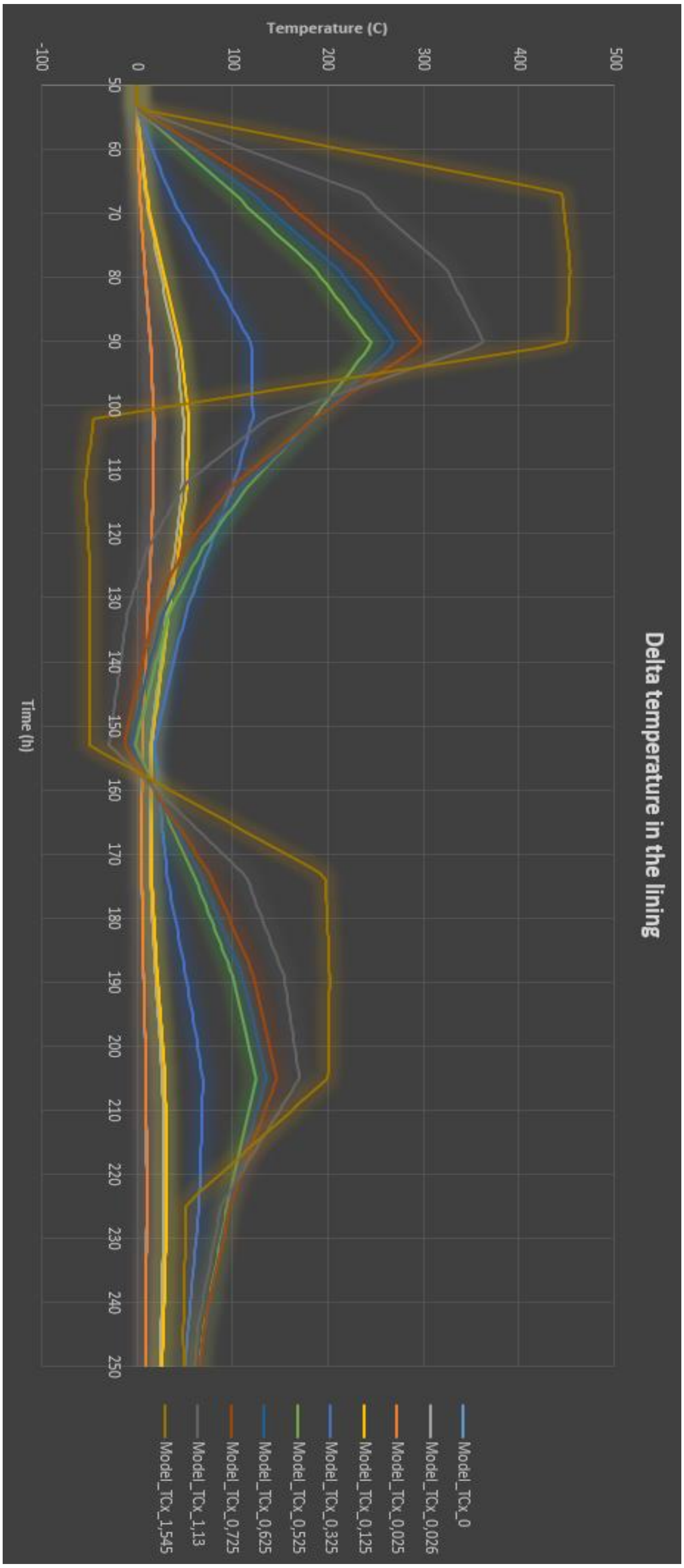
Figur 25 shows the lining temperature for Model_TC9_0.325



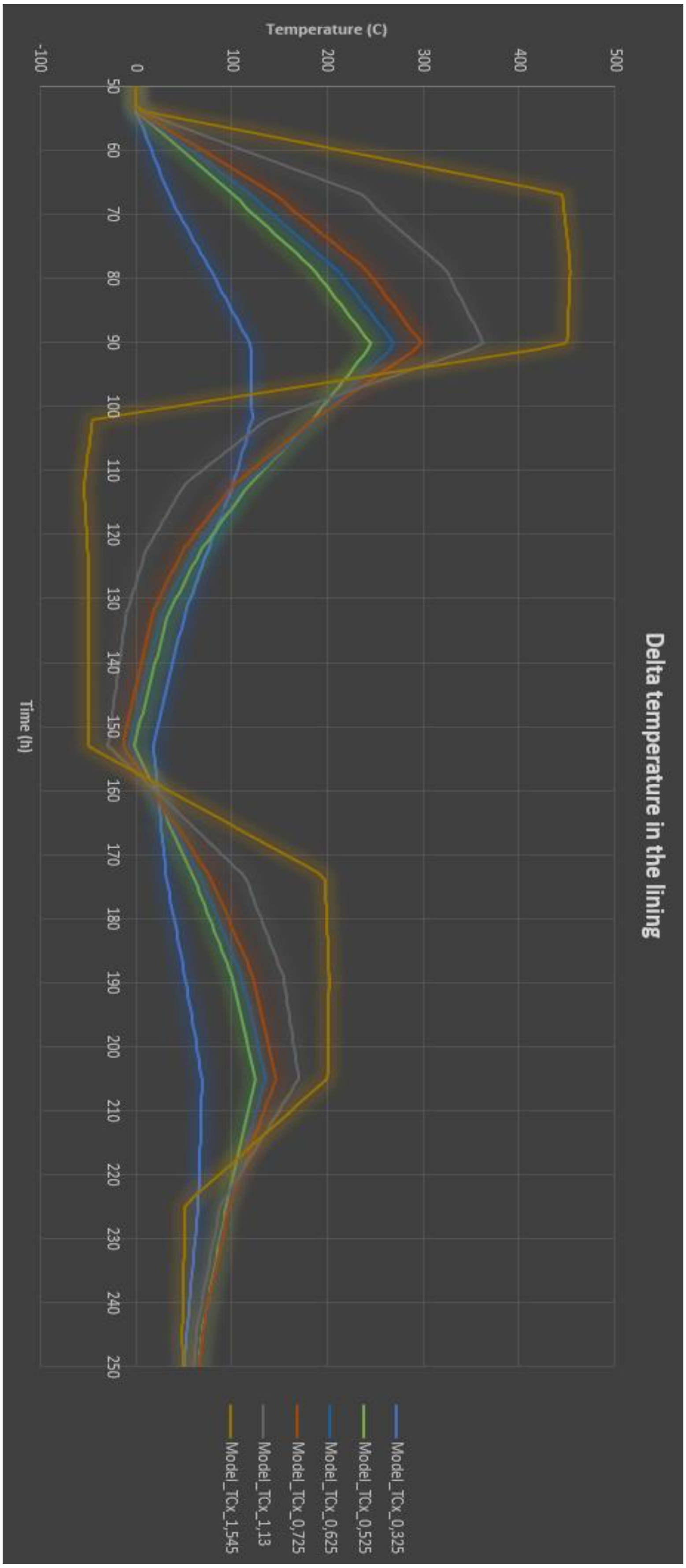
Figur 26 shows the lining temperature for Model_TC9_0.026 - Model_TC18_0.125



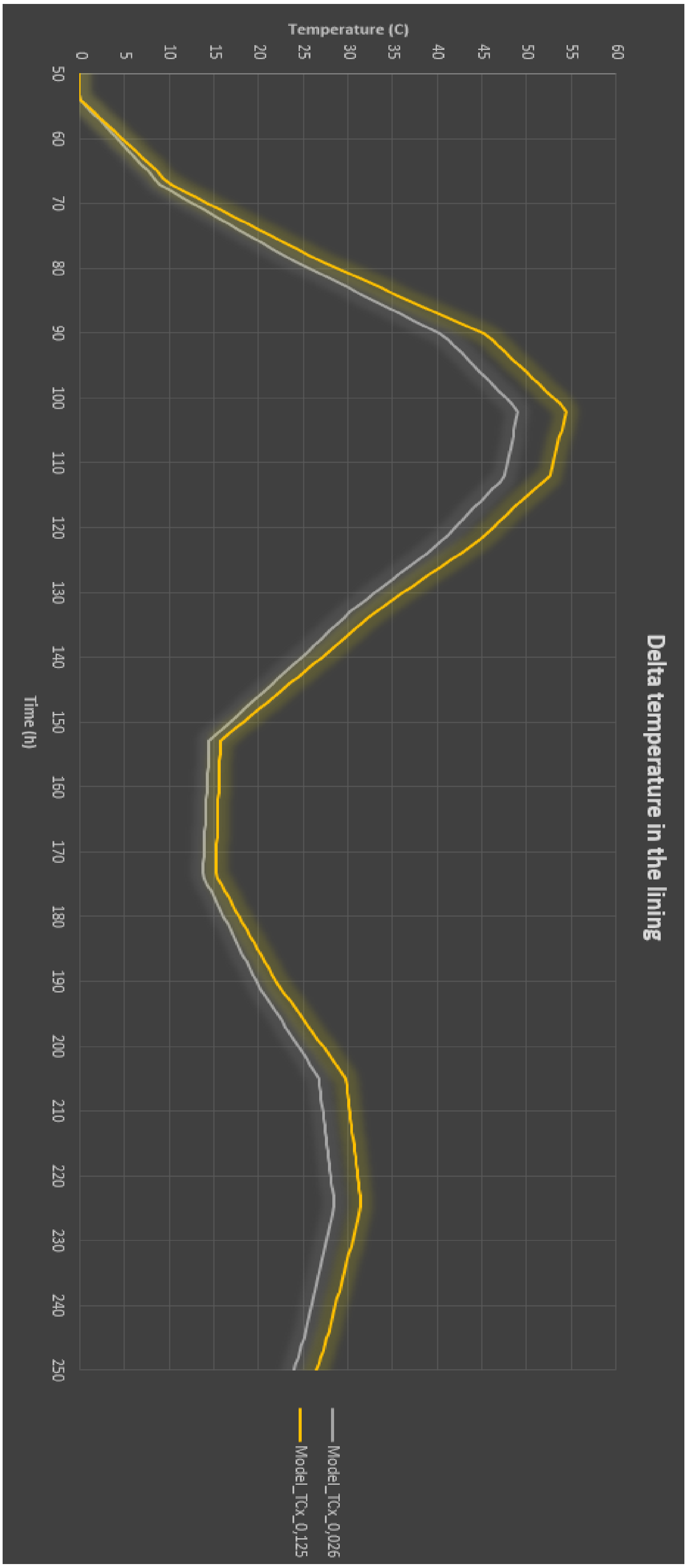
Figur 27 shows the lining for Model_TC9_0 and Model_TC9_0.025



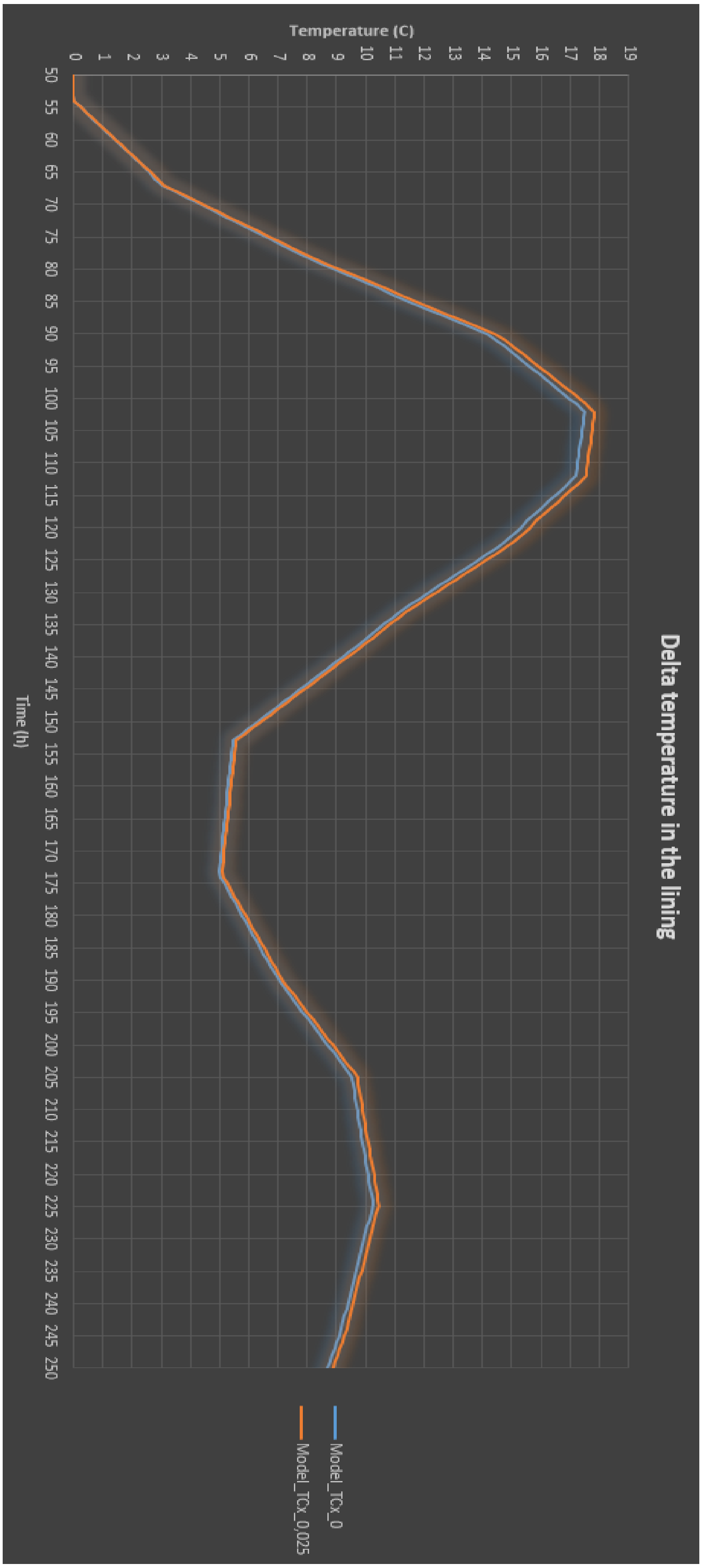
Figur 28 Shows delta temperature over time for Model_TC9_0 - Model_TC9_1,545



Figur 29 Shows delta temperature over time for Model_TC9_0.325 - Model_TC9_1,545

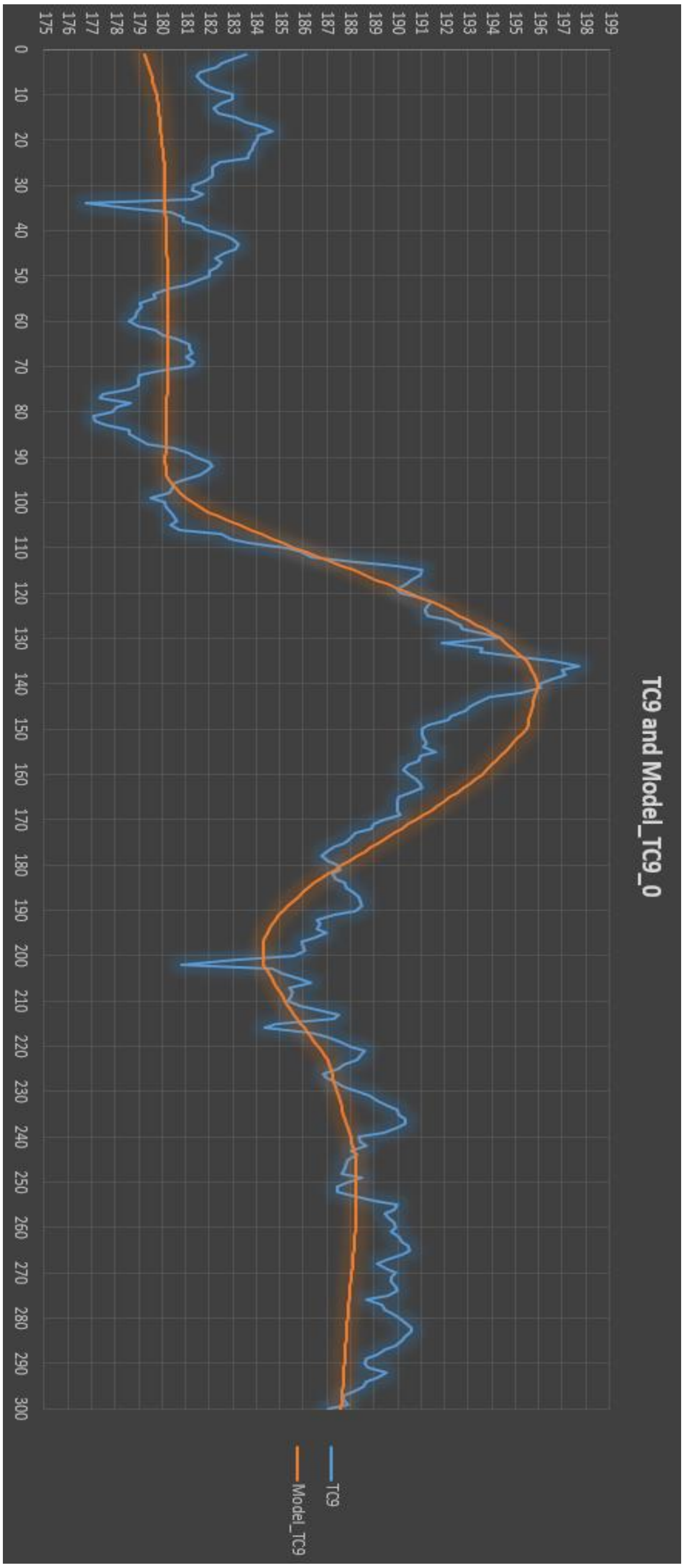


Figur 30 Shows delta temperature over time for Model_TC9_0.026 - Model_TC9_0.125

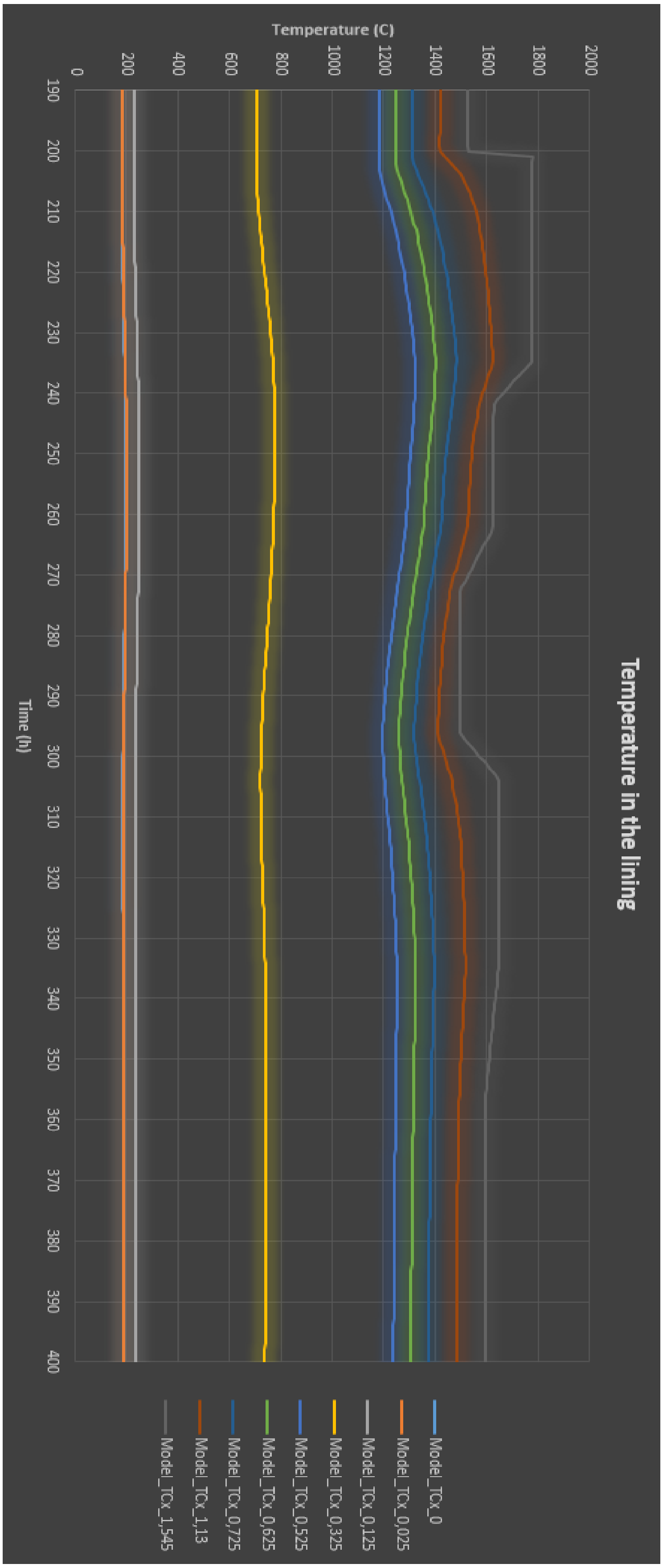


Figur 31 Shows delta temperature over time for Model_TC9_0 and Model_TC9_0.025

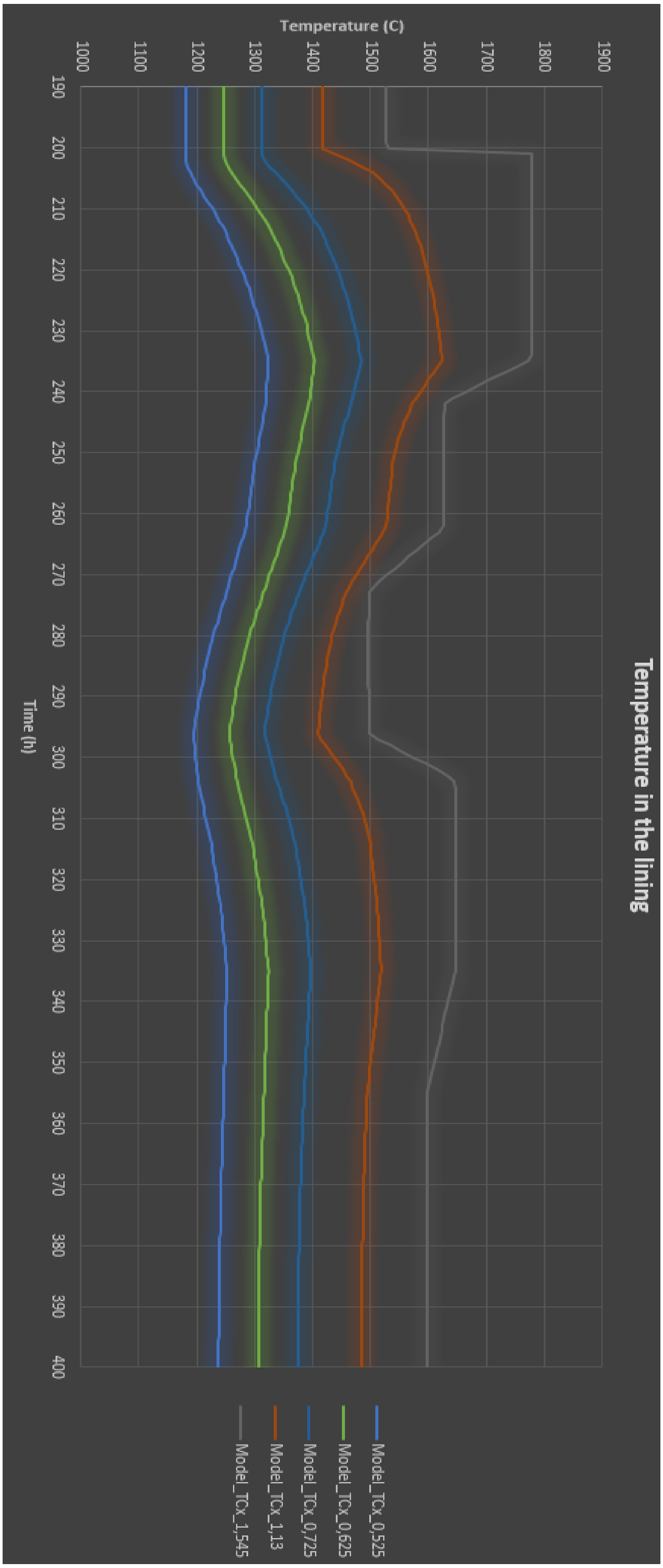
12.6 Case 2 with the isolating layer



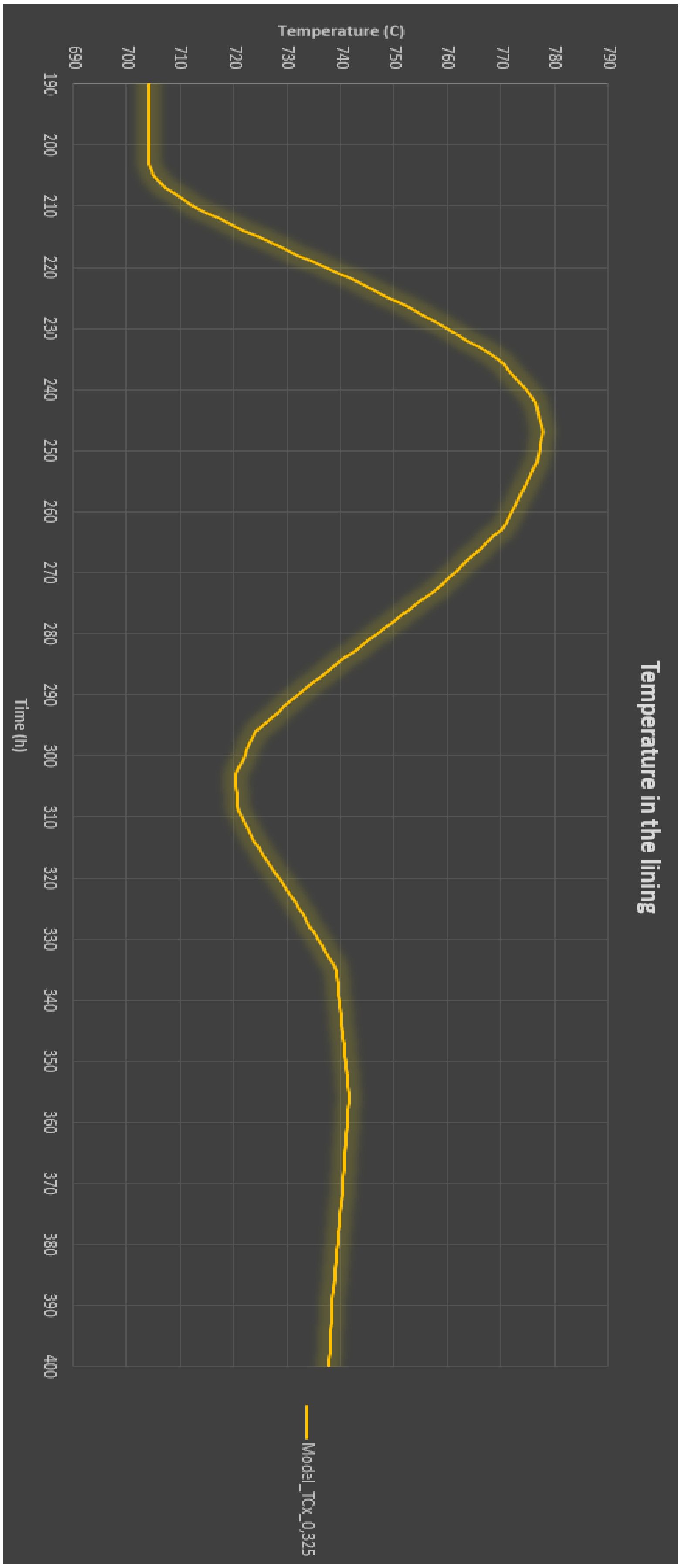
Figur 32 shows TC9 and Model_TC9_0, modelled without the isolating layer



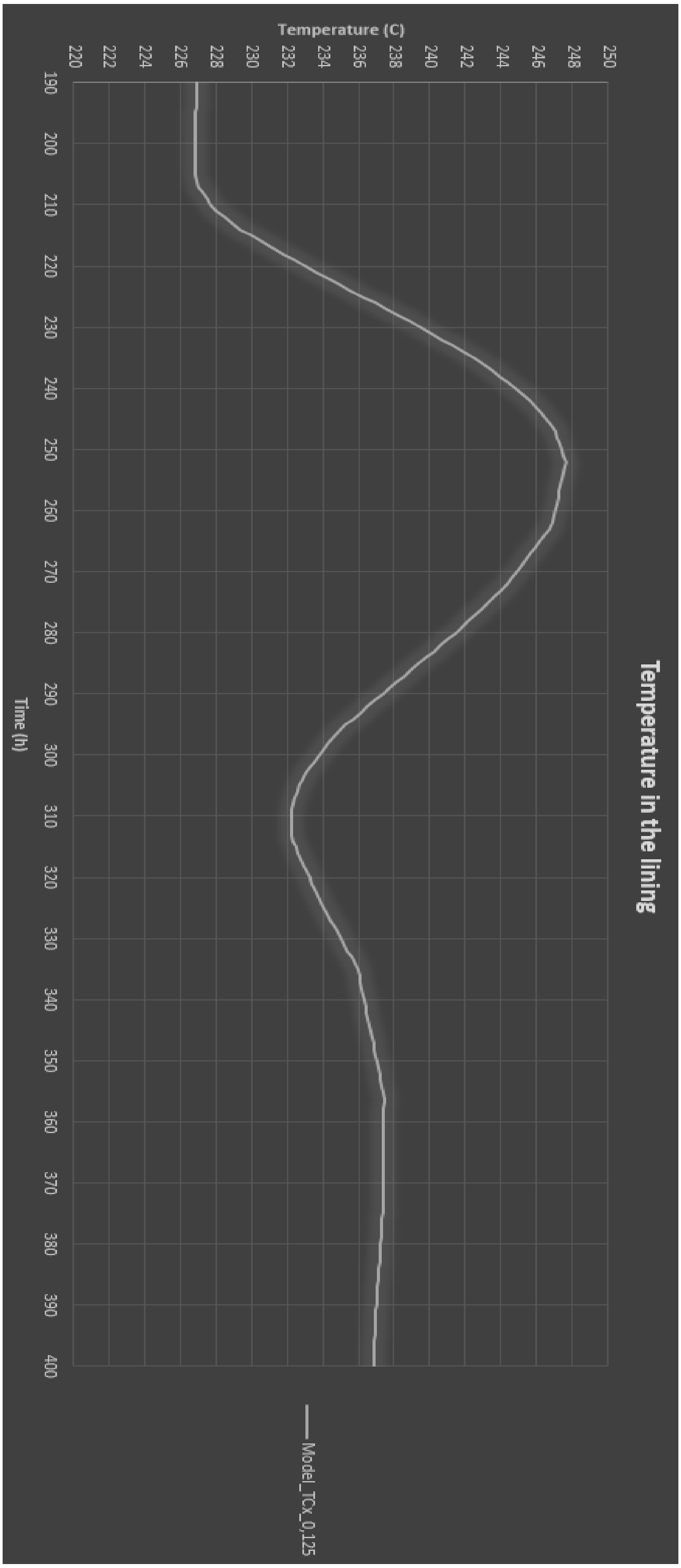
Figur 33 shows the lining temperature for Model_TC9_0 - Model_TC9_1.545 without the isolating layer



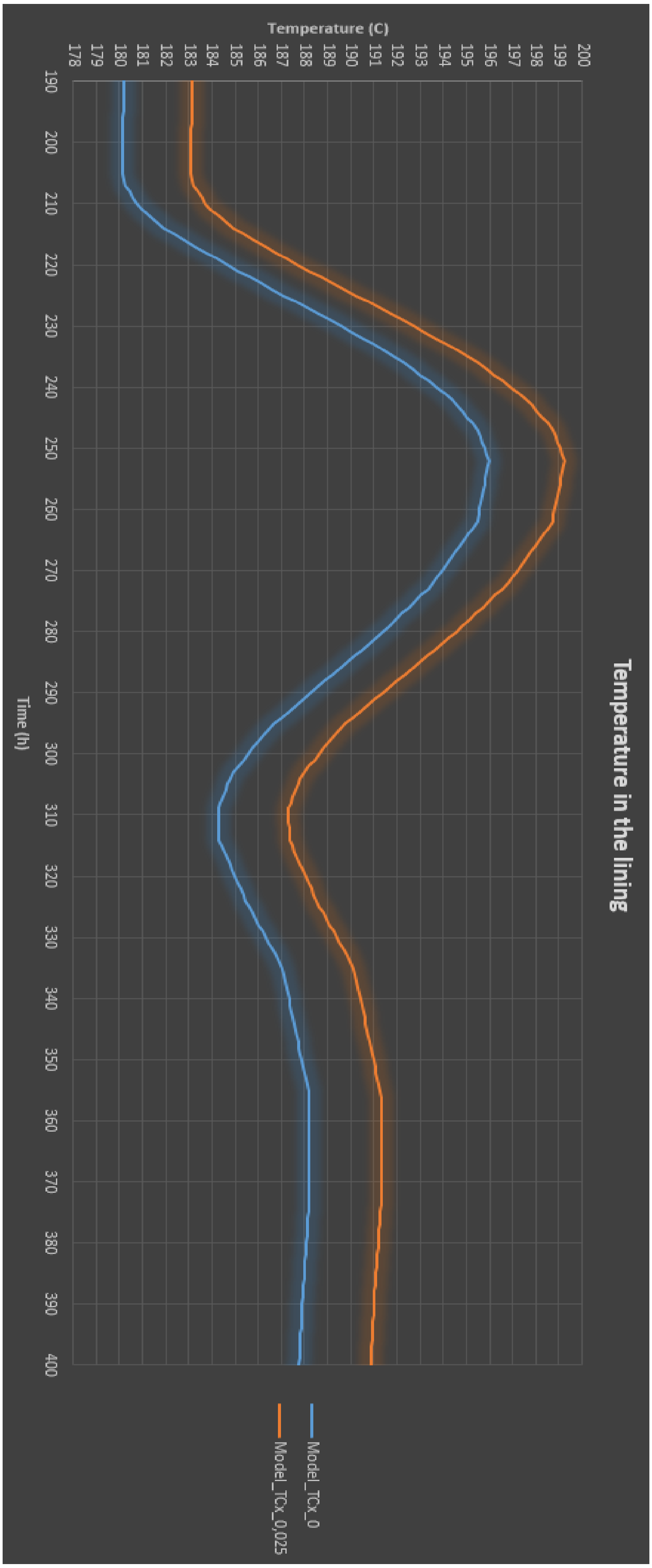
Figur 34 shows the lining temperature for Model_TC9_0.525 - Model_TC9_1.545 without the isolating layer



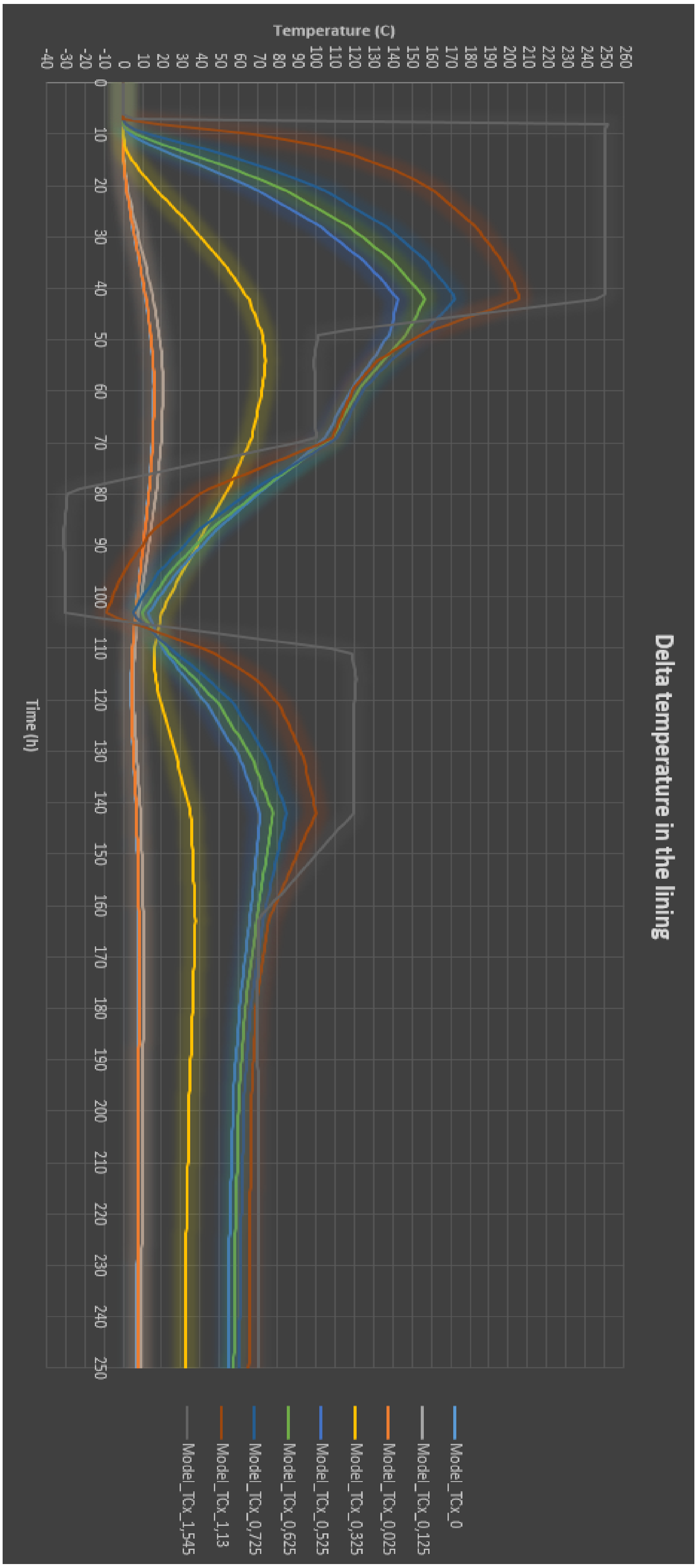
Figur 35 shows the lining temperature for Model_TC9_0.325 without the isolating layer



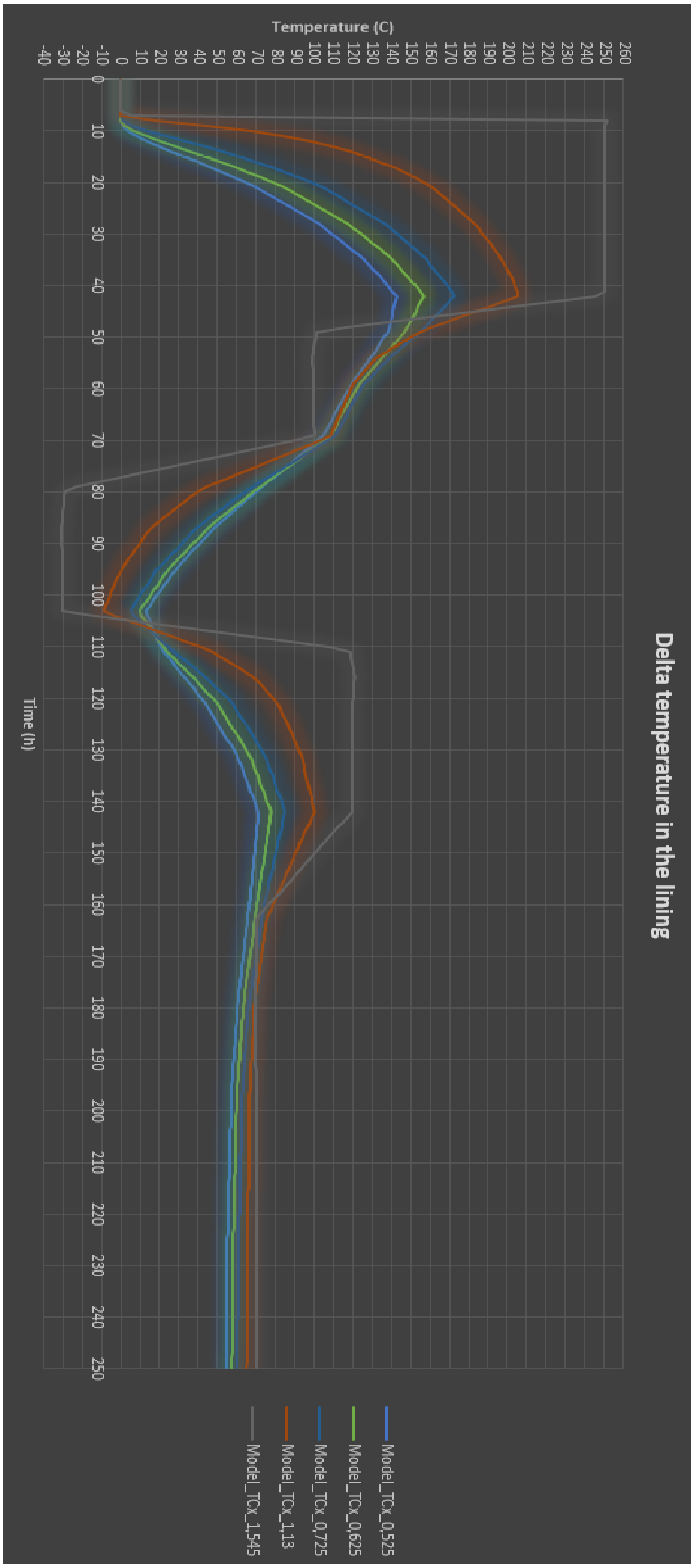
Figur 36 shows the lining temperature for Model_TC9_0.125 without the isolating layer



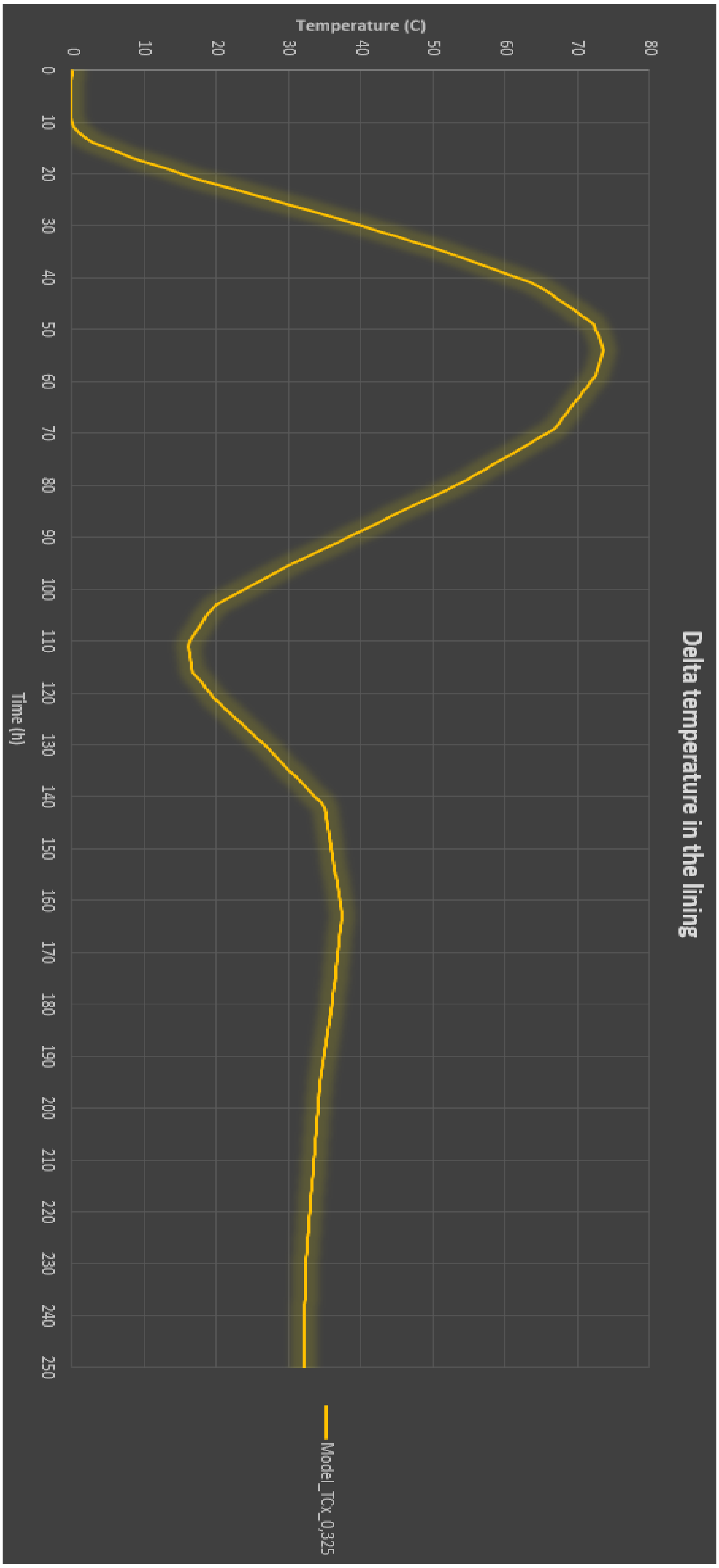
Figur 37 shows the lining temperature for Model_TC9_0 - Model_TC9_0.025 without the isolating layer



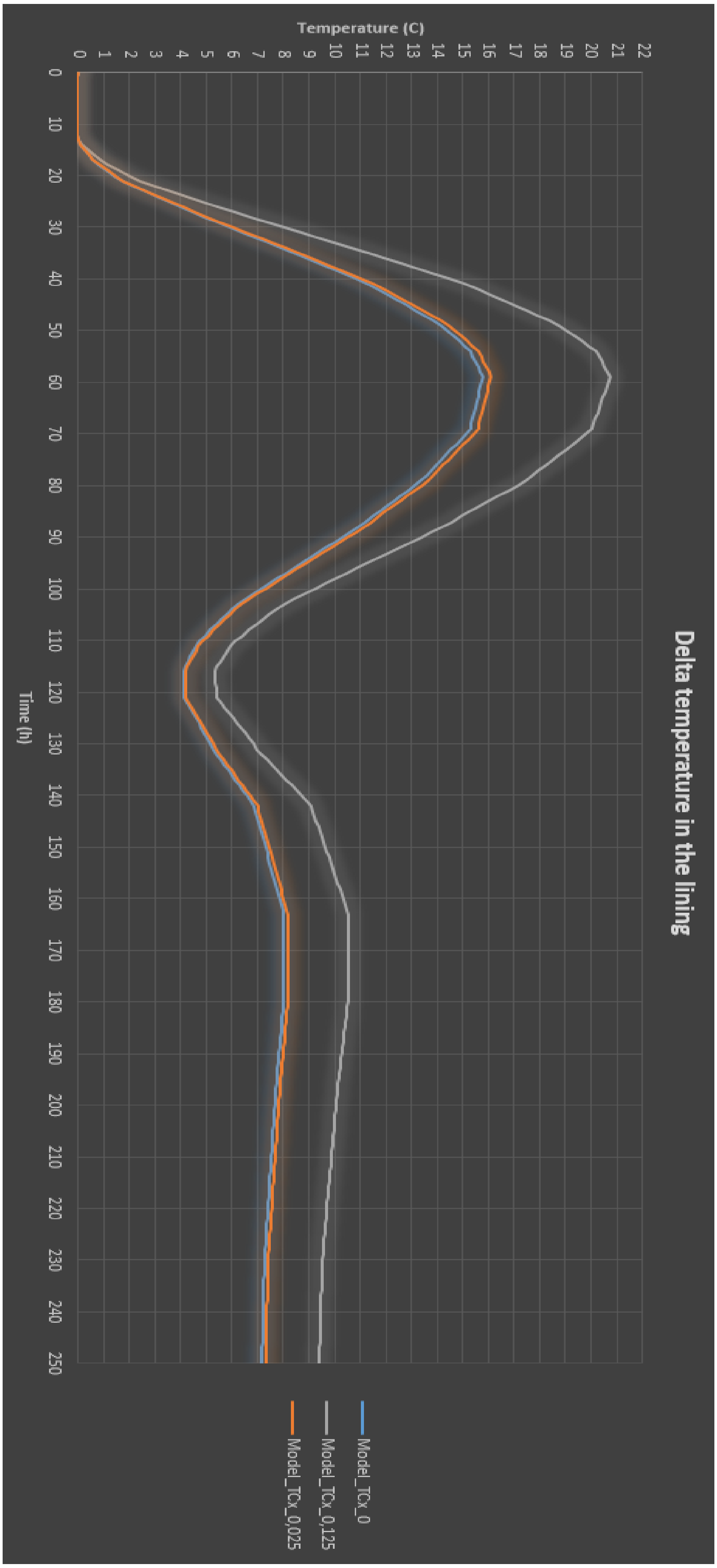
Figur 38 Shows delta temperature over time for Model_TC9_0 - Model_TC9_1,545 without the isolating layer



Figur 39 Shows delta temperature over time for Model_TC9_0.525 - Model_TC9_1,545 without the isolating layer

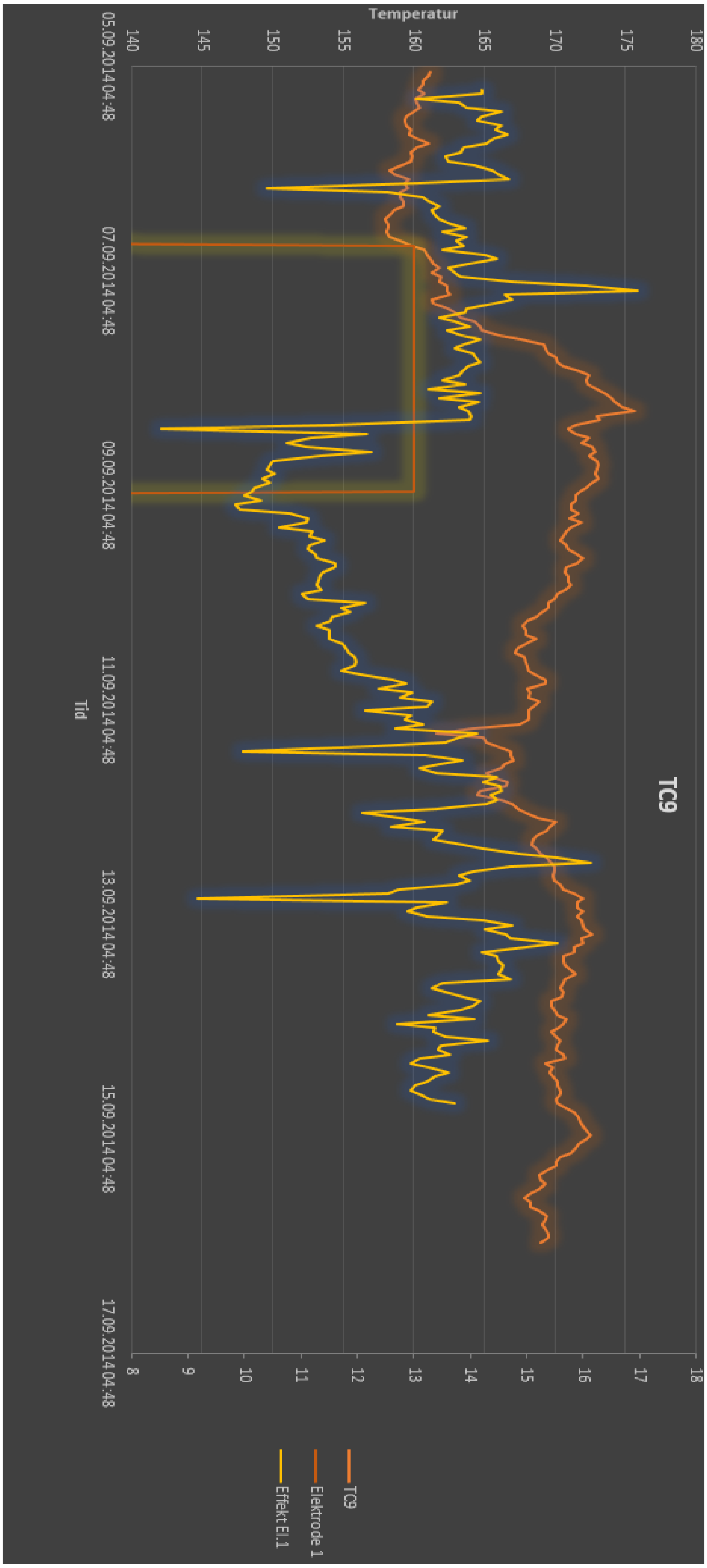


Figur 40 shows delta temperature over time for Model_TC9_0,325 without the isolating layer

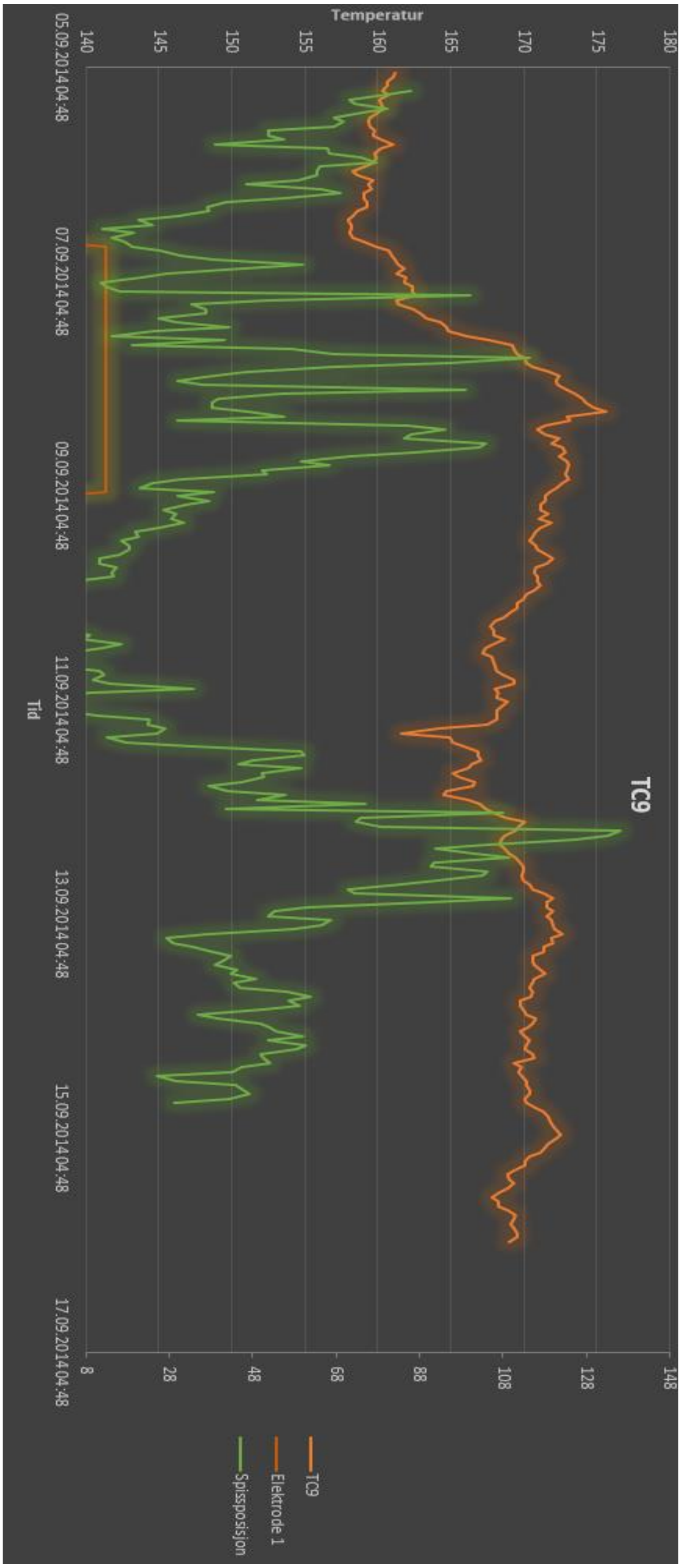


Figur 41 Shows delta temperature over time for Model_TC9_0 - Model_TC9_0,125 without the isolating layer

12.7 CASE 2 EXSTRA



Figur 42 Shows the electrode position, furnace load and TC9 for the furnace



Figur 43 shows the electrode point position, electrode passing (position) and TC9