Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Dag Olav Snersrud

Effects of external cooling on smoldering fire in wood pellets

-An experimental parameter study

Master's thesis in Energy and process engeneering
Supervisor: Ivar Ståle Ertesvåg
Co-supervisor: Ragni Fjellgaard Mikalsen and Kemal Sarp Arsava
November 2021

NTNU
Norwegian University of
Science and Technology

Dag Olav Snersrud

Effects of external cooling on smoldering fire in wood pellets

-An experimental parameter study

Master's thesis in Energy and process engeneering
Supervisor: Ivar Ståle Ertesvåg
Co-supervisor: Ragni Fjellgaard Mikalsen and Kemal Sarp Arsava
November 2021

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

Smoldering fire is a slow exothermic reaction where fuel and oxygen is consumed to generate heat. What separates smoldering from other kinds of combustion's is the absence of a visible flame. Smoldering fires are also significantly easier to ignite, and the persistent behavior of the fires makes them one of the leading causes of casualties in residential fires. The environmental aspect of smoldering is also important because smoldering peat fires are responsible for the destruction of carbon sinks and the release of severe quantities of environmentally hostile gasses.

The main goal of the experiments was to explore the effects of external cooling on smoldering fires in wood pellets. This was done by putting a sample of wood pellets inside an insulated steel cylinder heated by an external heating source until a smoldering fire ignited. Around the steel cylinder, water was circulation in a copper spiral. During the tests, the temperature was carefully monitored, along with mass, airflow, and the pressure of the system, which enabled calculations to be made after the tests. A total of 24 experiments were conducted, three of which suffered equipment malfunctions, making the data basis for this thesis 21 tests. Each with a purpose of uncovering more information on the topic of smoldering by investigating different parameters.

The first parameter being heating duration, where ignition was the main focus. The ignition of smoldering under the influence of external cooling was a demanding task. With the flow rate used in this section of the study, a consistent, predictable smoldering fire was impossible to create, and heating duration's up to 30 hours were tested without the initiation of smoldering. Compared to the work by Mikalsen in 2018, this translates to an increase in heating duration equaling a 400% increase of what was needed to initiate smoldering without external cooling. Next, the target was to explore what impact different flow rates of water in the cooling jacket would have, and how this affected the heat transfer. Using a flow rate of 0.29 L/min, the heat loss to water was 103 W. When the flow rate was increased to 0.42 L/min, the heat loss to water only increased to 106 W, indicating that the heat transfer may have reached a stagnation point. This phenomenon was not further investigated due to time restrictions.

The total combustion time was significantly lower in the smoldering cases where external cooling was used, making the fire more rapid, and with a higher heat production rate than in the cases without external cooling. Looking at this result in light of the results from the ignition test series, indicating that when external cooling is applied, the ignition is more difficult, but when ignited, the fire burns more violent and rapid.

This study sheds light on the not particularly well-known phenomenon of smoldering fires, by studying the effects of external cooling on smoldering fires in wood pellets.

Sammendrag

Ulmebrann er en saktegående eksoterm reaksjon, der brensel og oksygen er konsumert for å produsere varme. Det som skiller ulmebrann fra andre forbrenningsformer, er at den brenner uten en synlig flamme. Ulmebranner er også markant lettere å antenne, som i kombinasjon med at brannen er vanskelig å håndtere, gjør at ulmebrann er en av de ledende årsakene til dødsfall i husbranner. Ulmebranners påvirkning på miljøet er også viktig, fordi ulmebranner i torv er ansvarlig for ødeleggelsen av karbonlagre, samt utslipp av store mengder miljøfiendtlige gasser.

Hovedmålet med eksperimentene var å utforske hvilke effekter ekstern kjøling hadde på ulmebranner i trepellets. Dette ble gjort ved å sette en testmengde med trepellets i en isolert stålsylinder, varmet opp av en ekstern varmekilde til det oppsto en ulmebrann. Rundt stålsylinderen sirkulerte det vann i en kobberspiral. Under testene ble temperaturer målt, samt massen, luftstrømmen og trykket i systemet, som gjorde det mulig å utføre beregninger etter testene ble avsluttet. Totalt ble det gjennomført 24 tester, der 3 av dem opplevde utstyrsfeil, som resulterte i at datagrunnlaget til denne oppgaven er 21 tester. Hver enkelt test med et formål om å avdekke mer informasjon om ulmebrann ved å undersøke ulike parametere.

Den første parameteren var oppvarmingstid, der tenning var hovedfokuset. Tenning av ulmebrann påvirket av ekstern kjøling var en utfordrende oppgave. Med vannstrømmen som ble brukt i denne delen av studiet, var det ikke mulig å få en forutsigbar tenning av ulmebrann, og oppvarmingstider opp til og med 30 timer ble testet uten å få tenning. Sammenlignet med arbeidet til Mikalsen i 2018 oversetter dette til en økning av oppvarmingstid lik 400% mer enn det som var nødvending for å tenne ulmebrann uten ekstern kjøling. Deretter var målet å utforske i hvilken grad ulike rater av vannstrøm i kjøleenheten påvirket varmeoverføringen. Ved å bruke en vannstrøm på 0.29 L/min var varmetapet til vannet 103 W. Da denne vannstrømmen ble økt til 0.42 L/min, økte varmetapet til vannet kun til 106 W, som indikerer at varmeoverføringen kan ha nådd et stagneringspunkt. Dette fenomenet ble ikke utforsket ytterligere, på grunn av tidsbegrensninger.

Den totale forbrenningstiden var tydelig lavere i tilfellene med ulmebrann der ekstern kjøling var tatt i bruk. Dette betyr at brannen går raskere og med en høyere varmeproduksjonsrate enn i tilfellene uten ekstern kjøling. Dette resultatet sett i lys av resultatene fra testserien som fokuserte på tenning, indikerer at når ekstern kjøling er tatt i bruk, er det vanskeligere å tenne ulmebrannen, men når den først tenner, brenner den raskere og mer intenst.

Dette studiet belyser det relativt uutforskede fenomenet ulmebrann, ved å studere hvilke effekter ekstern kjøling har på ulmebrann i trepellets.

Acknowledgements

There are many people I would like to thank for their efforts, helping me conducting experiments and writing my thesis. First of all, I would like to extend a sign of appreciation towards my three supervisors Ivar Ståle Ertesvåg at NTNU, Ragni Fjellgaard Mikalsen at RISE and Kemal Sarp Arsava at RISE. These people have not only helped me with academical questions directly connected to my thesis, but also created an environment where scientific curiosities were encouraged. Next, I would like to thank my main contact in the laboratory, Morten Daffinrud, for literally helping me putting all the pieces together in the lab. I would also like to thank the rest of the crew at RISE Fire Research AS for granting me the opportunity to write a thesis with them, and for guidance when I felt lost. Next, I would like to thank Hallingdal trepellets AS for supporting this study by sending pellets from their factory for free. Lastly, I would like to thank Katrine Fossen, for putting up and supporting me throughout the duration of this project.

Without the efforts of these people, this thesis would not have been what it is today, and for that I am grateful.

Trondheim, November 2021
Dag Olav Snersrud

Table of Contents

1 Introduction

1.1 Background

Smoldering fire is a slow exothermic reaction where, as in all forms of combustion, fuel and oxygen is consumed to generate heat in addition to some bi product. What separates a smoldering fire from a more typical fire, is the absence of flames. Smoldering can transcend to flaming but smoldering as a phenomenon burns completely without flames. Another key aspect of this type of fire, is the duration of which a smoldering fire last. The slow, persistent burning in a smoldering fire, makes the combustion long lasting and hard to extinguish with current methods. New and better quenching methods is therefore needed, but in order to know what works, and what doesn't work, a wider knowledge base is needed.

The environmental scene also suffers due to smoldering fires in the nature. Smoldering fires in peat is responsible for both the destruction of carbon sinks, and release of environmentally hostile gasses [19]. Despite many hazards connected to smoldering fires, few studies have been carried out over the years, and throughout this master's thesis, it is sought to shed more light on the so far unknown mysteries of smoldering fire.

1.2 Previous own work and literature

This master's thesis serves as a continuations project, building on the research conducted in the fall of 2020 where a basecase scenario with pellets was experimented on [20]. This basecase scenario was established by performing a series of tests with pellets heated by an external source until smoldering. The results showed that for this particular setup, the pellets started smoldering after being heated for 6 hours. In this master's thesis, different parameters are going to be tested and compared to the results from the basecase scenario. This will give an indication on how the given parameter affects the smoldering, and hopefully shed more light on the mysterious behaviors of smoldering fires. The study performed by Snersrud in 2020, was a specialization project for NTNU in close cooperation with RISE.

Some experimental studies on smoldering fire in wood pellets have been carried out in recent years before Snersrud's study from 2020. The two most relevant being Mikalsen's doctoral dissertation from 2018 and Rebaque's master's thesis from 2017 [11][15]. In Mikalsen's study, the ignition, extinguishing and propagation of smoldering fires were tested, as well as the effect of changes in air supply. The experimental setup used in by Mikalsen and Rebaque is roughly the same as what is used in this thesis, which makes data comparison possible. The results from Mikalsen's study shows that water cooling could be a feasible method for avoiding smoldering fires in biomass storage in addition to granting the world a better foundation of knowledge on the phenomenon of smoldering. Rebaque's study from 2017 focused on smoldering behavior when affected by different airflow, namely semi-reverse and forward. The results showed that airflow propagation had an impact, and that smoldering fires burned more violent in the forward case than in the semi-reverse. Both these studies provided useful background information to this study.

1.2.1 Silo fires

Silos are large containers used to store a diversity of things, for example biomaterial, such as wood pellets. When large quantities of biomaterial is placed together in tanks, a process starts where heat is generated. This can lead to a fire. But because there is not a sufficient amount of oxygen in the silos for a violent, aggressive fire, chances are it could start smoldering instead. When a smoldering fire erupts in a silo, several difficulties arise. First, smoldering in itself causes damage to the material in the silo, and the silo itself. Secondly, the exact place inside the silo which is burning is hard to determine without any monitoring, which makes quenching a difficult task. Especially without destroying the content of the silo. Third, quenching a smoldering fire in general is difficult even if no measures are taken to save some of the content from destruction in the process. And last but not least, these fires can develop to become flaming fires, and in some cases also explode [13]. Quenching of silo fires will be discussed more in section 2.4.3.

Some fire stations are trained to extinguish smoldering fires, but most places this is something the staff is not trained for.

1.2.2 Peat fires

Peat is the organic matter forming as a bi product of decomposition of tress, grass etc. This storage of organic matter works as one of the best carbon sinks in the world, and the emissions connected to peat fires are therefore immense [9]. In addition to being an environmental threat, these fires pose threats to ecosystems and people all around the world. When a peat fire erupts, the duration of which the peat smolders can range from some hours and days, to years [19]. These fires tend to put up quite a fight against quenching. During the North Carolina's Evans Road Fire in 2008, 7.5 billion liters of water was pumped into the fire to eventually extinguish it [19]. This is one of many examples of fires which have devastated large areas without effective countermeasures.

A study on quenching of smoldering peat fires from 2021 found that the usage of a plant based wetting agent suppressant mixed with water, suppressed the fire up to 39 % faster than with normal water, on average [18]. In the study from 2021 it is also emphasized that too little knowledge is uncovered about smoldering fire in general, but more specific, the quenching of smoldering fire. When water is poured onto a smoldering fire, the water finds canals in the peat where it flows, and the fire is temporarily quenched in those specific locations, but the majority of locations the fire is able to persist [19]. This means that other, more effective methods is needed to win the fight against smoldering.

These fires are sometimes referred to as "zombie fires" due to their less aggressive behavior. It can be difficult to discover a peat fire in its early stages, due to its lack of open flames, low intensity and tendency to arise below the surface of the ground. This can make it hard to see if a fire is extinguished or not, because it may just be dormant, and reignite somewhere nearby. [19]

Figure 1: Picture of a peat fire. [4]

1.2.3 Home insulation fires

Insulation is used in houses and structures all around the world for the purpose of creating a more friendly indoors environment. Whether it is used to make it warmer in cold climates or colder in warm climates, it is used in most buildings inhabited by humans. There are different types of insulation, with different positive aspects, but also some negative. The issue of smoldering fires in home insulation has become a problem, and is one of the leading causes of fatalities in residential fires. In the current regulations for insulation, there are therefore gaps of knowledge leading to the possibility of home insulation fires. In order to hopefully be able to create insulation without risk of smoldering, more knowledge and data needs to be collected on the subject of smoldering. [2]

1.3 Scope of work

The aim of this thesis, is to further increase the knowledge base on the phenomenon of smoldering. The main goal is to test and learn how external cooling can affect smoldering, and translate the specific case results into something which can be said in general about smoldering. In addition to this, the study is used to gain insight into methods used in experimental studies, which can be applied in other studies later.

1.3.1 Problem statement

Smoldering is a flameless type of combustion. Smoldering fires pose a serious hazard, as they are one of the leading causes of fatalities in residential fires. Damages caused by smoldering fires are responsible for major economic losses in the biomass and waste deposit industries each year. Smoldering in wildland fires and in coal seams are the cause of emissions equivalent to more than 15% of man-made greenhouse gas emissions yearly. Still, many of the basic principles of smoldering combustion remain unknown to the scientific community, and only a handful of studies on the phenomenon have been carried out during the past decades. The project work is a part of FRIC – Fire Research and Innovation Centre, by RISE Fire Research, NTNU and Sintef with private and public partners. RISE Fire Research has provided test facilities for the project and research staff has been working on experimental smoldering studies in parallel with the student project. A small-scale test set-up has been used to study the impact of varying different input parameters on the ignition and propagation of a smoldering fire. The master project is a continuation of the specialization project, fall 2020. The main aim of the project is to study how external cooling affects smoldering. In close cooperation with the supervisors, a test program has been prepared that is designed to study the relevant factors. The number of tests and the number of variations of test parameters shall be sufficient to allow for a proper data analysis, using available tools for analysis and presentation of data.

1.3.2 Research questions

1. Does the heating duration required for ignition of smoldering change when cooling jacket is applied, compared to a non-cooling situation?

2. Does an increase in flow rate in the cooling jacket always result in an increase in heat transfer away from the system, or is there a critical flow rate, at which this effect stagnates?

3. How does the duration of a smoldering fire change when applying the cooling jacket around the sample?

4. How does the heat transfer change when fixing the cooling jacket to the bucket with a thermal adhesive?

1.3.3 Limitations

Smoldering fire is a slow, but persistent form of combustion. The tests which resulted in smoldering in this study lasted between 45 and 65 hours, and time is therefore a factor that can’t be taken lightly.

There is only a finite number of tests that can be conducted in the time available in this master's thesis, and with covid-19 raging throughout the world, restrictions was made which sometimes limited the availability of the research lab. Some tests therefore had to be put on hold in order to follow local rules, such as mandatory quarantine etc.

2 Theory

In this section, relevant theory for the report will be provided. A background for what affects the initiation and propagation of a smoldering fire will also be established, in addition to other key aspects of the experimental setup used in this thesis.

2.1 Smoldering as a phenomenon

Smoldering is a persistent, flameless exothermic reaction, where biofuel and oxygen reacts, releasing heat, CO2 and other bi products. The exact contents of these bi products will be further described in section 2.2. An exothermic reaction is a reaction where energy is released to the system, and not consumed by the reaction as it is in an endothermic reaction.

Smoldering fire separates itself from most other forms of fires due to the absence of visible flames. When a fuel smolders, the combustion happens at an incredibly slow rate, compared to a flaming fire. This is reflected by the temperature differences of the overall system, where the flaming fires have higher temperatures over a shorter time span, and smoldering fires have lower temperatures over larger time spans. To visualize this, the energy in a fuel can be thought of as a tank of water, where the water represents the energy in the system. If a large hole is made in the bottom of the tank, the water pours out faster, and more violently than if the hole was small. The same amount of water (energy) is released from the tank, but the difference between the two scenarios is the duration from which the tank started emptying until it is empty[16][11][15].

In all forms of combustion, oxygen is required for the reaction to occur [16]. The special feature about fires in bio masses, such as the wood pellets in this thesis, is that oxygen is not needed in the system at first. Therefore, there has to be a process before the combustion happens where oxygen is produced as a product of the reaction. This process is called pyrolysis and is what enables the smoldering to happen.

2.2 Pyrolysis

Pyrolysis has different meanings based on the discipline of science, and to clarify: the pyrolysis in this study is based on the interpretation from fire science. This is therefore defined as a process in organic materials where the matter decompose due to chemical processes induced by heat in the absence gaseous of oxygen. It is virtually impossible to get a system without any oxygen, which means that in this context, absence of oxygen means that the pyrolytic systems run with less than stoichiometric quantities of oxygen. [22]

As stated, heat is needed for a smoldering fire to initiate. Without heat, the biofuel will not be able to 1; initiate the pyrolysis, and 2; dry the fuel sufficiently for a fire to start. When heat is applied to a fuel, it allows the pyrolysis to take place. There are many sub reactions happening during this phase, and many species are formed and decomposed again and again. However, the investigation of these species is outside the scope of this study, and the overall global reaction is therefore of more importance, and can be seen in Eq. 1. Here, pyrolyzate, char and ash forms from the fresh fuel when adding heat to the system [16].

$$Fuel(solid) + Heat \longrightarrow Pyrolyzate(gas) + Char(solid) + Ash(solid) \tag{1}$$

Next, the products from the pyrolysis have two possible reactions:

1. An exothermic reaction consisting of the solid char and oxygen, where heat is released to form carbon dioxide, water, ash and various other gasses, Eq.2. This reaction leads to smoldering fire, because of the solid state oxidation of char [16].
2. A gas phase reaction consisting of pyrolyzate and oxygen, where flaming fire will occur due to both reactants being in gaseous state, Eq.3 [16].

$$Char(solid) + O_2(gas) \longrightarrow Heat + CO_2 + H_2O + ash(solid) + othergasses \tag{2}$$

$$Pyrolyzate(gas) + O_2(gas) \longrightarrow Heat + CO_2 + H_2O + othergasses \tag{3}$$

The heat released in reaction 2 and 3 is the driving mechanism for a self sustained smoldering fire. The heat released in the exothermic reactions, Eqs. 2 and 3 supports the endothermic reaction, Eq.1. This circle of exothermic and endothermic reactions is what makes a smoldering fire persist. As long as the heat balance is positive i.e more energy is generated than lost, the fire can keep going for as long as there is fuel in the system [16].

2.3 Heat transfer

This section is dedicated to help the reader getting a clearer view of different ways heat is transferred trough different states of matter, using various mechanisms.

2.3.1 General introduction about smoldering heat transfer

There are three mechanisms for heat transfer: convection, conduction and radiation [16]. In a smoldering fire, all three types are represented. Energy, in the form of heat always travels from hot to cold locations, and the exact way this happens is what separates the different types of transport from each other [1]. Both conduction and convection transfers heat due to collisions with particles, and the most important difference between the two types is if the medium moves as independent particles, or in bulks. Otherwise, the mechanism is similar, but the free motion of particles in the convective scenario introduces some differences in behavior. Radiation separates itself from the other two mechanisms by not relying on an immediate proximity between substances [5].

In the smoldering fires used in this study there are wood, metals, air, insulation, and other test equipment, all affecting the heat flow of the system. It is therefore important to identify what mechanism is seen where, and also be able to calculate the heat flow crossing the system boundaries. This will be further described in the discussion. [5]

2.3.2 Thermal conduction

Conduction, also referred to as diffusion, transfers heat through the colliding atoms in a medium moving as a bulk. Temperature can be viewed as a measure of the amount of movement in a particle. This movement is transferred to the neighbor particle due to collisions. For each collision some of the energy in a given particle is transferred to the next particle, and so on. In the end, this dissipation of energy can go on until the energy in the system is equally distributed within the system boundaries. The movement, or vibrations in the particle, does not have a preferred direction, and dissipates energy equally in all directions, making heat distribute radially. The magnitude of the heat flux is dependent on material properties and the difference in hot/cold temperatures. [5]

A general equation can be derived for a one-dimensional conduction model. By introducing Fourier's law in combination with the assumption that heat flux equals heat rate divided by area, yielding the following equation, Eq. 4. [5]

$$Q = qA = -kA\frac{dT}{dx} \tag{4}$$

Where Q is the heat transfer rate $[W]$, q is the heat flux density $[W/m^2]$, k is the conductivity of the material $[W/mK]$, A is the area of which heat is transported through $[m^2]$, T is the temperature $[K]$ and x is the spatial coordinate $[m]$

Equation 4 can also be transformed to describe cylindrical shells, which varies in surface area based on the radius. Factoring in this variable, yields the following equation for a cylindrical conduction model, Eq. 5. [5]

$$Q = qA = 2\pi rL(-k\frac{dT}{dr}) \tag{5}$$

Which when integrated with respect to r becomes Eq. 6.

$$Q = \frac{2\pi kL(T_1 - T_2)}{ln\frac{r_2}{r_1}} \tag{6}$$

Where r_1 and r_2 is the radius at location 1 and 2 $[m]$, L is the length of the cylinder $[m]$, k is the conductivity of the material $[W/mK]$, T_1 and T_2 are the temperatures at locations r_1 and r_2 $[K]$.

2.3.3 Thermal convection

Convection is a mechanism where heat is transported though a fluid where the particles can move around independently. The cold fluid shrinks in size, and the warm fluid increases in size, making buoyancy a driving factor for circulation, and thereby also mixing the hot and cold fluids to a uniform temperature. For a complete picture of the heat flow due to convection, a sufficient background from fluid dynamics is also required. This is outside the scope of this study, and the overall heat transport is sufficient for understanding how the heat moves through the system. [3]

In a fire, the convection, and movement of hot gasses is an important driving force, keeping the fire going. Heat released from the chemical reactions heat up material sufficiently for the previously cold material to react, releasing more heat. This positive feedback-loop of energy is the one of the most important aspect of a self going fire. [16]

The heat transfer trough a medium due to convection can be calculated through the following expression, Eq. 7. [3]

$$Q = qA = h_c A(T_s - T_\infty) \tag{7}$$

Where Q is the heat transfer rate $[W]$, q is the heat flux $[W/m^2]$, A is the area $[m^2]$, h_c is the convective heat transfer coefficient of the material $[W/m^2K]$, T_s and T_∞ are the temperatures of hot and cold side, respectively $[K]$.

For calculations on heat transfer in systems with mass flow, which in this thesis will be water, it is easier to use an equation with less variables and taking advantage of the specific heat of water. Assuming constant specific heat across the temperature span, and using the following relation, Eq. 8. [12]

$$h(T_2) - h(T_1) = c_p(T_2 - T_1) \tag{8}$$

Where h is the enthalpy $[J/kg]$, T_1 and T_2 is the temperature in location 1 and 2 $[K]$ and c_p is the specific heat capacity of the substance $[J/kgK]$.

The total heat transfer rate of water becomes, Eq. 9

$$Q_w = \dot{m}_w c_{p,w}(T_2 - T_1) \tag{9}$$

Where Q_w is the heat transfer rate of water $[W]$, $\dot{m}_w$ is the mass flow of water $[kg/s]$ and $c_{p,w}$ is the specific heat capacity of water $[J/kgK]$

2.3.4 Radiation

In contrast to convection and conduction, heat transfer by radiation occur without direct contact. For distances with characteristic length longer than 0.2 m, radiation is the main heat transport method [21]. The heat transport from a black body due to radiation can be calculated through the Stefan–Boltzmann law of thermal radiation, Eq. 10. [6]

$$Q = \sigma A T^4 \tag{10}$$

Where Q is the heat transfer rate $[W]$, A is the area $[m^2]$, σ is the Stefan–Boltzmann constant $[W/m^2K^4]$ and T is the temperature $[K]$.

From this, the heat transfer between two black bodies can be described, Eq. 11, which is the equation used to calculate heat transfer from radiation.[6]

$$Q = \sigma A(T_{hot}^4 - T_{cold}^4) \tag{11}$$

Where Q is the heat transfer rate $[W]$, A is the area $[m^2]$, σ is the Stefan–Boltzmann constant $[W/m^2K^4]$, T_{hot} and T_{cold} is the temperature of hot and cold side, respectively $[K]$.

2.4 Extinguishing smoldering fires

2.4.1 Effects of porous materials versus rigid materials

When quenching a smoldering fire, there are many important aspects to keep in mind. First, the organic matter in which smoldering usually occurs is a porous material, and do not behave as a rigid body. In a smoldering fire, this means that airflow and "reachability" is drastically lower. In a normal everyday bonfire, wood sticks are put on top of each other, layer by layer to ensure airflow. This is not the case in porous wood pellets etc, where the fuel becomes denser, closing the system and reducing airflow. The reachability in this dense block of fuel is much lower, because it is harder to separate and penetrate than in a regular bonfire, in order to get to the core of the fire. When quenching a normal fire, it is usually enough to drench it in water, because when water vaporizes, this "steals" energy from the combustion, and given enough water, the energy in the system is lowered to the point where temperature drops sufficiently for the fire to die out. In the smoldering case, when loads of water is applied, the dense structure of the porous material functions as a barrier trough which water struggles to flow. This means that water can extinguish the upper layer, but not penetrate and quench the core of the fire. If this core keeps smoldering, and heat from the combustion reheats and dries the upper layer fuel, the fire can return to the same state as before water was applied. This is the phenomenon which makes the reachability much lower for smoldering fires than regular fires -the ability to reach all corners of the fire, making it important to think of other methods for extinguishing smoldering fires. [11][19]

2.4.2 Energy balance

In all forms of systems with energy generation and energy losses, an equation can be created taking care of the balance of these two. In its most basic form this will just be the energy generated in the system, minus the energy losses to the environment, equals something with either a positive or negative sign, Eq. 12.

$$E_{in} - E_{out} = E_{tot} \tag{12}$$

Where E_{in} represents all the different sources of energy into the system $[J]$, E_{out} represents all losses to the environment $[J]$ and E_{tot} represents the result of these two factors $[J]$. If E_{tot} is positive, the total energy of the system increases, and if E_{tot} is negative, the energy of the system is lowered.

This is of course a simplified way of viewing a system, but is in the end what decides whether a smoldering fire persists or dies out, given that the fire never runs out of fuel. If more energy is generated than the amount lost, the fire is self perpetuating, and can go on for as long as fuel is available. While there are many ways to go by when extinguishing fires, the most basic idea of quenching a fire is increasing the E_{out} in Eq. 12, making $E_{out}>E_{in}$, and by that making E_{tot} negative. [16]

2.4.3 Methods for quenching smoldering fires

For a fire to exist, fulfillment of three requirements are necessary. These three are oxygen, a combustible material and temperature, displayed in Fig. 2. Based on this fire triangle, in order to quench a fire, only one of these needs to be taken away. Different ways of extinguishing a fire will now been presented based on the three different parameters.

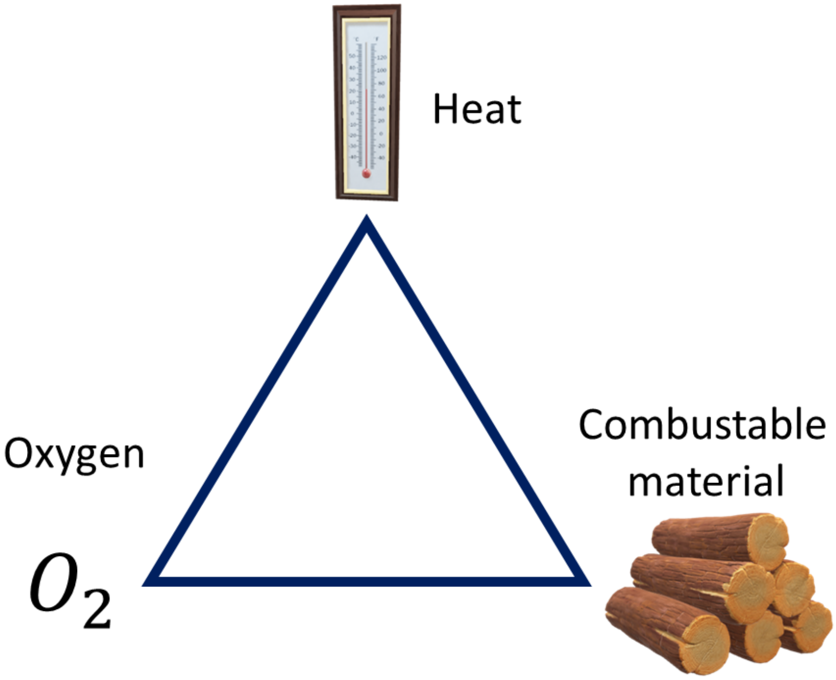


Figure 2: Sketch of the necessary elements in a fire. Oxygen, a combustible material and sufficient heat are all needed for a fire to exist.

Combustible material

The first way to extinguish a fire is to remove the combustible material. Using this method, the fire simply runs out of fuel and can therefore no longer persist. This might be a difficult task, especially in silos and other containers where smoldering occurs. But this can, however, be an effective way of containing smaller smoldering fires in peat. Simply digging a ditch around the smoldering can keep it from spreading endlessly. Even though this can prove to be practically difficult to perform, it can serve as viable solution if need be.

Another way to implement this method is to divide the silos and containers into sections. If a fire ignites in one of the sections, it can burn out that particular section, but the rest of the silo is safe. To ensure no ignition of neighboring sections, running water can also be implemented in the dividers, working as a heat sink.

Heat

The second method is to reduce the heat in the system via a heat sink, which is the parameter tested in this thesis. Heat can be removed in many different ways, but the common denominator amongst the different methods is that some mechanism adsorbs heat within the system and carries it out into the environment. In a study from 2018, by Mikalsen, cooling by this method was tested using a copper water pipe through the center of the sample, absorbing heat and transporting the hot water away. [11]

Another way of removing heat is to increase the heat loss by introducing air flow. This increases the convection coefficient, and by that increasing the heat transport [3]. In this thesis cooling by running water along the outside of the sample is used. This method makes use of increasing the heat transfer between outer wall and water pipe.

Oxygen

The third and final parameter that can be exploited to extinguish a fire is to remove the oxygen from it. Without oxygen all combustion's fails to react, and without reactions, no heat is released. Removing oxygen, however, is a difficult task in porous materials such as wood pellets, as briefly described in section 2.4.1. In addition to this, during pyrolysis oxygen is produced, making it hard to remove all oxygen created. Biomasses such as pellets can also contain about 40% oxygen, making the removal of oxygen even harder. Smoldering also requires little amounts of oxygen, because the reactions happen slowly in contrast to an open flame fire. CO_2-extinguishing is therefore also not a viable solution, because it does not affect the production of oxygen in the sample. A study conducted in 2018 found CO_2 to be a poor choice of quenching method, due to explosion hazards.[7]

2.5 Key points of interest in a smoldering fire

Heating period: Is the time during which the electrical heater is fueling the sample with energy in the form of heat. This is what initiates the smoldering and is therefore a crucial part of the experiments.

Turn around point: Is the point where the temperature profile changes from going downwards in a steady rate to upwards. This tells how low the temperatures can be while still being able to turn around and smolder.
Local and global temperature peak: Both local and global temperature peaks are spikes in the temperature profile, marking a high combustion rate. The global peak temperature is the maximum temperature experienced in the sample over the entire duration of the test. The local peak temperature is a local peak in temperature, but not necessarily the highest measurement throughout the entire test.

The reason why these measurements are brought forth as important, is due to the research conducted by Mikalsen and Rebaque [11] [15]. In these studies, the aspects of smoldering mentioned in this section were used to explain important features about the combustion, and is therefore also explained here to give the reader a better understanding on the subject. In addition to this, the different outcomes of the tests, as can be seen in section 2.6, were first presented by Mikalsen and Rebaque. The different key aspects of a smoldering fire can be viewed in Fig. 3, while the examples in section 2.6 are made using data from this study.

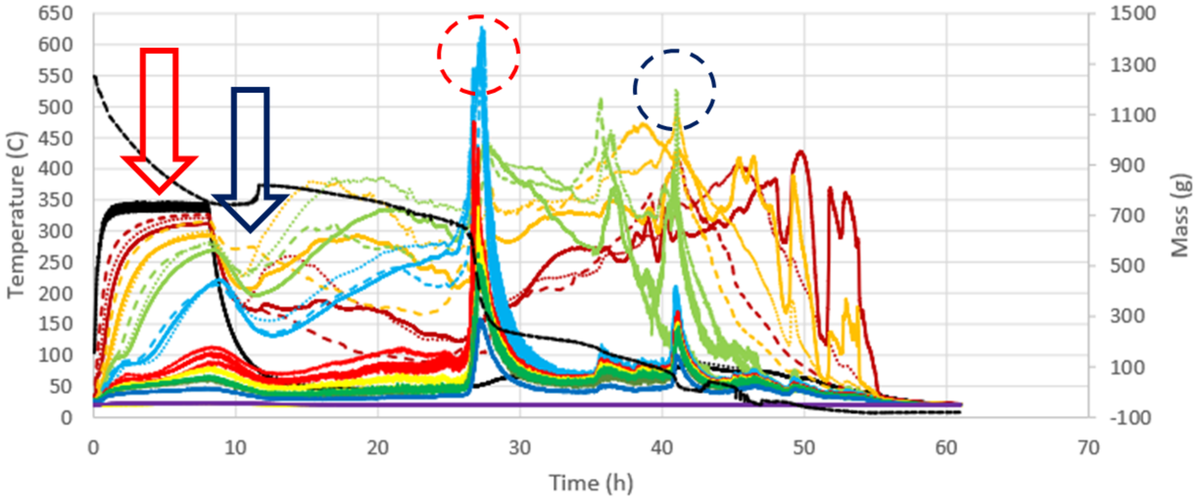


Figure 3: Displaying a regular case of smoldering. The heating duration is marked with a red arrow, turnaround temperature is marked with a blue, local temperature peak is marked with a blue circle, and the global temperature peak is marked with a red circle.

2.6 Possible outcomes of tests

The main different outcomes of the tests are:

1. Self sustained smoldering
2. Partial self sustained smoldering
3. No self sustained smoldering

These can further be divided into subgroups, but this is not necessary for the overview of the tests. In this section, the differences between the three main outcomes will be described, and key aspects of each type will be presented.

2.6.1 Self sustained smoldering

When a test undergoes a complete combustion even after the external heating is removed, there has to be a source of energy propelling the fire forward, making it independent of external energy. This independence and self going nature, is the key aspect of a self sustained smoldering fire. Bringing back the rudimentary energy balance presented in the theoretical background, Eq. 12, this would correspond to having $E_{in} > E_{out}$ making the total energy balance positive. There are of course more important factors, like airflow and fuel availability to take into consideration when figuring out if a fire will be self sustained, but energy wise, this is the deciding factor. Another important feature for the self sustained case, is a significant reduction in mass. For a fire to persist by itself, energy is required. If this energy comes from within the system, it has to be coming from the combustion of materials. The combustion makes the fuel (wood pellets) react and form CO_2 and other bi products. This is then removed from the system as flue gas, and is therefore responsible for a mass loss. If the combustion is complete, it means that as much material as possible has reacted, and the mass of the system is thereby reduced significantly. Both the typical temperature profile and mass loss can be seen in Fig. 4.

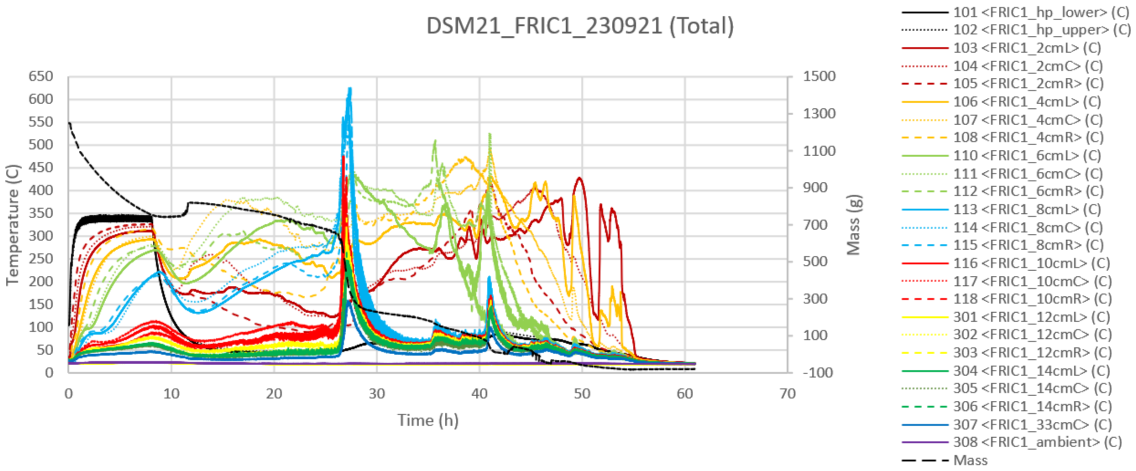


Figure 4: Temperature profiles and mass graph for test DSM21, resulting in complete self sustained smoldering. The temperatures are shown on the primary axis, and the pellet mass is displayed on secondary axis.

2.6.2 Partial self sustained smoldering

For the partial case, smoldering occurs in the sample, but not enough for the fuel to burn down completely. There might be a higher heat generation than heat loss at times, but the general trend tends to go downwards, and the system loses more energy than what is generated by the reacting fuel. The important aspects of the partial case, is that temperatures do not reach particularly high numbers, and mass loss is reduced significantly compared to the complete self sustained case. Both these attributes can be seen in Fig. 5. A smoldering combustion like the ones in the experiments in this thesis is balancing on a fine line, where it's easy for the fire to tip the scales towards quenching, or complete smoldering in the other direction. A case of partial self sustained smoldering is simply an outcome depicting exactly how fine this line is. It may seem that smoldering occurs in a rate capable of transitioning to become completely self sustained, but as it turns out, it fades out to nothing. This is one of many obstacles that arise in the quest for determining a heating duration suited for the creation of smoldering fire.

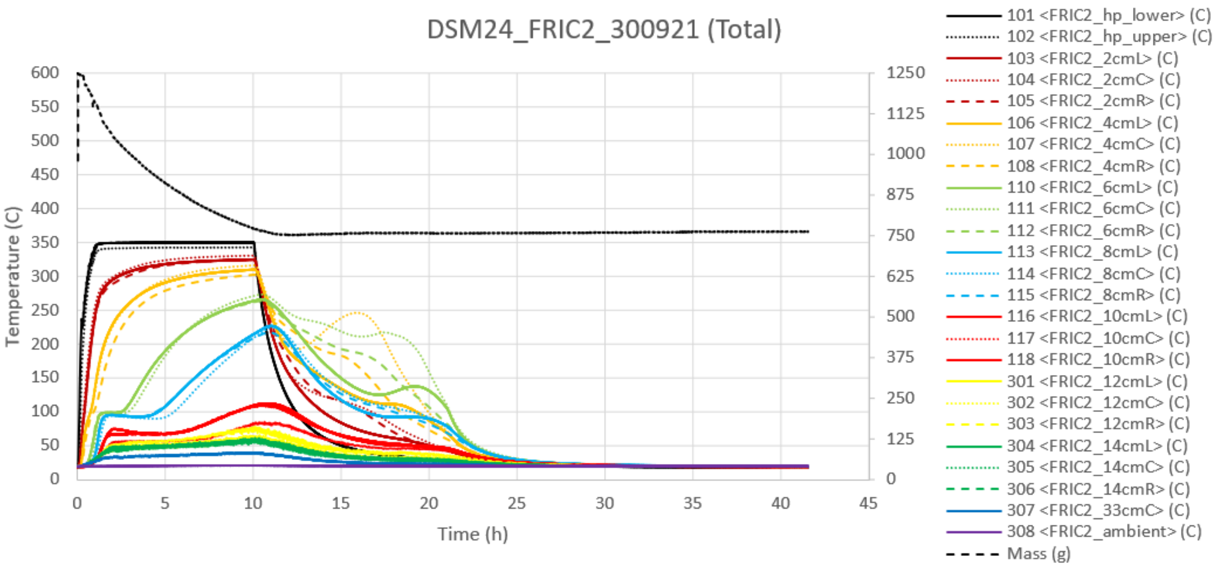


Figure 5: Temperature profiles and mass graph for test DSM24, resulting in partial self sustained smoldering. The temperatures are shown on the primary axis, and the pellet mass is displayed on secondary axis.

2.6.3 No self sustained smoldering

The final category of possible outcomes of a smoldering experiment, is the case where no self sustained smoldering occurs. There can be many reasons as to why this happens, but the main ones are that insufficient heat is granted to the system in the heating period, or too much heat is drawn away from the system by the cooling, resulting in $E_{out} > E_{in}$, making the total energy balance negative. The temperatures of the sample rarely reaches temperatures higher than the aluminum plate, which is responsible for the transporting the external heat to the sample, and is between 325 and 350 °C. The mass loss is equal to the amount of water in the pellets, which gets evaporated. This translates to about 94 g of water in a 1250 g sample, and can be seen in Fig. 6.

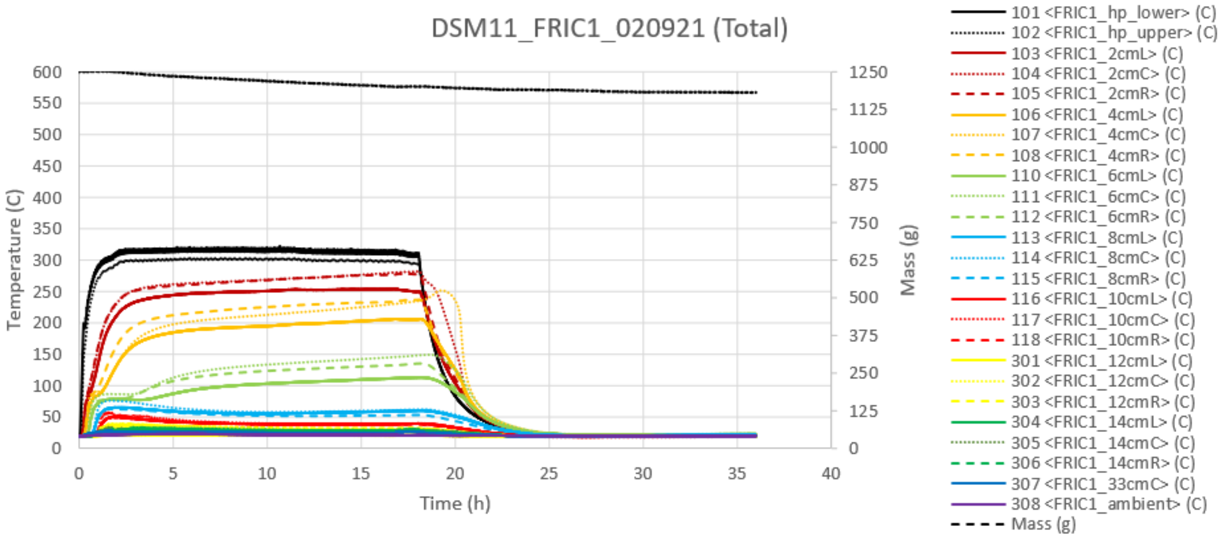


Figure 6: Temperature profiles and mass graph for test DSM11, resulting in no self sustained smoldering. The temperatures are shown on the primary axis, and the pellet mass is displayed on secondary axis.

3 Materials and method

3.1 Wood pellets

The material used as fuel in all the experiments conducted in this thesis, is wood pellets. Relevant properties of the wood pellets will therefore be described here.

The pellets used in the experiments is produced in Norway, at Hallingdal trepellets AS, and consists of the following species of wood, Table 1. Moisture content and size measurements of fresh, frozen and black burned pellets can be seen in in Tables 2 and 3, respectively.

Table 1: Properties of wood pellets used in all experiments.

Property	Value and unit
Pine content	20-50%
Spruce content	50-80%
Unit density	710 kg/m3
Bulk density	1020 kg/m3
Porosity	30.4 %

Moisture content

The moisture content of the wood pellets was measured by extracting a sample of wood pellets, noting down the weight of said sample and placing it in an oven at 100 °C. The sample was taken out of the oven at certain intervals, and mass was again noted. Once two separate measurements were identical, with a minimum of 24 hours spacing, the pellets were considered dry. The result of this test can be seen in Table 2, and the moisture content was determined to be 7.49 wt%.

Table 2: Displays the results from the test determining water content.

Time (h)	Mass (g)
0	100.1
21	92.6
66	92.6
118	92.6

Size measurement

The diameter of frozen, dry and black burned pellets was measured and the results are displayed in Table 3. The sequence of measurements consisted of measuring 20 separate and randomly chosen pellets to get an average diameter of each type.

Table 3: Shows the results of diameter-testing. A caliper was used to determine the diameter (NBL-419).

Pellet number	Frozen [mm]	Fresh, dry [mm]	Black burned [mm]
1	8.1	7.94	7.15
2	7.9	8.24	7.33
3	8.14	7.88	7.13
4	8.03	8.09	7.24
5	8.40	7.95	7.31
6	8.03	7.91	7.26
7	8.35	8.06	7.29
8	8.12	8.14	7.62
9	8.09	7.92	7.29
10	7.90	8.05	7.77
11	8.01	8.15	7.20
12	8.14	7.98	7.07
13	8.22	7.97	7.22
14	8.11	7.92	6.88
15	8.02	7.94	6.87
16	8.34	7.92	7.17
17	8.09	8.30	7.85
18	8.11	8.07	7.44
19	8.26	8.19	7.10
20	8.06	8.03	7.37
Average	8.12	8.02	7.23

Storing

When pellets arrived at the test location, they were put directly into a freezer, and kept there until used in tests. A study from 2017 revealed that biomasses tend to get less reactive when stored at higher temperatures, and this led to the decision of storing the wood pellets in a freezer to slow down this decrease in reactivity. The pellets were brought out of the cold storage batch wise in time for it to be room tempered at the start of each test. [8]

3.2 Method

3.2.1 Experimental setup

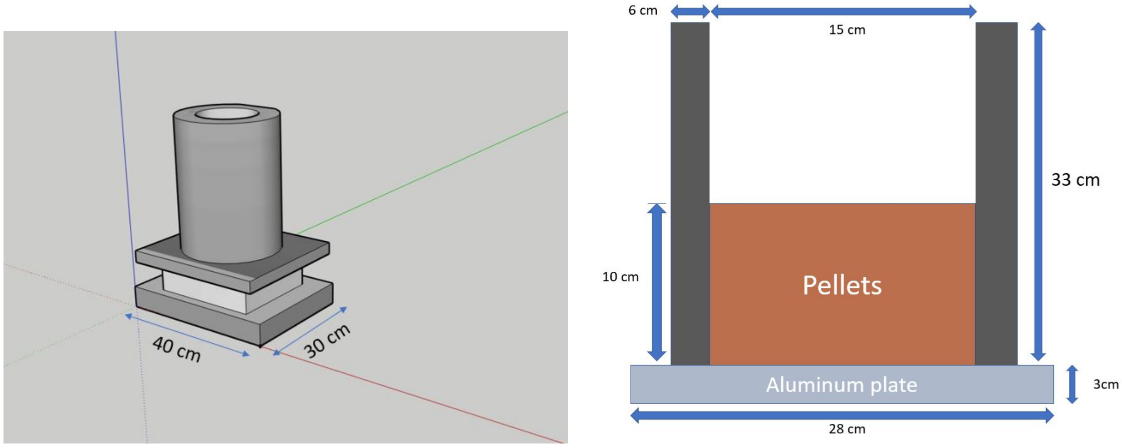
The experiments conducted in this study were conducted in a pairwise manner, meaning there were two identical test setups, where two separate experiments could be held simultaneously. This is depicted in Fig. 11. The setup used in this study is based on the setup used by Rebaque and Mikalsen [15] [11] and only some differences are noteworthy. The cooling method in Mikalsen's study was trough the center of the sample, while in this study this is done externally. In Rebaque's study there was no cooling system and measurements of the contents of flue gas was gathered. This is not done in this study, and the device responsible for doing this is therefore not present in this setup.

The experimental setup consisted of a scale, electrical heating unit, aluminum plate, an insulated steel pipe, pellets, cooling jacket and thermo-couples, Figs. 7a, 7b and 13a.
A scale which at certain intervals recorded a voltage was put at the bottom. The voltage was then translated into the wanted unit by calibration, Fig.9a. The scale was a Systec IT1000-scale and was calibrated to record grams. It had a range from 200 g to 30 000, and a margin of error equal to 1 gram.

On top of the scale, an **electrical heater** was placed, Fig. 9b. The purpose of the heater was to maintain a given temperature for a target duration. This was done to heat the pellets in the pipe until self sustained smoldering was achieved. The heater was a 2000 W Wilfa CP1 heater.

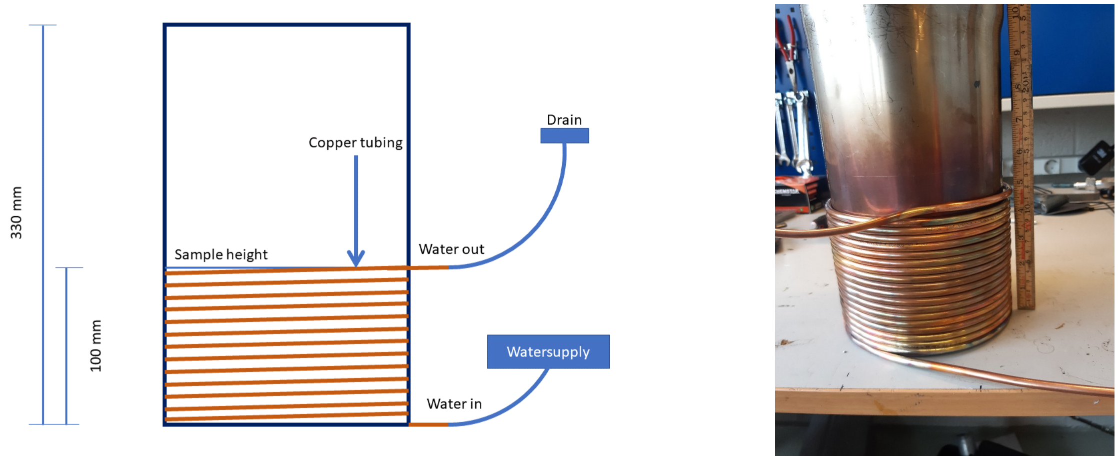
To spread the heat uniformly across the entire cross-section of the pipe, an **aluminum plate** was put on top of the electrical heater. This distributed the heat and ensured a uniform heat-transfer from the heater to the pellets, Fig.10.

Lastly the **steel pipe and cooling jacket** was placed on top of the aluminum plate. The steel pipe is an insulated pipe, and is where the smoldering will take place. The cooling jacket is a copper tubing around the steel pipe, with the purpose of absorbing heat from the system. Figs. 7a and 7b display the dimensions of the setup.



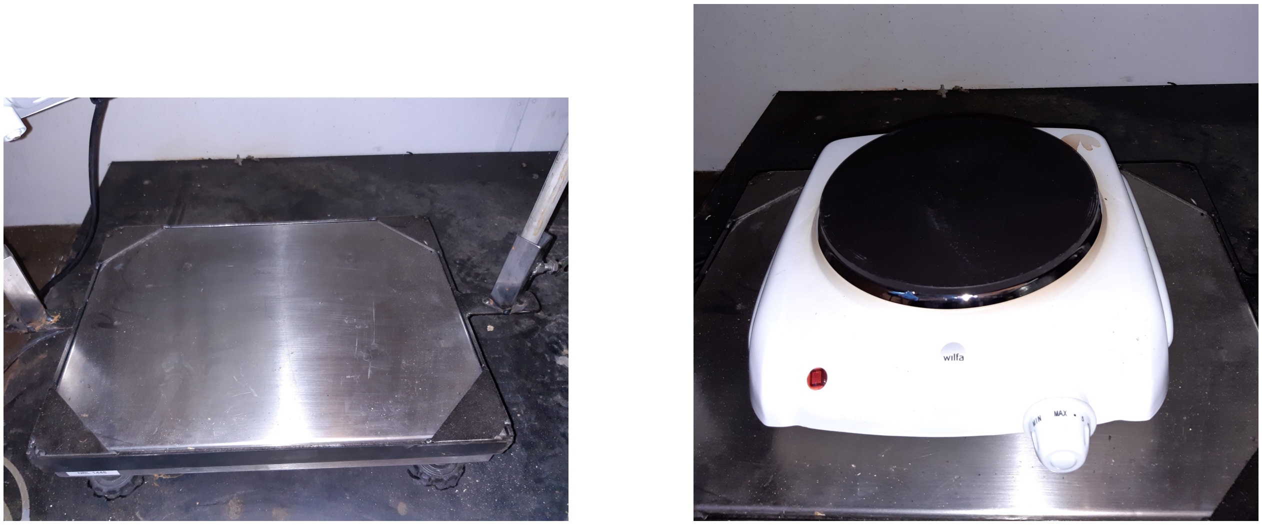
(a) **(b)**

Figure 7: Sketch of the setup, excluding thermo-couple positions. From bottom to top, the setup consists of a scale, an electrical heating unit, an aluminum plate and an insulated pipe (a). Sketch of the pipe, insulation, aluminum plate and pellets (b).



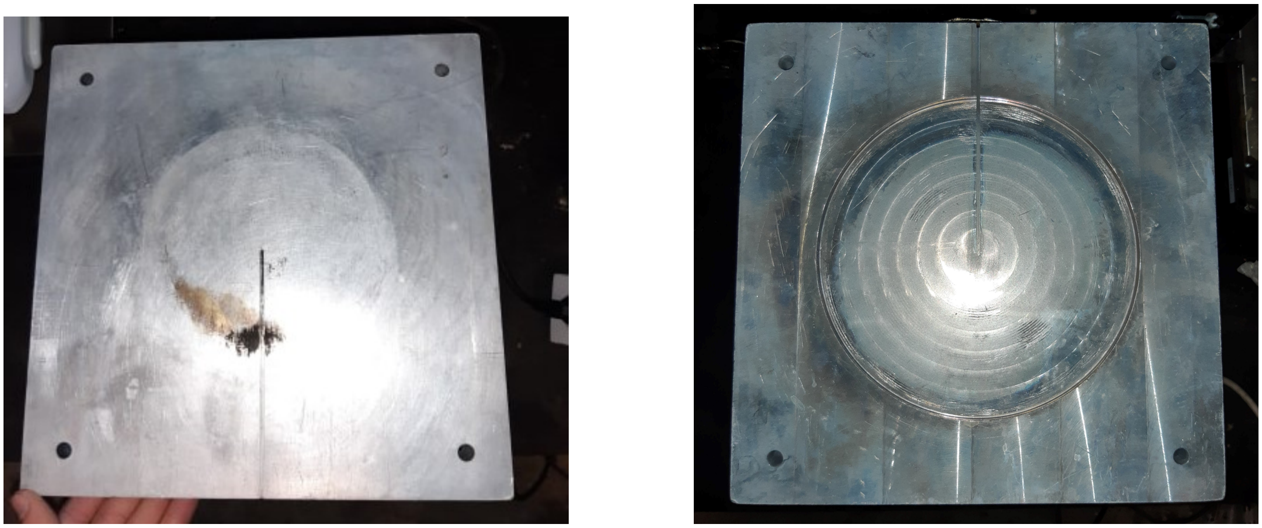
(a) (b)

Figure 8: **(a)** Sketch of the cooling jacket. Water entering the tubing at the bottom, and exiting at the top. **(b)** Picture of the steel pipe "wearing" the cooling jacket. The copper is welded to the pipe in the top, fixing it into a locked position.



(a) (b)

Figure 9: Picture of the scale, which was located at the bottom of the experimental setup (a). And the electrical heating unit standing on top of the scale (b).



(a) **(b)**

Figure 10: Photo the upper surface (a) and lower surface (b) of the aluminum plate. A milled track in the plate enabled the insertion of thermocouples (a). And the lower surface of the aluminum plate where there has been milled out both a space to fit the top of the electrical heater and a track for thermocouple insertion (b).

Figure 11: Picture of the complete setup. FRIC 1 setup to the left and FRIC 2 setup to the right.

3.2.2 Water loop

Water was connected to the cooling jacket with small plastic tubes, Fig. 12.

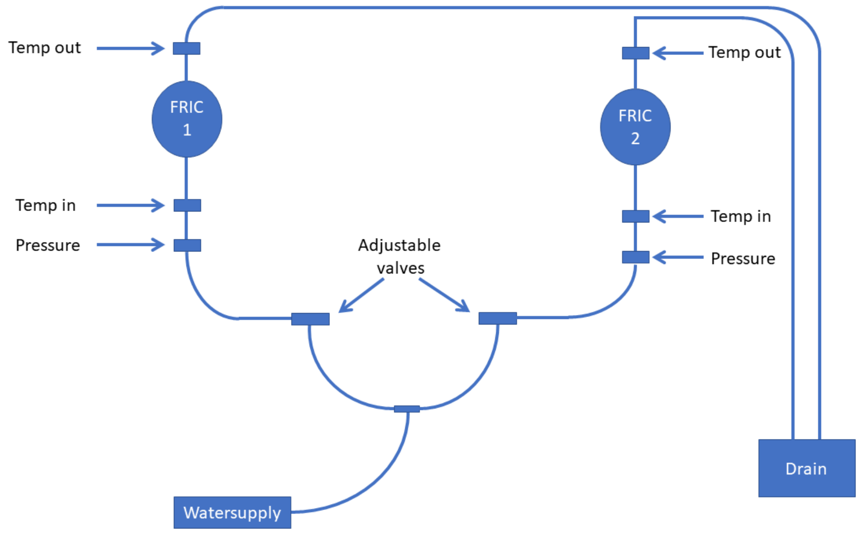


Figure 12: Water runs from the supply, then divides into two separate paths. Each path is independently monitored with pressure measurements to ensure equal flow conditions. Temperature recordings both before and after the water enters the cooling jacket are also logged. Finally, the water is lead to a sink where the water is drained.

3.2.3 Thermocouples

In order to accurately measure temperature during testing, thermocouples were employed. When a thermocouple experiences a difference in temperature, a small electric current flow in the wire. This voltage can be used to determine the temperature difference between a reference-point and the temperature at a wanted location [14].

There are several different types of thermocouples with different temperature-ranges. In this experiment, the k-type was employed. This is because of its temperature range, which spans from negative 270 °C to 1260 °C above zero. Smoldering fires does typically not reach temperatures higher than 1000 °C [16]. The k-type also has a relatively low error of +/- 2.2 °C, and works well in oxidizing atmospheres [17]. Because of this, the k-type thermocouple was found to be a suitable candidate.

For the purpose of replicating the experiments done by Mikalsen, the same positioning of thermocouples was used in this study, in addition to some new ones. This makes data from testing easier to compare. The location and purpose of the TC-locations are mentioned below.

Thermocouple ladder (tc-ladder)

A tc-ladder was used to record temperature in the pipe during the experiments, Fig.13. A total of 22 thermocouples was spread to different strategic locations on the ladder, which was then lowered into the pipe during testing.

Aluminum plate

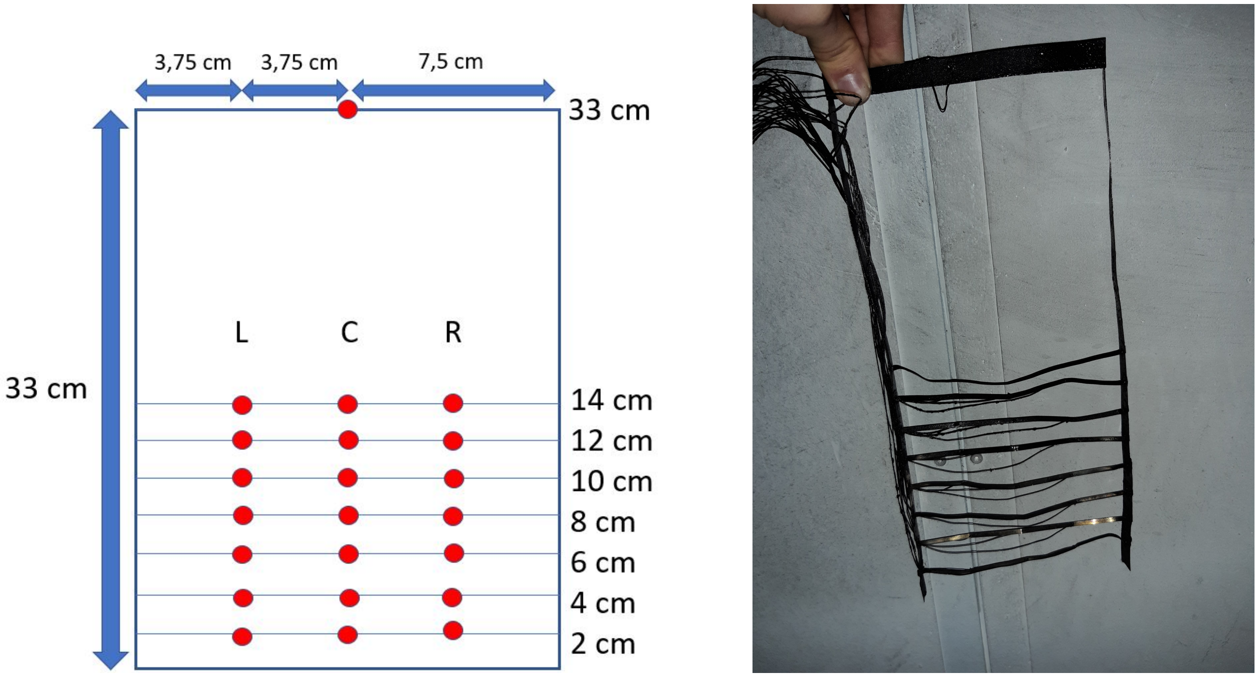
In addition to the ladder, one thermocouple was placed over and one under the aluminum plate, Fig. 14a. This served the purpose of collecting temperature data for analyzing, and for surveillance of the electrical heating unit.

Steel cylinder

To further improve the data foundation, after tests DSM9 and DSM10 thermocouples was placed on the outside of the steel cylinder (between steel cylinder and insulation) at heights 2cm, 4cm, 6cm, 8cm and 10 cm, Figs. 14a and 14b. This was done to better estimate the heat flux through the pellets.

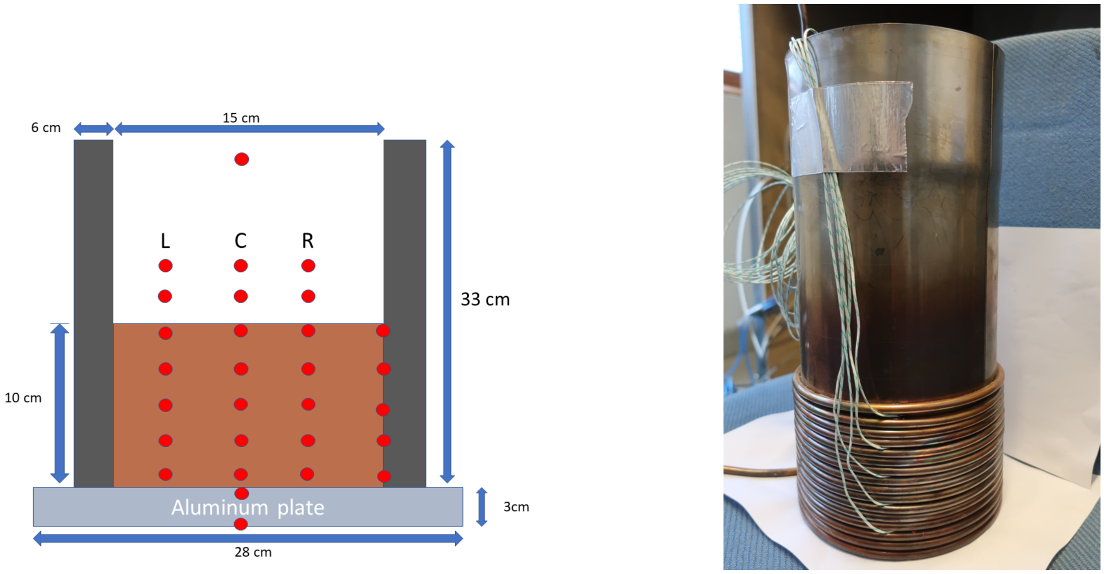
Water pipe

Two thermocouples were put in the center of the water pipes. One for the inlet water, and one for the outlet, Figs. 15a and 15b.



(a) **(b)**

Figure 13: Sketch of thermocouple-ladder, where a red circle represents a thermocouple in position left (L), center (C) or right (R). The different heights is also marked on the side (a). Photo of the thermocouple-ladder (b).



(a) **(b)**

Figure 14: Sketch of thermocouple positions, where a red circle represents a thermocouple at height intervals as seen in 13a (a). Photo of the pipe wearing the cooling jacket, where the tc-elements are carefully welded to the outside of the pipe, between the copper coiling (b).

(a) **(b)**

Figure 15: The water temperature is measured on the way into the coils (inlet) and away from the coils (outlet) using the same method. Water flows through the center, where a thermoelement is placed. It is important that the thermoelement is not touching the walls, because the goal is to capture the water temperature, and not the wall temperature (a). Side view of the the device displayed to the left (b).

3.2.4 Bidirectional probe

To enable the measurement of air flow, a bidirectional probe connected to a pressure transducer was employed. A bidirectional probe is a device consisting of two steel pipes and two chambers -one entrance and one exit, Fig.16a. In Fig. 16b a picture of the bidirectional probe seen from above can be seen.

(a) **(b)**

Figure 16: Sketch of a bidirectional probe as seen from the side (a). Picture of the bidirectional probe seen from above(b).

The purpose of having a bidirectional probe connected to a pressure transducer was to measure a pressure difference. When a fluid is flowing into and around the bidirectional probe, the pressure increases on one side, and decreases on the other [10]. The pressure transducer registers this difference, which can be used to determine the flow coming out of the top of the pipe. In order to get the right unit, a set of equations is employed, assuming steady state.

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 \tag{13}$$

Assuming $V_1 = 0$, and $z_1 = z_2$ yields an expression for V_2, Eq.14.

$$V_2 = \sqrt{\frac{2\Delta P}{\rho}} \tag{14}$$

The density can be expressed as

$$\rho = \frac{P_{amb}}{R_{gas} T_{33cm}} \tag{15}$$

Mass flow rate can be expressed as

$$Massflowrate = \rho A_{air} V \tag{16}$$

Inserting Eqs.14-15 into Eq.16 gives the final equation used to calculate mass flow rate, Eq.17.

$$Massflowrate = A_{air}\sqrt{2\Delta P(\frac{P_{atm}}{R_{gas}T_{33cm}})} \tag{17}$$

Where:

P is pressure $[Pa]$
V is velocity $[m/s]$
ρ is Density $[kg/m^3]$
g is gravity $[9, 81m/s]$
z is height $[m]$
ΔP is difference in pressure $[Pa]$
P_{atm} is standard atmospheric pressure $[101325Pa]$
R_{gas} is the specific gas constant of dry air $[287, 06J/kgK]$
T_{33cm} is the temperature at 33cm above the aluminum plate $[K]$

3.2.5 Data logging

All data point were connected to a KEYSIGHT 34972A LXI logger, which was further connected to a computer. The computer used the software Agilent BenchLink Data Logger 3 to record data every 10 seconds. The channel names used in this study is displayed in Table 4.

Table 4: Displaying the channel, name and descriptions of the different data point used in the experiments in this study.

Channel	Name	Description
101	hp$_{lower}$	Lower surface of aluminum plate
102	hp$_{upper}$	Upper surface of aluminum plate
103	2cmL	Two cm above aluminum plate - left
104	2cmC	Two cm above aluminum plate - center
105	2cmR	Two cm above aluminum plate - right
106	4cmL	Four cm above aluminum plate - left
107	4cmC	Four cm above aluminum plate - center
108	4cmR	Four cm above aluminum plate - right
110	6cmL	Six cm above aluminum plate - left
111	6cmC	Six cm above aluminum plate - center
112	6cmR	Six cm above aluminum plate - right
113	8cmL	Eight cm above aluminum plate - left
114	8cmC	Eight cm above aluminum plate - center
115	8cmR	Eight cm above aluminum plate - right
116	10cmL	Ten cm above aluminum plate - left
117	10cmC	Ten cm above aluminum plate - center
118	10cmR	Ten cm above aluminum plate - right
120	thermostate	Thermostate
121	scale	Mass measurement
301	12cmL	Twelve cm above aluminum plate - left
302	12cmC	Twelve cm above aluminum plate - center
303	12cmR	Twelve cm above aluminum plate - right
304	14cmL	Fourteen cm above aluminum plate - left
305	14cmC	Fourteen cm above aluminum plate - center
306	14cmR	Fourteen cm above aluminum plate - right
307	33cmC	Thirty three cm above aluminum plate - center
308	ambient	Ambient room temperature
309	biprobe	Air flow
311	wat press	Water pressure measurement
313	T Water in	Temperature of water entering the cooling jacket
314	T Water out	Temperature of water exiting the cooling jacket
316	Outside 2cm	Outside of cylinder, 2 cm above aluminum plate
317	Outside 4cm	Outside of cylinder, 4 cm above aluminum plate
318	Outside 6cm	Outside of cylinder, 6 cm above aluminum plate
319	Outside 8cm	Outside of cylinder, 8 cm above aluminum plate
320	Outside 10cm	Outside of cylinder, 10 cm above aluminum plate

3.2.6 Experimental procedure

First, the sample was removed from the freezer and left at room temperature until the sample also was room tempered. Next, the empty pipe and cooling jacket were placed on the scale, and the hoses enabling water flow were connected to the cooling jacket, making water flow in a circular motion around the steel pipe. Then, insulation, thermocouples, bidirectional probes and all the equipment was put into place. When everything was in the right position, the pellets was poured into an empty container until the total mass of the pellets reached 1250 grams. This weight was decided to be used based on bulk density of the pellets. The 1250 grams of pellets resulted in 10 cm sample-height in the pipe, which was the target height of the tests.

The pellets were then transferred from the container, and into the pipe using a smaller cup. This ensured uniform distribution of pellets, and with a careful hand the pellets were evened out using a stirrer. Once everything was in place, the timer and electrical heating unit was turned on and the logger was started. During the test, a vent was used to draw flue gas away from the smoldering-chamber.

Next, a timer connected to the electrical heating unit was used to cut the power to the heater at a target time. This duration varied for each test. The thermocouple positions and bidirectional probe can be seen in Figs. 13a and 17.

After each test, the remaining mass was weighed and all the equipment was cleaned.

Figure 17: Photo of the bidirectional probe, thermocouple-ladder with regards to the pipe and sample.

3.2.7 Test scheme

This subsection serves the purpose of helping the reader understand the reasoning as to why certain experiments was prioritized over others.

The first target of the experimentation was to test heating duration in order to get a predictable pattern of the cases smoldering/non smoldering versus heating duration. The plan was therefore to begin at 6 hours heating duration, to see if there were any differences between the non-cooling and cooling case. After this, 14 hours heating duration test was performed because it was believed to be an absolute maximum heating duration based on previous work and literature studies. This proved to be wrong, and additional tests was needed to determine the required heating duration. In order to get data which could be trusted, a repetition on every other increase in duration was performed. Next, the focus was shifted to look at a passive cooling system and active cooling system. The difference of these being flowing versus non-flowing water. Test matrix and the results of this can be viewed in sec 4.1.

All tests have names following this pattern: DSMxx_ FRICy_dd.mm.yy. Here DSM stands for "Dag Snersrud Master", to identify the person and project. The xx specifies the chronological sequencing of the experiments, and ranges from 0-24. FRICy is used to determine which setup that is being used for the given experiment, where FRIC tells that it is a part of FRIC-program at RISE. It is important to separate between the two setups, because even though the two setups used in this thesis were made to be as similar as possible, small differences are expected. The y can therefore have the values 1 and 2, based on which setup that is being used. The last part of the test name is simply the date of which the experiment was started, written in "dd.mm.yy"-format. By following these rules, test 14 on setup 2 at 24th of December 2021, will be named: DSM14_FRIC2_24.12.21.

4 Results

4.1 Test overview

Below, an overview of all the tests can be seen. This overview tells the outcome of the test (smoldering, no smoldering or partial smoldering), the test parameter, which setup was used for the test and the heating duration. In Fig. 18, self sustained smoldering is abbreviated "sss" and equipment is abbreviated "eq."

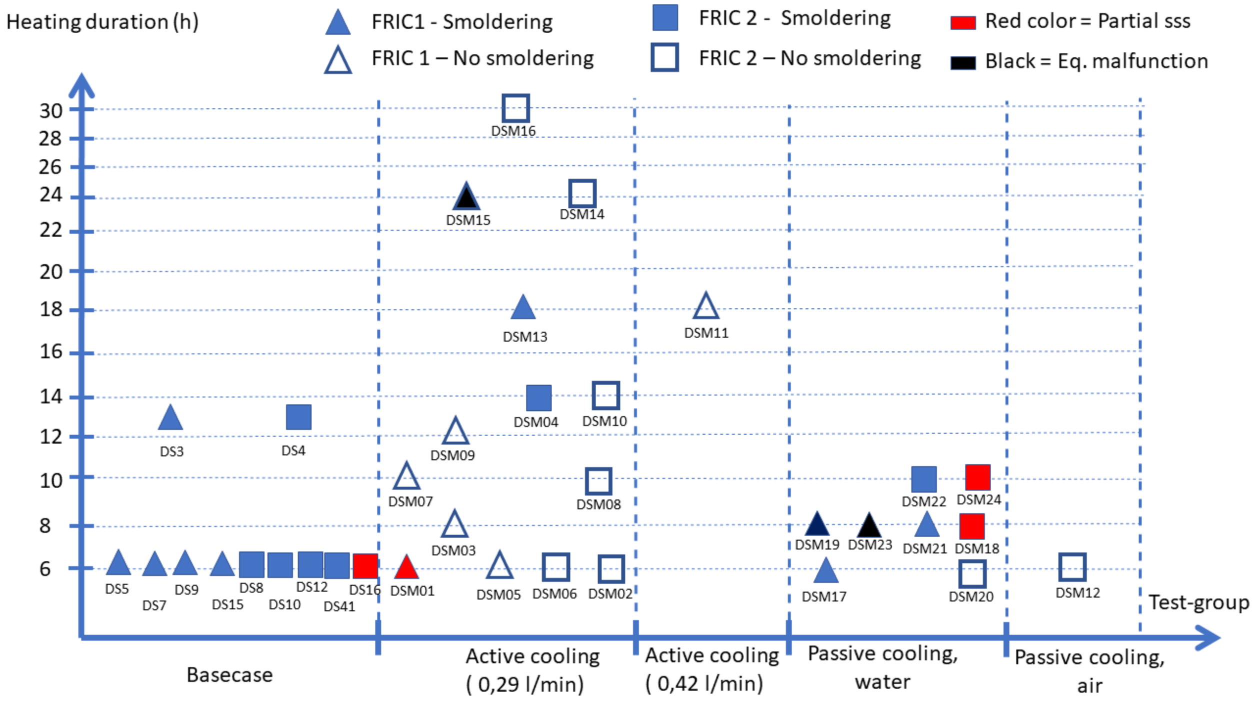


Figure 18: Review of all the tests conducted in this experimental study, as well as all experiments conducted in the study from 2020 by Snersrud [20]. Because there are two setups, a triangle was used to identify one, and square for the other. The meaning of the different colors can be view in the upper part of the figure.

4.2 Data presentation

All the different data points in Table 5 were collected from the files containing all the data, and were analyzed in respect to some important definitions. Heating duration, turn around temperature, max temperature and mass loss are just a direct read from the files, no calculations required. There was a total of eight tests resulting in smoldering. Three of which experienced partial self sustained smoldering, and five underwent complete self sustained smoldering. For the purpose of conserving space, self sustained smoldering is abbreviated "sss" in Table 5, and "equip.mal" stands for equipment malfunction.

1 - A test was considered finished when all temperature loggings were beneath 20.8 °C ± 1.5 °C. This was the average ambient temperature in the room, and therefore marks the point where no heat is transferred across the system boundaries, and thus, the system is at rest.
2 - The average temperature is calculated by taking all the temperature data points in the steel cylinder while a test is running into account.

Table 5: An overview of the heating duration, turn around temperature, average temperature maximum temperature, total test duration and mass loss of each test. Test DSM24 did not have a turn around temperature, because the fire died out too fast. It is, however, still recognized as a case of partial self sustained smoldering.

Test	Outcome	Heating dur.	Turn around	Average	Max	Test dur.	Mass loss
		[h]	[°C]	[°C]	[°C]	[h]	[g]
DSM1	Partial sss	6	180	82	415	30	200
DSM2	No sss	6	-	-	-	-	68
DSM3	No sss	8	-	-	-	-	53
DSM4	Complete sss	14	200	143	550	50	1163
DSM5	No sss	6	-	-	-	-	44
DSM6	No sss	6	-	-	-	-	43
DSM7	No sss	10	-	-	-	-	70
DSM8	No sss	10	-	-	-	-	68
DSM9	No sss	12	-	-	-	-	59
DSM10	No sss	14	-	-	-	-	95
DSM11	No sss	18	-	-	-	-	80
DSM12	No sss	6	-	-	-	-	260
DSM13	Complete sss	18	240	141	650	53	1123
DSM14	No sss	24	-	-	-	-	85
DSM15	Equip.mal	24	-	-	-	-	20
DSM16	No sss	30	-	-	-	-	97
DSM17	Complete sss	6	240	90	530	51	1154
DSM18	Partial sss	8	235	76	350	44	390
DSM19	Equip.mal	8	-	-	-	-	27
DSM20	No sss	6	-	-	-	-	250
DSM21	Complete sss	8	245	144	640	55	1152
DSM22	Complete sss	10	250	126	490	65	1100
DSM23	Equip.mal	8	-	-	-	-	2
DSM24	Partial sss	10	-	103	325	25	326

4.2.1 Complete self sustained smoldering

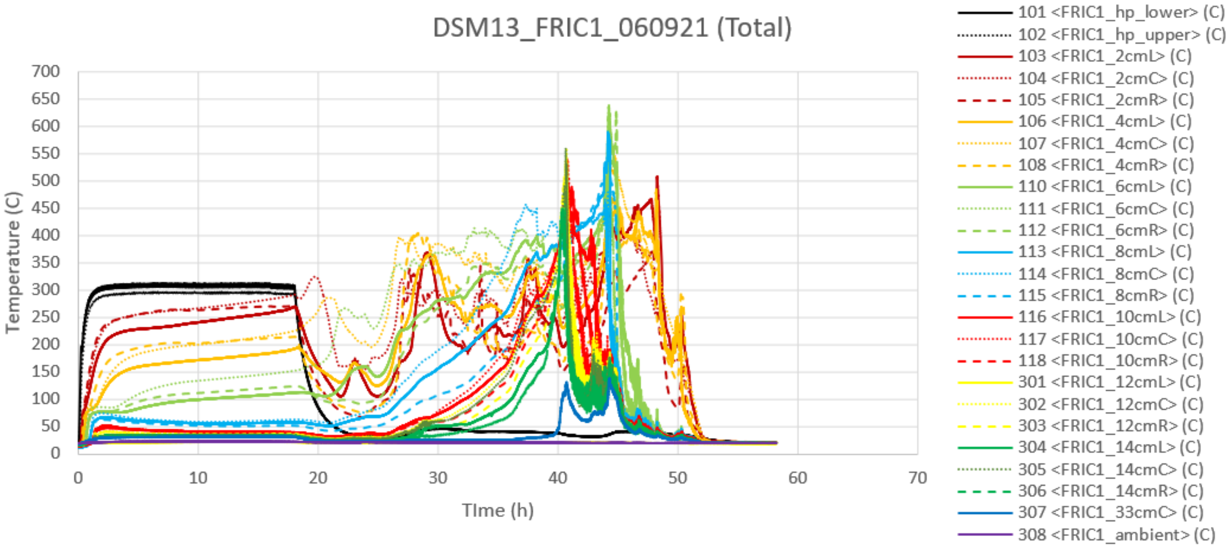
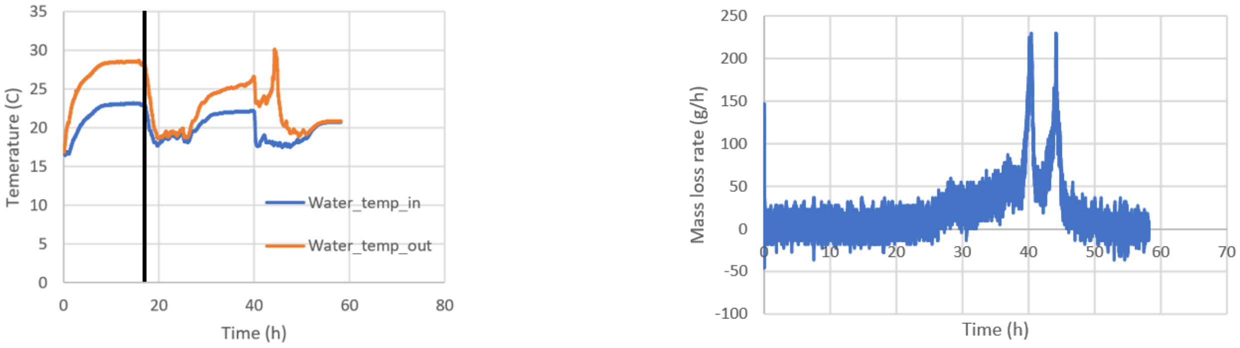


Figure 19: Temperature profiles for test DSM13, which was a test with active cooling, and experienced a case of complete self sustained smoldering.



(a) **(b)**

Figure 20: Temperature profiles of the water coming in and going out of the cooling jacket. The black line represents the time at which the external heater was turned off. This data is from test DSM13, which resulted in complete self sustained smoldering (a). Mass loss rate for the same test (b).

In the Figs. 19, 20a and 20b it can be seen that there are spikes in the water temperature at the same point in time as where the combustion is most intense, corresponding to the spikes in mass loss rate and temperature profile of the total test. This happens between hours 39 and 45 in the test. The mass loss was equal to 1123 grams, and the average mass loss rate was 22.96 g/h.

4.2.2 No self sustained smoldering

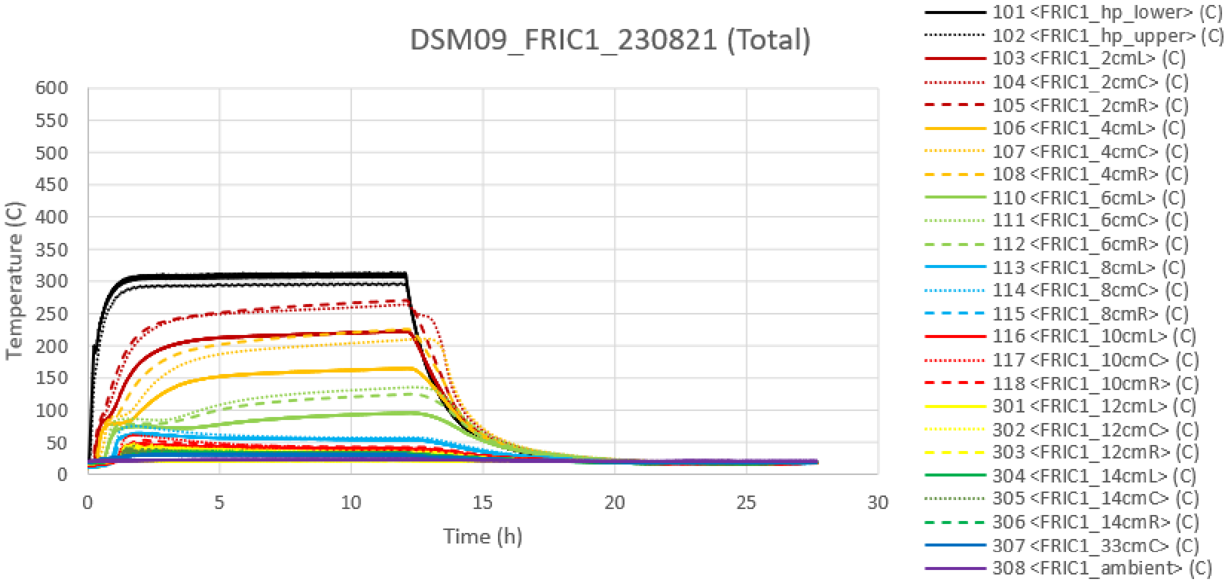
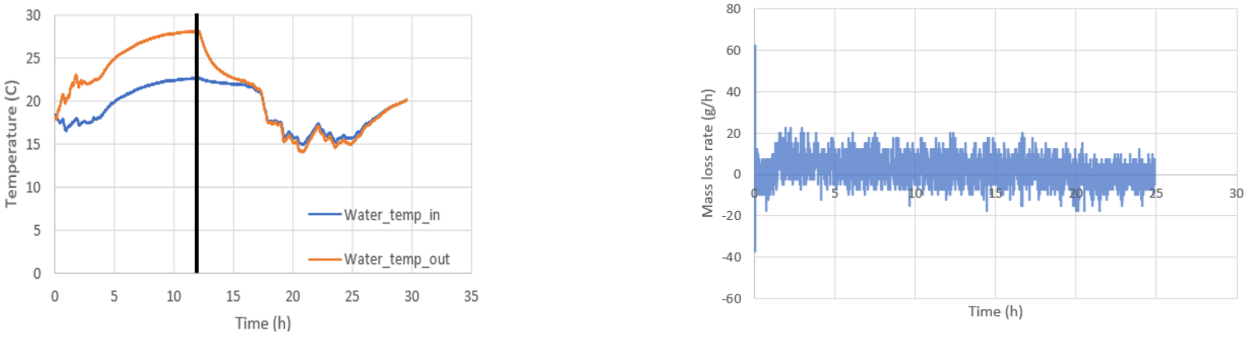


Figure 21: Temperature profiles during test DSM09 which was a test with active cooling, and experienced no self sustained smoldering.



(a)

(b)

Figure 22: Temperature profiles of the water coming in and going out of the cooling jacket. The black line represents the time at which the external heater was turned off. This data is from test DSM09, which resulted in no self sustained smoldering (a). Mass loss rate for the same test, and in order to see the values on the x-axis, the line has been made somewhat transparent (b).

In Figs. 21, 22a and 22b it can be seen that the water temperature of the inlet and outlet is different while the heating period is ongoing, as well as for a little while after. This, however, is not the case after the 17 hour-mark, where they are virtually equal for the rest of the test duration. In Fig. 22b it can be seen that the mass loss rate lies at zero for the majority of the test, which makes sense because the total mass loss of the test was equal to 59 grams of pellets. The average mass loss rate was calculated to be 3.51 g/h.

4.2.3 Partial self sustained smoldering

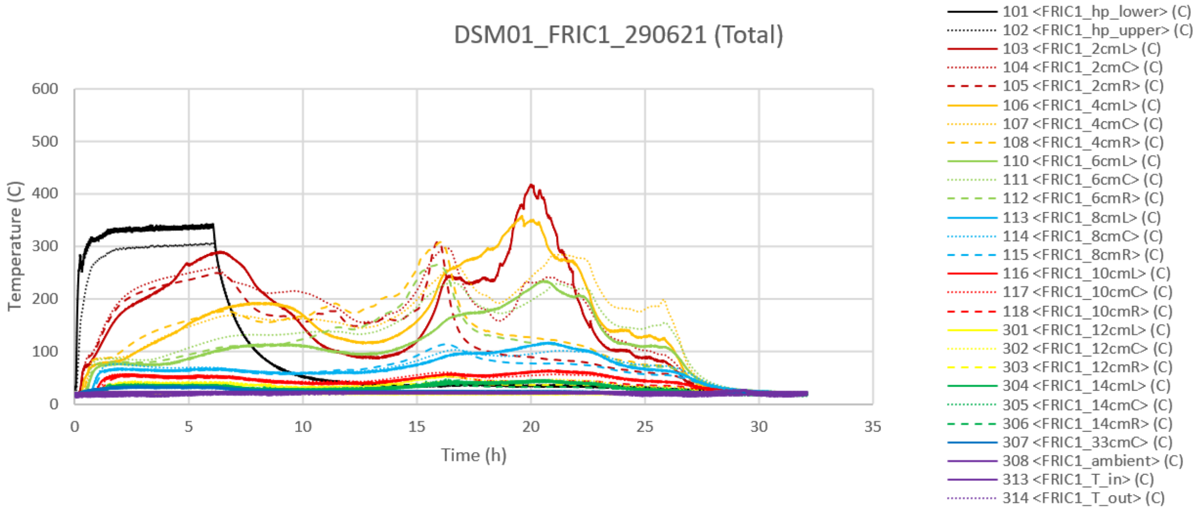
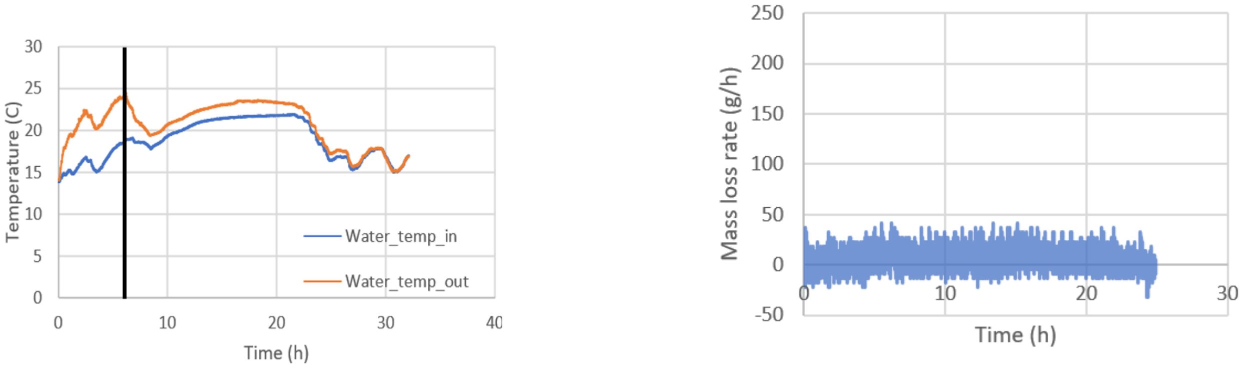


Figure 23: Temperature profile of the test DSM01, which was a test with active cooling, and experienced partial self sustained smoldering.



(a) **(b)**

Figure 24: Temperature profiles of the water coming in and going out of the cooling jacket. The black line represents the time at which the external heater was turned off. This data is from test DSM01, which resulted in partial self sustained smoldering (a). Mass loss rate for the same test, and in order to see the values on the x-axis, the line has been made somewhat transparent (b).

In Figs. 23, 24a and 24b, the overall temperature profile, water temperature and mass loss rate can be seen. It can be seen that after the external heater is turned off, smoldering continues on its own until it slowly fades out. The combustion is not complete, which is reflected in the mass loss data, which showed a mass reduction of 199.5 grams. The average mass loss rate was calculated and equal to 7.13 g/h.

4.3 Total combustion time

The total combustion time is the duration from which the external heater is turned on, to the sample is cooled all the way down to ambient temperature. This is key information, and says something about how rapid the fire is.

4.3.1 Non smoldering

For the non smoldering cases, the total combustion time was between 5 and 7 hours longer than the heating duration. This is not that interesting to look at, because it is just a steady decent to zero.

4.3.2 Smoldering

For the cases where smoldering was able to persist, it is separated between the two different cooling types, namely active and passive cooling. In Fig 25, the total combustion times can be seen, and in Table 6, the mass loss data is also included, to get the full picture. The active case had an average of 44.33 hours while the passive case had a higher average of 48.00 hours

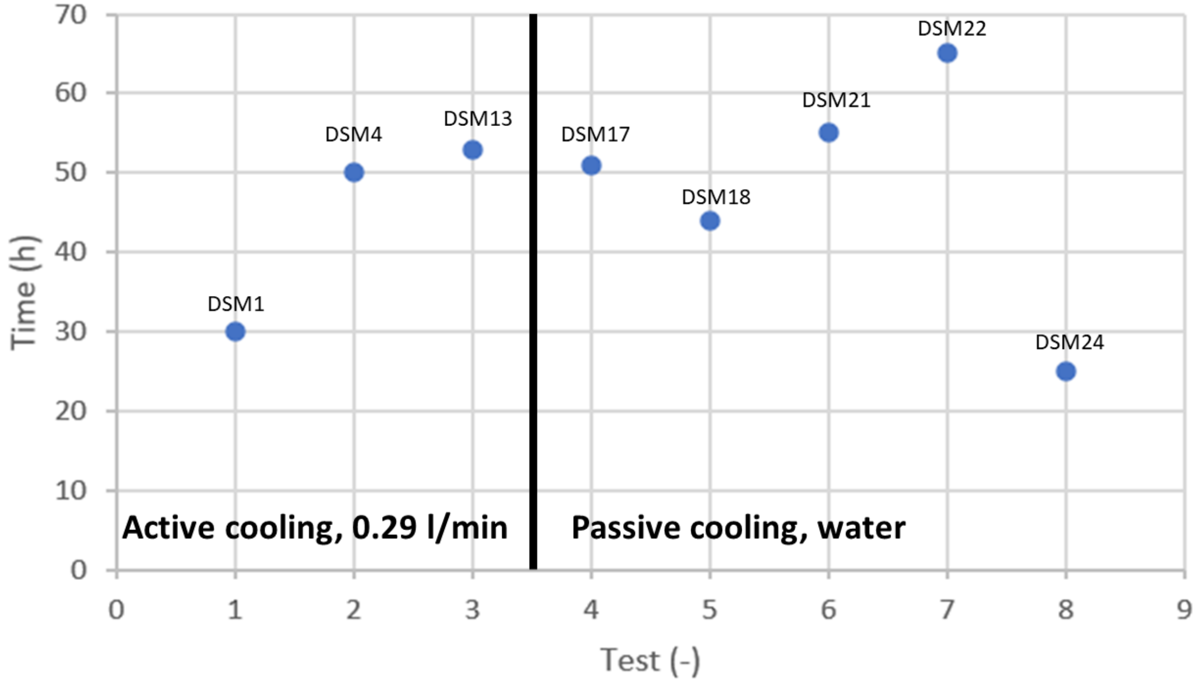


Figure 25: The total combustion time for the cases which smoldered. On the left hand side, the cases of active cooling can be seen, and on the right hand side, the passive case.

Table 6: All tests resulting in smoldering where test duration, mass loss and the type of cooling is noted.

Test	Heating duration	Cooling type	Mass loss	Test duration
	[h]		[g]	[h]
DSM01	6	Active, 0.29L/min	200	30
DSM04	14	Active, 0.29L/min	1163	50
DSM13	18	Active, 0.29L/min	1123	53
DSM17	6	Passive, water	1154	51
DSM18	8	Passive, water	390	44
DSM21	8	Passive, water	1152	55
DSM22	10	Passive, water	1100	65
DSM24	10	Passive, water	326	25

4.4 Water data

Different cooling methods were used throughout this study, and it is important to be clear on the difference between these. Active cooling means that there is a flow inside the cooling jacket, while passive means that it is stationary. In this study both these are looked into to determine if the difference in flow rate affects the cooling. The passive case can be viewed as an active case where the flow rate is set to zero. But in order to be separate the two cases with clarity, they are given different names, active and passive cooling. In Tables 7, 8, 9, 10 and 11, ΔT represents the difference in water temperature of the inlet and outlet.

4.4.1 Full duration tests

To get a clear view of the effect of water cooling, knowing the difference in temperature of the inlet and outlet of water is important. In Table 7 this is noted, along with heating duration, test duration and flow rate of the water.

Table 7: Displaying important details about all tests with active cooling which resulted in partial or complete self sustained smoldering.

Test	Heating duration	Test duration	Flow rate	Average Δ T	Maximum ΔT
	[h]	[h]	[L/min]	[°C]	[°C]
DSM01	6	30	0.29	2.05	5.86
DSM04	14	50	0.29	3.32	10.08
DSM13	18	53	0.29	3.47	12.2

And to have some grounds to compare the ones that experienced smoldering, to those who did not smolder, Table 8 displays water data for three of the tests that did not smolder. Three tests with as close to the same heating duration as possible were chosen to represent this case.

Table 8: Displaying important details about three tests with active cooling which resulted in no self sustained smoldering.

Test	Heating duration	Test duration	Flow rate	Average Δ T	Maximum ΔT
	[h]	[h]	[L/min]	[°C]	[°C]
DSM02	6	14	0.29	2.43	5.91
DSM10	14	22	0.29	4.21	6.24
DSM14	24	30	0.29	5.65	7.32

4.4.2 Ignition

In order to say anything about the initiation of smoldering, a closer look at the water data differences in the same cases as displayed in Tables 7 and 8. This being 6 cases where three smoldered and three did not smolder, and the focus here is just the initiation of smoldering, and not the actual smoldering. In Table 9, the smoldering cases can be seen.

Table 9: Displaying important details about all tests with active cooling which resulted in partial or complete self sustained smoldering, but here restricted to the external heating period.

Test	Heating duration	Flow rate	Average Δ T	Maximum ΔT
	[h]	[L/min]	[°C]	[°C]
DSM01	6	0.29	4.75	5.86
DSM04	14	0.29	5.12	5.80
DSM13	18	0.29	5.10	7.72

In Table 10, the water temperature differences for the non smoldering cases can be seen.

Table 10: Displaying important details about all tests with active cooling which resulted in partial or complete self sustained smoldering, but here restricted to the external heating period.

Test	Heating duration	Flow rate	Average Δ T	Maximum ΔT
	[h]	[L/min]	[°C]	[°C]
DSM02	6	0.29	4.91	5.91
DSM10	14	0.29	5.48	6.54
DSM14	24	0.29	6.65	7.32

4.4.3 Change in heat transfer due to increase in flowrate

There were only time for one test with the increased flow rate of 0.42 L/min. This is not enough data to come to any conclusion, but it does give an indication on the matter. The one test with 0.42 L/min flow rate, was DSM11. This test was an 18 hours heating duration test with active cooling, and resulted in no self sustained smoldering. In Table 11, DSM11 and DSM13 can be seen together, because they are the only two tests with the same grounds for comparison. Both tests have 18 hours heating duration, and the only difference is the flow rate, which is the parameter of interest. In this comparison, the key section is the heating period. This is due to the fact that after the heating duration is over, one goes to smoldering, and one goes cold. It is therefore interesting to see what happened before this point, in order to see what differences caused the different results.

Table 11: Displaying important details in test DSM11 and DSM13, which had active cooling where one smoldered and one did not smolder. The data in this table is restricted to the external heating period.

Test	Heating duration	Flow rate	Average △ T	Maximum ΔT
	[h]	[L/min]	[°C]	[°C]
DSM11	18	0.42	3.64	4.18
DSM13	18	0.29	5.10	7.10

The average temperature in the pellets was 130 °C in DSM11, and 124 °C in DSM13. The temperature difference between the water inlet and water outlet is lower in the high flow rate than in the low flow rate scenario. In the same time period as what is displayed in Table. 11, the mass loss in the high flow rate case was 49 grams, and in the low flow rate case it was 51 grams. On average, the moisture content in the fresh pellets was 7.49%, which in a 1250 gram sample is equivalent to 94 grams. It is hard to say whether or not the mass loss experienced in this period is only due to the drying of pellets or if some of the lost mass is gone due to smoldering. Therefore it is hard to say anything about the heat production by pellets in this period, compared to the heat loss due to the water cooling. However, in section 5.2.2, the effect of the increased flow rate is discussed and heat transfer due to water cooling is calculated.

4.5 Negative mass in passive cooling series

In the passive cooling series, some tests resulted in a mass loss larger than 1250 grams, which should be impossible because the test sample was weighed to 1250 grams making this the maximum theoretical mass loss. The reasons why this happened is discussed in section 5.1.2, but an example of the observation is provided here, Fig. 26.

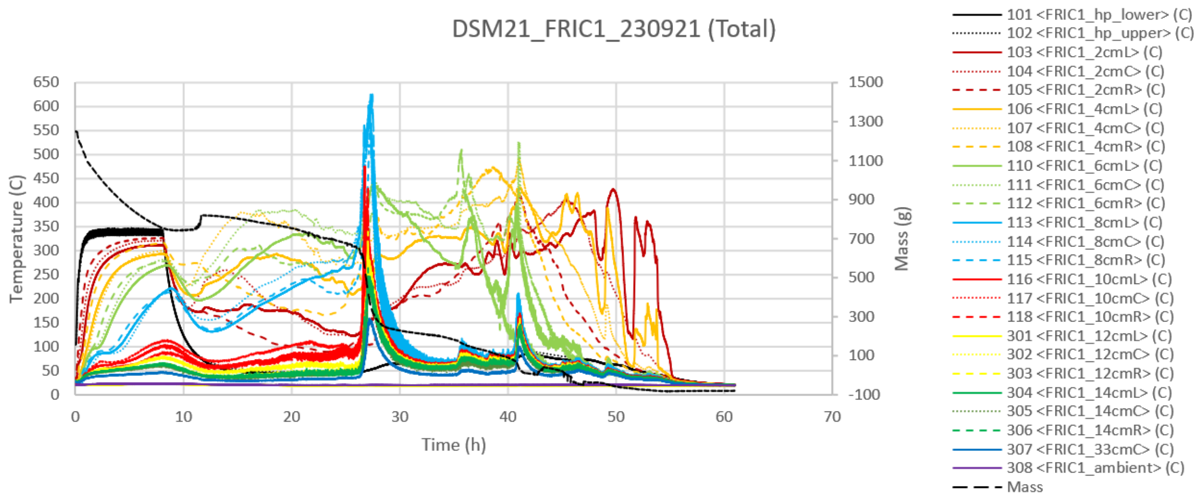


Figure 26: Temperature profiles and mass graph for test DSM21.On the secondary axis, the remaining mass can be seen, which is equal to -97 grams at 60 hours.

5 Discussion

In this section, the test setup, research questions and the phenomenon of bridging will be discussed. Practical applications of the study and future work will also be presented.

5.1 Test setup and experimental procedure

In this section, different challenges that arose during the study will be presented, discussed, and reflected upon. This serves the purpose of informing the reader about parts in the experiments that could be improved.

5.1.1 Separate water flow completely

The tests conducted in this study takes use of two separate test setups, but the water supply is connected to the same outlet. The water tubes are the same length, and the same valves are used on both setups, making the two separate setups run perfectly identically when they run with the same water flow. This, however, changed when performing tests with no flow on one setup, and normal flow on the other. Because there was no pressure valve on the inlet of each setup, the change in flow rate on one side affected the flow rate on the other. This can be dealt with by adding a pressure valve at the inlet of each setup, making it possible to keep the same pressure on both sides, and thereby making the flow rates independent of each other. If the opportunity to run tests with different water flow is unnecessary and not needed, the setup works perfectly fine with the configuration used in this study.

5.1.2 Flow back of water and negative mass in passive cooling series

In the test series with passive cooling, where water is stationary in the cooling jacket, meaning no flow of water, the mass graph showed an increase in mass some hours after the external heating was turned off. This can be seen at the 12-hours mark during a test with passive cooling, Fig. 27. The black dashed line representing the mass had an increase where the weight seemed to increase before going further down. The initial hypothesis was that water got hot enough for it to boil in the cooling jacket and condensate further down the pipe, and flow back into the cooling jacket.

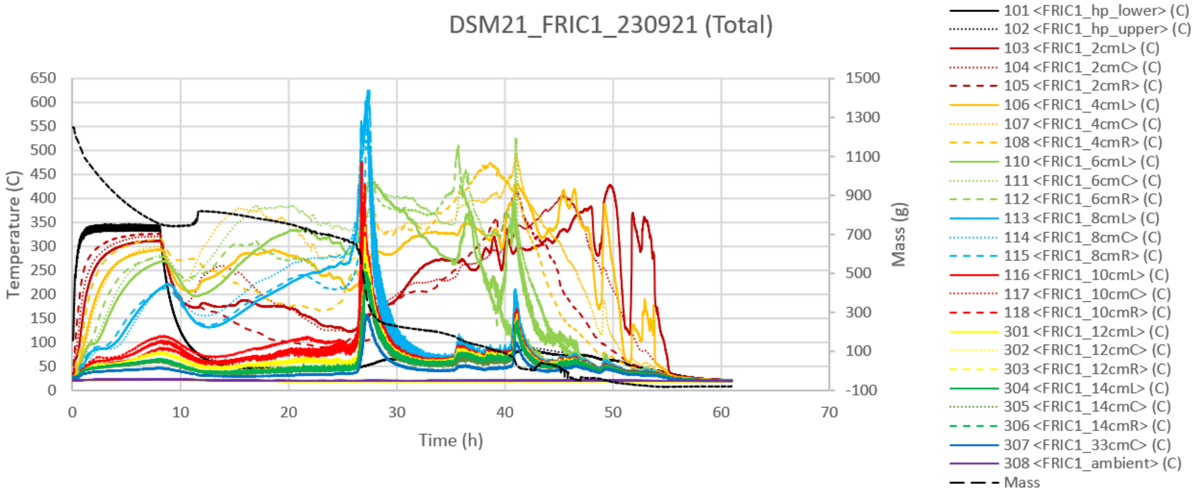


Figure 27: Temperature profiles and mass graph for test DSM21.

During this test, the drainage tubes were taped to the side of the wall, higher above the ground than the location of the cooling jacket, with made sure water would not flow out of it. But, if the water starts boiling, it can exit the cooling jacket and leave the tube as steam. Because of the length of the drainage tubes, the water can also cool down and condense on the inside of the tube, and flow back into the cooling jacket after the most intense combustion's have passed. This is possible because the tube is surrounded by ambient tempered air after it leaves the cooling jacket. In Fig. 28 the temperature data of the inlet and outlet of water can be seen. This graph shows that the water has the potential to vaporize, as can be seen 42 hours into the test, where the water reached a peak temperature of 97 °C.

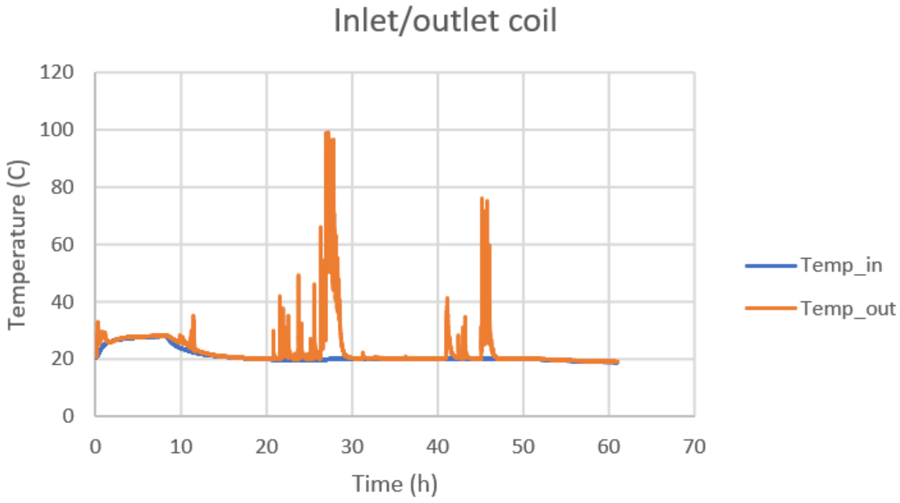


Figure 28: Temperature graphs for inlet and outlet of water.

The water temperature at the 12-hours mark only reached 37 °C, which is not enough for the water to vaporize, and therefore does not agree with the hypotheses of condensed water flowing back. But, there is also a slight chance that the temperature reads are based on the air or water in the pipe, and not the heated water vapor. This is of course just speculations, because there was not enough time to further explore this phenomenon. The only conclusion that can be drawn on this subject is that the water in the pipe reached high enough temperatures for it to vaporize, which raises the possibility of vaporization, condensation and flow back. A test was performed where the water tubes were separated from the cooling jacket, making it impossible for the vaporized water to condensate and flow back. This test resulted in the same negative mass as for the other tests with passive cooling, but the mass graph was without the sudden increase as experienced at the 12-hours mark in test DSM21, Fig. 27. This indicates that the flow back could be caused by the condensation of vaporized water, but one test is not enough data foundation to arrive at a conclusion on this matter, and more tests are therefore required.

If the flow back is put aside, and only the negative value of mass after the test is dealt with, it can be seen on the secondary axis in Fig. 27, that the mass at the endpoint is -97 grams. This is caused by vaporized water. The tests with passive cooling all experienced this negative mass read, and some water was missing from the cooling jacket after the completion of each experiment, supporting this conclusion.

5.1.3 Experimental procedure

The experimental procedure was exactly how it needed to be, and with the procedure used in this study, the wood pellets was in the same state each time an experiment was started. This is due to the the cold storage, and the duration of which the pellets was resting in room temperature before test start, which was the same for all tests. The most time consuming part of the experiments was the cleaning of the steel pipe after each test, but this was a necessary step to make sure all experiments had the same conditions, and the procedure used in this study is therefore estimated to be good.

5.2 Discussion of research questions

5.2.1 Ignition while affected by cooling

The ignition of smoldering fires was greatly affected by the cooling jacket, compared to a scenario without cooling. In the study by Snersrud from 2020 [20], self sustained smoldering was achieved in 7 out of 9 tests while having a heating duration of 6 hours. This is a much higher percentile than what is experienced in this study. In total, 4 tests were performed with a heating duration of 6 hours while having water running in the cooling jacket. Out of these, 1 experienced partial self sustained smoldering, and 3 did not show any signs of ignition whatsoever. After the 6-hours tests were completed without achieving predictable smoldering, the next goal was to find a duration of which smoldering occurred every time. In order to determine a heating duration the ignition of smoldering happened consistently, a step wise process was started where heating duration's were gradually increased in the hopes of at some point getting a consistent smoldering fire. This, however, proved itself to be harder than anticipated, and at one point no more time could be spent exploring heating duration's, and the experiments had to move on to check more parameters. This was done in order to try to find answers to the rest of the research questions as well, not just the question about ignition. The longest heating duration that was tested was in test DSM16, where the sample underwent a 30 hours heating duration without the occurrence of smoldering. This arose the question whether or not it was possible to ignite a smoldering fire with the current flow rate. Based on the temperature profiles of the tests with different heating duration's, Figs. 29 and 30 this doubt that a fire could predictably ignite with the current flow rate was strengthen, and the decision to move on to different cases was made. Even though smoldering was achieved once with 14 hours and once with 18 hours heating duration, the occurrence of consistent, predictable fires was not observed.

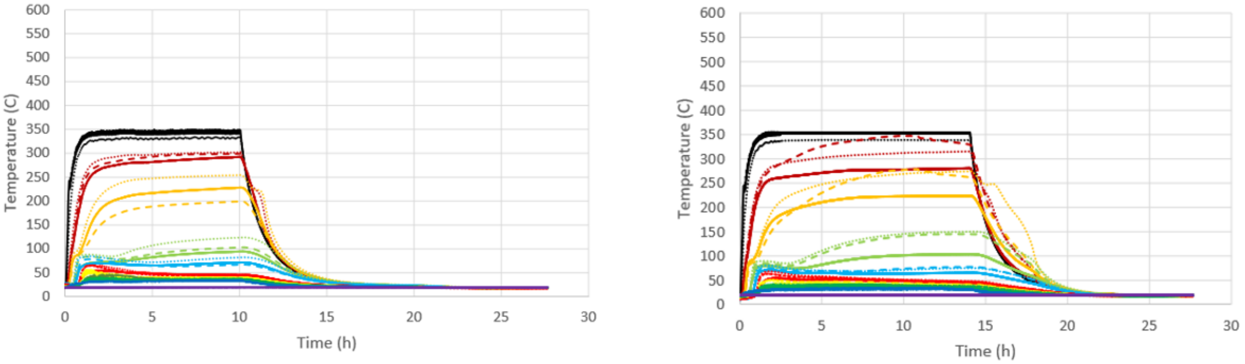


Figure 29: Temperature profiles of tests with heating duration 10 hours (left) and 14 hours (right).

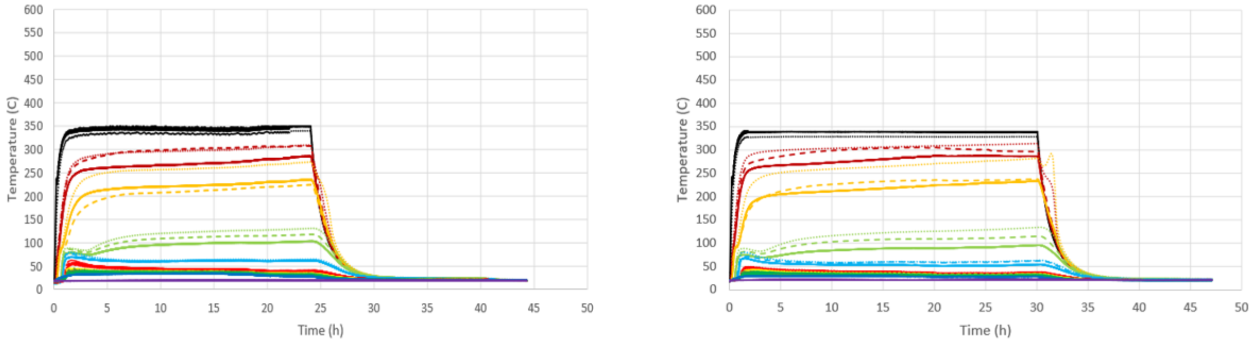


Figure 30: Temperature profiles of tests with heating duration 24 hours (left) and 30 hours (right).

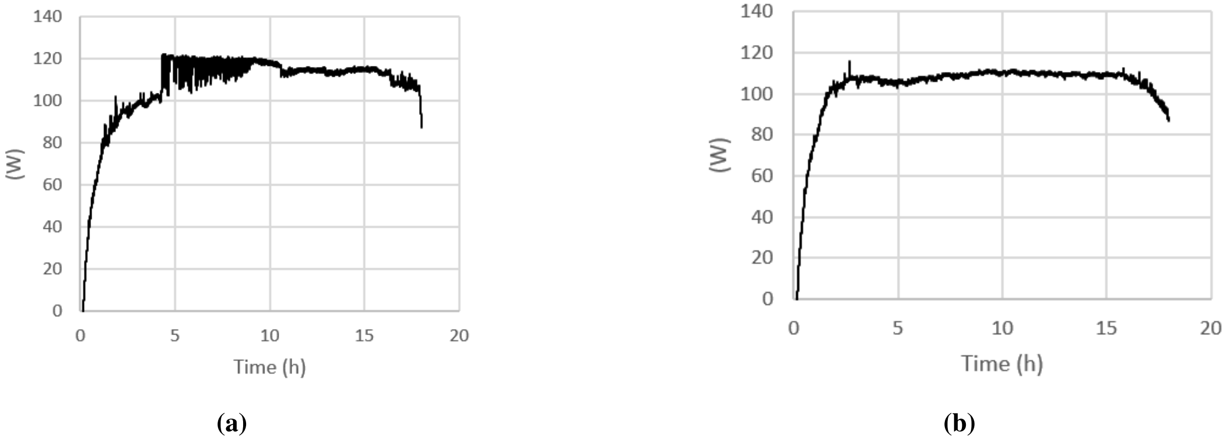
In the passive cooling, ignition was achieved in five out of seven tests. One out of three times with 6 hours heating duration, and four out of four times where heating duration was either 8 or 10 hours. The passive case consisted of six tests with water in the cooling jacket (originally two more, but these suffered equipment malfunction, and is therefore not used here) and one where air was in the cooling jacket. This is a dramatic increase in cases with ignition for passive cooling (zero flow rate), compared to active cooling. This is a clear indication that the flow rate is an important factor when it comes to the ignition of smoldering fires, and will be discussed more in section 5.2.2.

5.2.2 Heat transfer and flow rate

It is important to understand how the cooling of a smoldering fire can be increased or adjusted to fit a specific need. The flow rate was therefore an important parameter to alter in different directions, and see how the cooling output responded to this. Unfortunately, time was not sufficient for a large amount of data on this subject to be collected. This means that it is hard to say anything with certainty when the data foundation is weak. Only one experiment was conducted with a different flow rate, and this section is dedicated to collecting as much information and many indications as possible from this test in comparison with the regular flow rate cases.

In Figs. 31a and 31b, the heat loss to the water in the cooling jacket is plotted against time for two tests, namely DSM11 an DSM13. The graphs show the first 18 hours of the tests, because one led to smoldering, and one led to no smoldering. It is therefore interesting to take a closer look at the differences in this period, to see what caused the diverging results. In DSM11, the average heat loss in this period was 106 W, while in DSM13, the average heat loss was 103 W. The average temperature in the sample in DSM11 was 130 °C and in DSM13 the average temperature was 124 °C. The difference in heat loss for the two tests is not as large as expected, because the increased flow rate from 0.29 L/min to 0.42 L/min corresponds to a 45% increase in flow rate. Eq. 9 was used to determine the heat transfer rates in Figs. 31a and 31b, where $C_{p,w}$ was set to 4.18 J/gK [11].

More tests have to be performed to see if this observation is an abnormality or if this is the case in general. However, the data so far reveals that the heat loss does most likely not increase linearly with increase in flow rate.



(a)

(b)

Figure 31: Graphs displaying the heat loss due to water cooling as a function of time in the heating period. (a) Is test DSM11 and (b) is test DSM13.

5.2.3 Total duration of smoldering fires

The total combustion time of the tests varied between 65 hours at most (smoldering), to 14 hours at the least (no smoldering). In this section, the focus will mainly be on the tests which smoldered, because these are the tests that contains the most relevant information. Cases of no smoldering experiences a fast decline in temperature at a steady rate as soon as the external heating is turned off, which is not of particular interest.

There were eight tests which experienced smoldering of some kind, partial or complete self sustained smoldering. These are the tests which will be in the spotlight here, and will further be divided into two groups because some of the tests were with the passive cooling, and some were with the active cooling.

Active cooling
In the case of active cooling, there were three tests where smoldering occurred, which can be seen in the results in Fig. 25. Two tests experienced complete self sustained smoldering, and one experienced partial self sustained smoldering. The combustion time is expected to be longer the more mass loss there is, assuming the smoldering fire doesn't transition to flaming, which is reflected by the results where the partial test lasted for 30 hours, and the two which smoldered completely lasted for 50 and 53 hours, which had 14- and 18- hours heating duration, respectively. In the base-case experiments conducted by Snersrud in 2020, the average combustion time of the experiments resulting in complete self sustained smoldering was 64.6 hours. The average duration in this study was 51.5 hours, in the case with active cooling.

Passive cooling
In the passive case, the average combustion time of the cases where complete self sustained smoldering occurred was 57 hours. The tests where partial self sustained smoldering is excluded from this section, because the interesting feature here is the total combustion time, and in a partial smoldering case, the combustion is finished before the fuel is burned completely, and can therefore not be compared.

For both cases the average combustion time was lower, but for the active cooling, this duration was significantly lower than what was experienced in a non-cooling scenario. This is interesting, because it seems that with cooling, a smoldering fire is drastically harder to ignite, but it burns more rapid. This is reflected in the average temperature, which for the two tests with active cooling in this study was 143 °C and 141 °C, respectively, and averaging on 142 °C, while in the basecase scenario without cooling the average was 115 °C. This is equal to an increase in average temperature of 23.5%, which is a significant increase.

5.2.4 Effects of thermal adhesive

The cooling jacket is made by heating and bending a copper pipe around the steel pipe. When a circular pipe is placed on a flat surface, the point where the pipe is in contact with the steel cylinder surface is a small. This is the downside of using rigid materials, because these materials do not deform and can therefore not access more than a small contact surface. When using a cooling jacket, the target is to optimize heat transfer, making the cooling jacket as effective as possible. The idea behind using a thermal adhesive to glue the cooling jacket onto the steel cylinder, was to increase the contact area, to gain a larger surface over which conductive heat transfer would occur. Without this glue, there is only a small fraction of the pipe in direct contact, and most of the surface area of the cooling jacket is therefore only affected by radiation, which is far less effective. However, time was of the essence, and there was not enough time for this to be tested. That being said, the cooling jacket transferred enough heat from the system for the active cooling series to work perfectly fine in this study. It is still a smart decision to optimize the heat transfer, because it makes it more effective, and could possibly end up with the same heat transfer with a lower flow rate.

5.3 The phenomenon of bridging

In the tests with active cooling, bridging in the sample was observed. Bridging is in its core a transformation where the granular wood pellets start sticking together, forming bridges, and was only observed in tests which did not burn down completely. This behavior was first noticed in the 6-hours tests with active cooling, and was present in all active cooling cases. In the low heating duration tests (6-10 hours external heating) this effect was present, but not in a drastic way. The pellets stuck to each other more than usual when removing the unburned pellets and TC-ladder from the sample, but with a small shake, the equipment got loose. This however, changed when the heating duration's got longer. After the tests with active cooling and heating durations longer than 14 hours, these layers of bridges reached a larger and larger percentile of the total sample. After the 24-hours and 30 hours heating duration tests, these layers had to be punctured by using a sharp tool and quite a force. In Fig. 32 the pellets are holding its own weight in the cylinder, because the picture is taken from directly beneath the sample.

Figure 32: Picture of the underside of the steel cylinder containing the sample. The picture is taken after a test, and the black burned pellets is at height 2 cm.

The phenomenon of bridging makes the pellets have enough structural integrity for it to support its own weight, as proven in Fig. 32. This can cause the fire to run out of fuel while there is still plenty of fuel left, because the pellets which normally crumbles and falls down as the fire goes on, is held up by the bridges throughout the sample. This can also be the reason why it was so hard getting a predictable fire when increasing the heating period, because it may be the case that there was no fuel left on the bottom, in contact with the heater. This is of course only speculations, but the phenomenon of bridging could be the reason, and is therefore discussed. In Fig. 33, a picture of pellets melted together can be seen. The bridging might not be as dominant in large scale tests, because the larger the scale is, the bigger the impact of the sample weight due to gravitation.

Figure 33: Picture of a piece of pellets after a test where bridging occurred.

5.4 Heat transfer calculations

Modelling how a smoldering fire will behave is a tremendously hard task, because there are a number of parameters and variables depending on each other, and a thesis could be written on that subject alone. In the example presented here, simplifications are made in order to give the reader a sense of scale when it comes to the efficiency of the external cooling jacket in a simplified case.

In Mikalsen's study from 2018 [11], the heat production of pellets was determined using the following correlation, Eq. 18

$$Q_{prod} = \dot{m}_s H_c \tag{18}$$

Where q_{prod} is the heat production rate $[W]$, $\dot{m}_s$ is the mass loss rate $[kg/s]$ and H_c is the effective heat of combustion for wood pellets $[6MJ/kg]$.

5.4.1 Calculating maximum radius of simplified system

A sample of pellets is smoldering, and has a constant heat production of 38.4 W. This value is an example value, based on Eq. 18 with $\dot{m}_s$ equal to $6.4 * 10^{-6} kg/s$, which was the average mass loss rate during one of the smoldering cases with active cooling. Next, this smoldering sample is put into a large cylinder with an infinite radius, containing wood pellets. The target of this calculation is to find the maximum radial distance at which cooling would still affect the smoldering. Because this is a simplified case, assumptions are made to make the calculations feasible, and the assumptions are as follows:

1. The pellets suffers no reduction in size when smoldering, making the system stationary, removing the effect of crumbling and possible voids in the sample.
2. Assuming that the conductivity model can be used for heat transfer in pellets.
3. Assuming the pellets around the initial sample, represented by the yellow color in Fig. 34 does not react.
4. A core temperature of 400 °C, which is a typical temperature of smoldering.
5. All the heat production is happening within the sample, illustrated in Fig. 34 as the dashed box (sample seen from the side) and blue circle (sample seen from above).

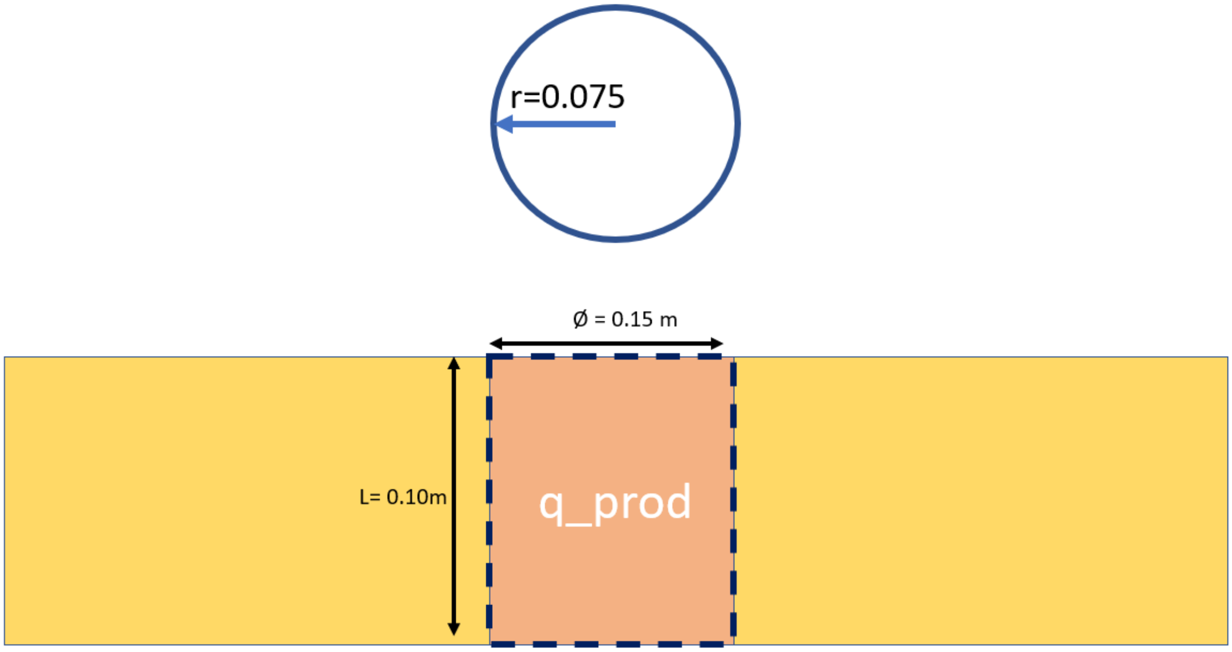


Figure 34: Sketch of the system, where the upper drawing is the cylinder seen from above, and the lower is the cylinder seen from the side with wood pellets around it, represented by the yellow color.

As stated in the assumptions, this example takes use of the conduction model, Eq. 6. To see the derivation for this formula, look at section 2.3.2, but the formula will be repeated here, Eq. 19.

$$Q_{prod} = \frac{2\pi k L(T_1 - T_2)}{ln\frac{r_2}{r_1}} \tag{19}$$

The value for k, is set to $0.15W/mK$ based on Mikalsen's study from 2018 [11]. L is the height of the cylinder $0.10m$, T_1 is the core temperature set to $400°C$, based on assumption 4. T_2 is set to $18°C$, because this is the water temperate, and thereby also a critical temperature, at which no heat will be transported away by the water, because ΔT in Eq. 8 would be zero. r_1 is set to $0.075m$, because this is the radius of the cylinder used in this thesis.

Rearranging Eq. 19 to solve for r_2, which then becomes:

$$r_2 = e^{\frac{2\pi kL(T_1 - T_2)}{q_{prod}}} r_1 = 0.19m \tag{20}$$

This answer represents maximum radial distance from the smoldering core an external cooling jacket could be placed with any influence on the sample. The reason why the dimensions of the sample cylinder is set to be the same as the dimensions of the test sample used in the experiments in this study, is to use the actual data from the experiments in the example. The heat production, mass loss rate, temperatures, r_1 and r_2 are dimensions and values experienced in this study. There are a lot of uncertainties in this calculation, because the assumptions which are made, are a bit harsh. In a real case, the surrounding pellets would start to react, due to the heat in the core, which would increase the diameter of the core and thereby increase the diameter of r_1. This will lead to an increased heat production, and a larger effective radius, r_2. However, this example was presented to give an indication on how effective heat sinks such as the cooling jacket is when transitioning to large scale tests and real life fires in silos, etc. The low conductivity of pellets makes it hard to extinguish the core of a smoldering fire by using external cooling when the distance between cooling unit and core is much larger than the 7.5 cm radius used in this study. For heat to be transported away in this manner, the heat has to travel through the pellets, making it a possibility that the pellets it goes through might heat up sufficiently and could also react, causing more heat production. In the study by Mikalsen from 2018, a proof-of-concept was provided using a centrally located cooling rod. With center cooling, the heat extraction happens in the core of the fire, which is beneficial because the heat doesn't have to travel through the sample before it is extracted from the system, as opposed to the case for external cooling. Please note that with a different model than the conductivity model, this result can be different, and that this model assumes that the core is already smoldering. If the case is prevention of smoldering, the result would also be different, because of the lower core temperature and heat production.

5.5 Practical application and scalability

The calculation performed in section 5.4.1 gives an indication on how the external cooling could work in large scale. In the large scale case, the thermal conductivity of wood pellets is too low for heat to effectively be transported through the pellets and walls, to then be carried away by a stream of water in a cooling jacket. This raises the question whether or not this type of cooling is possible to scale into larger systems, with the same degree of efficiency as what is experienced in this study. There are, however, some practical applications to this study. First of all, the knowledge adapted in this thesis, is added to what was already known about the phenomenon of smoldering. Secondly, this thesis gives an indication on the positive and negative aspects of ignition, propagation and quenching of smoldering fires, using external water cooling. Lastly, this study gives a basis from which future studies can be built upon. Suggestions for possible topics that can be investigated further, is presented in section 5.6.

5.6 Future work

This thesis has brought more information about external cooling to the table, but much is yet to be discovered. In this section, some suggestions are made, concerning future research on the phenomenon of smoldering fires.

5.6.1 Flow rate

Going forward from this point, conducting more experiments with different flow rates, preferably a flow rate in between the two main test series performed in this study, which was 0.29 L/min and 0 L/min. Hopefully the results from tests with varying flow rates, will give a clear correlation between flow rate and heat transfer. The almost identical heat transfer for the 0.29 L/min and 0.42 L/min flow rates, (3 W difference) may indicate that a this is close to a maximum heat transfer for this system, and that further increasing the flow rate may not change anything. However, by turning down the flow rate, this may give much more information about the how heat transfer is affected by flow rate.

5.6.2 Bridging

This phenomenon was observed in all active cooling cases, but not discovered in the basecase without cooling. As talked about in the discussion, the bridging in wood pellets enables the sample to gain some structural integrity, preventing crumbling and collapse of pellets. This is interesting to look further into for two reasons.

1. If external cooling is used to keep silos from igniting, the bridging can occur in the sample, which may cause irreversible damage to the sample.
2. If the bridging can prevent the spread of smoldering by adding structural integrity to the sample, this is something worth looking into.

5.6.3 Large or medium scale smoldering fires

The experiments conducted in this study are all small scale tests, and behaviors is never identical when scaling up the proportions. Performing tests where the size of the sample is made larger is therefore an important step towards seeing the full picture of smoldering fires. It would also be interesting to see the effect of water cooling on large scale smoldering fires, in order to accurately create a model that can predict the behavior of a smoldering fire in large scale, with and without a heat sink.

6 Conclusion

This is a parameter study exploring the effects of external cooling on smoldering fire in wood pellets. Through different test series, this study sheds light on how the ignition and propagation of smoldering is changed while under the influence of external cooling. The external cooling used in this study was a cooling jacket made from copper, with water circulating the sample, transporting heat across the system boundaries and thereby cooling the fire. External heating was used to initiate the smoldering process and the heating duration required for smoldering to arise was explored.

The ignition of smoldering fire proved to be more difficult than anticipated. Without external cooling, the sample started smoldering in a predictable pattern after being heated for 6 hours, as found by Mikalsen's study from 2018 [11]. This was not the case when the external cooling was applied, and this study was unable to determine a heating duration where the initiation of smoldering could be predicted. The maximum heating duration tested in this study was 30 hours, which is a 400% increase in heating duration compared to no external cooling, without the sample resulting in smoldering. This is a significant increase, and it emphasizes the influence of cooling as used in this study.

Different flow rates in the cooling jacket were also tested, ranging from 0 L/min to 0.42 L/min. The majority of tests were performed with a flow rate of 0.29 L/min, which yielded an average heat loss of 103 W over the duration of a smoldering fire. When focusing on the heat transfer during the heating period, it was discovered that increasing the flow rate from 0.29 L/min to 0.42 L/min resulted in a 3 W increase in heat transfer. This suggested that the heat transfer was approaching a stagnation point, and flow rates of lower values (between 0.29 L/min and 0 L/min) should be tested.

The total test duration was also affected by the external cooling, and surprisingly, the experiments resulting in complete self sustained smoldering burned down quicker in the case of external cooling than without the cooling, despite needing a longer heating duration. This indicates a more violent combustion, where the mass loss rate is higher with the external cooling than without cooling. Looking at these results in light of the ignition difficulties, this indicates that when external cooling is applied, the ignition is more difficult, but when ignited, the fire is harder to control. This is an important feature to be aware of, especially in the industrial scene, where this more violent combustion has the potential of causing more harm.

An interesting phenomenon that was discovered was the occurrence of bridging in the pellets during the active cooling series. The bridges forming within the sample gave the pellets more structural integrity, which can have many implications further down the road. This, however, was outside the scope of this study, and was therefore left for future studies to explore.

References

[1] Adrian Bejan, A.K., 2003. Heat Transfer Handbook. John Wiley and sons, Inc, Hoboken, New Jersey.

[2] Ahrens, M., 2019. Home fires started by smoking. National Fire Protection Association URL: `https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Smoking-Materials`.

[3] Atreyan, A., 2016. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. doi:`10.1007/978-1-4939-2565-0_19`. page 51-101.

[4] Davies, J., 2020. Underground peat fire. ABC news URL: `https://www.abc.net.au/news/2020-01-03/underground-peat-fire-1/11839808?nw=0`.

[5] Ezekoye, O.A., 2016. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. doi:`10.1007/978-1-4939-2565-0_19`. page 25-50.

[6] Ganji, D.D., Sabzehmeidani, Y., Sedighiamiri, A., 2018. Chapter 3 - radiation heat transfer, in: Nonlinear Systems in Heat Transfer. Elsevier, pp. 105–151. doi:`/10.1016/B978-0-12-812024-8.00003-5`.

[7] Hedlund, F.H., 2018. Carbon dioxide not suitable for extinguishment of smouldering silo fires: Static electricity may cause silo explosion. Biomass and Bioenergy 108, p. 113–119. doi:`10.1016/j.biombioe.2017.11.009`.

[8] Ida Larsson, A.L.e., 2017. Development of a Screening Test Based on Isothermal Calorimetry for Determination of Self-Heating Potential of Biomass Pellets. doi:`10.1002/fam.2427`.

[9] Krisnawati, H., Adinugroho, W.C., Imanuddin, R., Suyoko, Weston, C.J., Volkova, L., 2021. Carbon balance of tropical peat forests at different fire history and implications for carbon emissions. Science of The Total Environment 779. doi:`10.1016/j.scitotenv.2021.146365`.

[10] Liu.C.Y., Wong, Y.e.a., 1990. Note on the robust bidirectional low velocity probe. Experiments in Fluids 9, 354–356. doi:`10.1007/BF00188768`.

[11] Mikalsen, R.F., 2018. Fighting flameless fires. Ph.D. thesis. Otto-von-Guericke-University of Magdeburg. doi:`10.13140/RG.2.2.34666.16329`.

[12] Moran, M.J., Shapiro, H.N., 2016. Fundamentals of Engeneering Thermodynamics. John Wiley & Sons, Inc, West Sussex, England. Page 107.

[13] Mulhollem, J., 2011. Why and where fires start in silos, and what to do if you have one. Agricultural Sciences URL: `https://news.psu.edu/story/156406/2011/08/05/why-and-where-fires-start-silos-and-what-do-if-you-have-one`.

[14] Pollock, D.D., 1991. Thermocouples, Theory and properties. first ed., CRC press, inc, Florida. Page 1.

[15] Rebaque, V.V., 2017. Experimental study of smouldering fires in wood pellets. Masters thesis, NTNU URL: `http://hdl.handle.net/11250/2454929`.

[16] Rein, G., 2016. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. doi:`10.1007/978-1-4939-2565-0_19`. page 581-601.

[17] REOTEMP.Instruments, 2020. Types of thermocouples. REOTEMP URL: `https://reotemp.com/thermocouple-types/#typek`.

[18] Santoso Muhammad A., e.a., 2021. Laboratory study on the suppression of smouldering peat wildfires: effects of flow rate and wetting agent. International Journal of Wildland Fire 30, 378–390. doi:`10.1071/WF20117`.

[19] Simon, M., 2021. Underground "zombie" peat fires release 100 times the carbon of wildfires. Bulletin of theatomic scientists URL: `https://thebulletin.org/2021/03/underground-zombie-peat-fires-release-100-times-the-carbon-of-wildfires`

[20] Snersrud, D.O., 2020. Smoldering fire in wood pellets. Specialization Project, NTNU .

[21] Tien, C., Lee, K., Stretton, A., 2016. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. doi:`10.1007/978-1-4939-2565-0_19`. page 102-139.

[22] Vallero, D.A., 2010. Chapter 10 - addressing biotechnological pollutants, in: Environmental Biotechnology. Academic Press, San Diego, p. 502. doi:`10.1016/B978-0-12-375089-1.10010-8`.

NTNU

Norwegian University of
Science and Technology