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Extinguishing smoldering fires in waste facilities

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WESTERN NORWAY UNIVERSITY OF APPLIED SCIENCES

Master Thesis in Fire Safety Engineering

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Master Thesis in Fire Safety Engineering

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This thesis represents the end of a master's degree at the Western Norway University of Applied Science in Haugesund. The master's degree has been taken part time over three years while working full-time with fire safety engineering. The goal of this master's thesis has been to increase the knowledge, both my own and for the industry, on smoldering fires and how to manage these in waste facilities. The subject was chosen after discussions with prof. Vidar Frette and Bjarne Christian Hagen at the university.

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Abstract

Waste facilities are filled with a range of combustible materials, and fires have been an issue for a long time. Fire is a risk, not only for economic reasons, but also for the consequences the toxic smoke and extinguishing water may have on the local environment. Smoldering fire in waste facilities are difficult to extinguish as the fire often sit deep in the waste piles and it can spread over a large area before it is detected or transitions to a flaming fire.

This thesis studies extinguishing methods that are based on viscous liquids to investigate whether this is more effective on smoldering fires than water, which traditionally is used by the fire department. Viscous liquids adhere better to material and might spread in a different way than water, as water tends to flow in the path of least resistance and forms channels. Therefore, water may not always reach the smoldering fire in a waste pile and large amounts of water are usually required.

Small-scale experiments were performed with wood waste placed in a steel tube. Inside the tube, seven thermocouples recorded the temperature changes in the sample. Sugar water was chosen as the viscous extinguishing agent because of well-documented viscosity of different mixtures. The extinguishing agent was applied to the smoldering fire one hour into the experiments, and temperatures were recorded for two more hours after extinguishing agent was applied to observe the extinguishing effect.

Results from the experiments indicates that liquids with a viscosity higher than water may be more effective on smoldering fires than water. The smoldering fire was extinguished in all three experiments where the mixture of water and 20 % sugar by mass was used as extinguishing agent. For the experiments with higher viscosity, the fire intensity was higher and fewer smoldering fires were extinguished. This is probably because the water evaporated, and the sugar contributed to the fire.

The viability of viscous liquids as extinguishing agent should be examined further with up-scaled experiments and other viscous agents. High-viscosity extinguishing agents may be useful for smoldering fires at waste facilities and there are other areas where it may be an more effective extinguishing agent than water, such as for densely built wooden settlements or bush fires to limit the fire spread.

Sammendrag

Avfallsanlegg er fylt med alle slags brennbare materialer, og brann har vært et problem i lang tid. Brann er en risiko, ikke bare av økonomiske årsaker, men også for konsekvensene den giftige røyken og slokkevannet har på nærmiljøet. Ulmebrann i avfallsanlegg er spesielt vanskelig å få slukket da disse brannene ofte sitter dypt i avfallshaugene og kan spre seg over et stort område før de blir oppdaget eller blusser opp i flammebrann.

Denne oppgaven tar for seg slokkemetoder som baseres seg på viskøse væsker for å undersøke om dette er mer effektivt mot ulmebrann enn vanlig vann som tradisjonelt blir brukt av brannvesenet. Viskøse væsker fester seg bedre til materiale og kan spre seg på en annen måte enn vann, da vann ofte renner i minste motstands vei og danner seg kanaler. Dette gjør at vannet ikke alltid treffer brannen når det er ulmebrann i store hauger og det kreves som regel store mengder med vann.

Forsøkene ble utført i små-skala og baserte seg på ulmebrann i treavfall plassert i en ståltube. Inne i sylinderen registrerte syv termoelementer temperaturforandringene i treavfallet. Som viskøst slokkemiddel ble sukkervann valgt, da denne væsken har en godt dokumentert viskositet. Slokkemiddelet ble påført ulmebrannen en time ut i forsøket og temperaturene ble videre registrert i to timer etter dette for å observere slokkeeffekten.

Resultatene indikerer at væsker med høyere viskositet enn vann kan være mer effektive på ulmebrann enn vann. Ulmebrannen ble slukket i alle tre forsøkene hvor det ble benyttet en konsentrasjon med vann og 20 masseprosent sukker. For forsøkene med høyere viskositet så ble brannintensiteten høyere og færre ulmebranner ble slokket. Dette er sannsynligvis fordi vannet fordampet og sukkeret bidro til brannen.

Viskøse slokkemidler bør undersøkes videre med oppskalerte forsøk og andre type viskøse væsker, da dette kan være nyttig for ulmebranner på avfallsanlegg. Slokkemidler med høy viskositet kan potensielt også være et mer effektivt slokkemiddel enn vann på andre områder, for eksempel på tett trehusbebyggelse eller skogbranner.

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1 Introduction

1.1 Background

Waste facilities are filled with a range of combustible materials, and fires have been an issue for a long time. Fire is a risk, not only for economical reason, but also for the consequences the toxic smoke and extinguishing water may have on the local environment [1].

Smoldering fire is a type of fire that is hard to detect and likely to occur in waste facilities due to the large quantities of various stored waste, such as lithium batteries and biomass . Deep-seated smoldering fires may develop by self-heating and be self-sustained. The fires may propagate through waste piles for a long period, sometimes weeks or months, before transitioning into a flaming fire [2] [3].

Figure 1-1 - Smoldering fire at landfill. (WitthayaP, Public domain [4])

Smoldering combustion is a complex process which depends on several factors such as fuel properties, ignition source and air flow to the reaction zone. A self-sustaining smoldering fire could spread to large areas and should be extinguished to limit the emitting of toxic gases. Water is the primary extinguishing agent for smoldering fires. However, a large amount of water is required to extinguish smoldering fires because they often are difficult to reach [5].

1.2 Fires in waste facilities

Fires have occurred quite frequently in waste facilities the last couple of years. Since 2016, there have been more than 200 registered fires in waste facilities in Norway and it is assumed that there have been many more [6]. In Sweden, there are registered 60-70 fires at waste facilities each year [7].

Extinguishing fires in waste facilities can be challenging and, in some cases, take many days to complete. The fires emit toxic fumes, and fire foam and extinguishing water can pollute the environment near the facility. Non-degradable heavy metals from electric waste are examples of toxic materials that may be released to local water sources when extinguishing fires at waste facilities [6].

Waste facilities often differ in terms of the types and amounts of waste they receive and how the waste is stored and treated. The risk of fire will therefore vary. Location, such as proximity to buildings, dwellings and industry, to vulnerable nature, water and agricultural areas could influence the consequences of fires at waste facilities [6].

Autoignition is often reported as the cause for waste fires, but for most cases, the cause of waste fires is unknown [8]. Smoldering fires can burn for a long time and have a transition to flaming fire before they are discovered. Little information on smoldering fires in waste facilities is available compared to flaming fires [9].

Figure 1-2 and Figure 1-3 show examples of fires in waste facilities. Figure 1-2 is from a fire at a waste facility in Oslo, Norway. The fire at Norsk Gjenvinning in 2018, which began in the morning of March 8th, was under control the same afternoon because of small piles of waste, good fire compartmentation and general tidiness at the facility. The fire was easy to locate, and an excavator could assist the fire department to remove the fire source from the rest of the combustible material [10].

Figure 1-2 - Fire at waste facility in Oslo. Reproduced with permission from Oslo Brann- og redningsetat [10].

Figure 1-3 is from Linnestad in Re, Norway. The fire started at approx. 06:30 in the morning the 21st of July 2014, most likely by self-ignition. The waste consisted of 1250 tons of environmentally sanitized electronic waste, placed outdoors [11].

The fire brigade first reported an extensive fire in a pile of painted plastic with heavy smoke development. The fire brigade covered the pile with fire foam. The fire was declared extinguished after 36 hours. 12 m^3 foam liquid and 1800 m^3 (1.8 million liters) water was used in the effort [11].

Water from the extinguishing was drained into a small stream. The fire foam with the extinguishing water led to oxygen loss in the water, which caused fish deaths [11].

Samples from the water several kilometers downstream of the discharge showed mercury, cadmium, lead, copper, zinc and nickel, above the limit of acute toxic effects on aquatic animals. 20 households were advised not to drink the water in their wells because of the pollutions from the extinguishing at the waste facility. These wells were declared healthy after a quarantine period of 63 days. Several farmers had their crop damaged due to irrigation with contaminated water [11].

The owner and two people in the management of the waste facility were sentenced to prison for crimes against the environment, mainly caused by poor waste management [12].

Figure 1-3 - Fire at waste facility in Re. Reproduced with permission from Vestfold Interkommunale Brannvesen [13].

1.3 Purpose and research question

The purpose of this thesis is to examine the effect a high-viscosity liquid will have on the extinguishment of smoldering fires in waste facilities. Water tends to flow along the path that has the least resistance, while a liquid with higher viscosity might flow in a different path and have a higher chance of reaching the fire than the water [3]. A high-viscosity liquid will also flow more slowly, increasing the cooling of the fuel and improving the extinguishment effect. The following question will be examined:

How is the extinguishing effect of high-viscosity liquids on smoldering fires in waste compared to water?

The research question has been investigated by conducting experiments. The experiments were small-scale and may indicate the differences in effectiveness of liquids with different viscosity. The existing research on extinguishing smoldering fires is limited [5] and these experiments may contribute to more efficient extinguishing methods for smoldering fires in the future.

1.4 Limitations

This thesis focuses smoldering fires occurring in waste facilities. An experimental approach will be used to investigate the effect a viscous liquid will have on smoldering fires and if this high-viscosity liquid can be a used as an extinguishing agent for fire fighters.

The thesis is limited to small-scale experiments with one fuel type. The experiments were conducted with biomass fuel, more specifically wood waste. The extinguishing of smoldering fires in other waste materials has not been tested experimentally.

2 Theory and previous work

Fires in waste facilities may be challenging to detect and suppress, especially with smoldering fires occurring deep into the pile of fuel. This chapter will discuss the properties of smoldering fires.

2.1 Smoldering Combustion

Smoldering combustion differ from a flaming combustion by being slower, flameless and with low temperature as it develops in porous fuels. Smoldering combustion require porous fuels because of the high surface area available for oxidation, reduced heat loss and easy oxygen flow to the reaction zone [14]. This type of fire is interesting from a fire-safety perspective, because it can burn and propagate slowly through the fuel for an extensive time, with low heat-release rate, leading to delayed detection and late, or no sprinkler activation. The flameless combustion is often oxygen deficit and release large amounts of toxic gases, for example carbon monoxide. Well-known examples of smoldering fires are a burning cigarette or glowing charcoal in the fireplace [8] [9].

Some combustible materials can self-heat without any external ignition source and start to smolder and release toxic gases. The smoldering fire may start by biochemical and biological degradation in a self-heating pile of biomass. How the fire develops depends on several factors, such as the volume of the pile, the ventilation in the pile and moisture content [1].

Smoldering fires do not require external heat exposure as they can develop from self-ignition when the amount of generated heat is larger than the heat loss. This type of fire can keep on burning for a long time, even for days, months and years, without being discovered. This is a problem in waste facilities because it can be difficult to notice, and transition to a flaming fire when oxygen is available [11]. Deep-seated smoldering fires can accumulate a large amount of energy before reaching the surface by slowly spreading over a large volume, and they are hard to reach by extinguishing agents. The low heat conductivity for most smoldering materials also means that it requires a lot of time and extinguishing agent to cool from the outside of a volume [15].

Figure 2-1 - Smoke rising from a smoldering peat fire (Chris Lowie/USFWS, Public domain [16]).

Smoldering fires is one of the leading causes for fire deaths in residential fires and is also an issue in the industry. The main reason for this is that, even though they are slow-burning, smoldering fires typically yield larger amounts of toxic gases than flaming fires. They are also harder to detected due to this slow-burning with low temperatures. The environment is also greatly affected by smoldering fires as they can cause destruction of ecosystems and emission of large quantities of greenhouse gases to the atmosphere [17]. An example is the huge deposits of coal underground [18] and peat fires which alone are responsible for 15 % of the greenhouse emissions worldwide. This type of peat fires is illustrated in Figure 2-1 [19].

Under right conditions, a smoldering fire can generate enough heat to transition to a flaming fire. This change could occur from a heat source that did not initially have enough energy to directly ignite a flaming fire. This is because combustion, both smoldering and flaming, is exothermic reactions that release heat. Whether the type of combustion is smoldering or flaming, depends on when and where the oxidation occurs. An oxidation in the gas phase causes a flaming fire and an oxidation at the surface of a solid material will cause an smoldering fire [17].

Smoldering fires typically have a lower temperature than flaming fires and peak temperatures are normally between 450-750 °C. Effective heat of combustion range between 6-12 kJ/g and heat release 10-30 kW/m^2. Therefore, smoldering fires usually propagates slowly through the fuel. Typically, the propagation velocity is 1 mm/min or less, but this varies with the chemical composition of the fuel [17].

2.2 Fire conditions

To start and sustain a fire, four conditions are required: heat, oxygen, fuel, and chemical chain reaction. The fire tetrahedron illustrates the elements needed for a fire to occur and to keep on burning, see Figure 2-2.

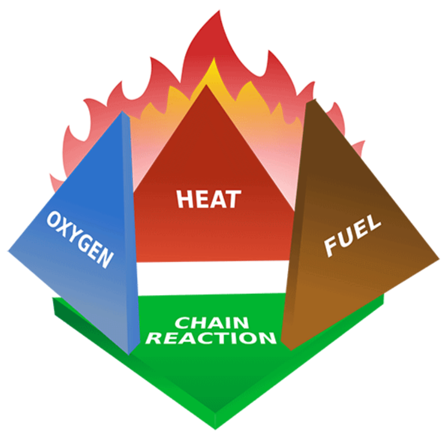

Figure 2-2 - Fire tetrahedron (Gustavb, public domain [20]).

2.3 Extinguishment of smoldering fires

The extinguishment of smoldering fires is based on removing or reducing at least one of the conditions from the fire tetrahedron.

2.3.1 Reducing heat

The primary method for cooling down a fire is by using water as extinguishing agent. Water absorbs heat from the fire when evaporating. The ensuing gas expansion leads to oxygen deprivation in the fire which yields a good extinguishment effect by reducing the oxygen and lowering the temperature. Water tends to flow in the paths that has the least resistance. This channeling can cause an uneven water distribution with the water flowing in paths that does not reach the combustion zone. Cooling methods are still in most cases the most practical way of extinguishing smoldering fires in waste facilities [3] [19].

2.3.2 Burnout

An extinguishing method for smoldering fires is to let the combustible materials burn out or removing the source of fuel. Burnout in waste facilities is, in most cases, unacceptable because of toxic smoke and release of greenhouse gases into the atmosphere. This is especially problematic for smoldering fires as they can keep burning over extensive periods of time [17].

2.3.3 Smothering

Extinguishing the fire by reducing or removing oxygen is called smothering. The smoldering fires can be sustained in environments with very low concentrations of oxygen. There is currently no good mechanism or technique to prevent the diffusion of oxygen into large volumes of waste [17]. Gaseous agents such as N_2 and CO_2 can be used to smother the fire in confined spaces, but smoldering fires do often occur in porous materials, and the oxygen concentration just above the fuel is not the same as inside the fuel. The monitoring of the oxygen level can be challenging because of this inhomogeneous oxygen concentration. Verification of the extinguishment is important to avoid reigniting if the extinguishment effort is stopped too early [21].

2.4 Viscosity

Viscosity is a measure of a fluids resistance to movement and to change in shape. This is a quantification of the motion of adjacent layers in a fluid [22]. Layers of a liquid move at different velocities and the shear stress between these layers that ultimately opposes any applied force depends on the viscosity of a fluid [23].

Viscosity affects the flow of liquids. The viscosity of some normal liquids at 25 °C is listed in Table 2-1. Water will for example flow easier than honey because of a lower viscosity. Motor oils with low viscosity is preferred in engines to minimize friction between parts, but a too low viscosity will force out the oil when the parts move relative to each other. In pumps and ventilation systems, a larger viscosity gives larger pressures losses, which must be compensated for when transporting liquids and gases [22].

Table 2-1 - Viscosity of selected fluids at 25 °C [24].

Fluid	Viscosity (mPa · s)
Acetone	0.3
Water	0.9
Blood	4
Olive oil	80
Glycerol	1400
Honey	2 000 - 10 000
Peanut butter	100 000

Both temperature and pressure have an impact on the viscosity of fluids. Viscosity decrease as the temperature increases. For example, water at 20 °C has a viscosity of 1 mPa · s while the value is almost halved at 50 °C and 31 % at 90 °C, see Table 2-2 [23].

The viscosity of water, as a function of temperature (K) is described as [25]:

$$\mu = 2.414 \times 10^{-5}\ Pa \cdot s \times 10^{247.8\ K/(T-140\ K)}$$

Table 2-2 - Viscosity of water at different temperatures [23].

Temperature (°C)	Viscosity (mPa · s)
10	1.31
20	1.00
50	0.55
70	0.40
90	0.31

The viscosity of different liquids and aqueous solutions vary over several orders of magnitude. For example, an aqueous solution with 70 % sugar has a viscosity which is 467 times higher than water, see Table 2-3 [23].

Table 2-3 - Viscosity of aqueous solutions of sucrose ($C_{12}H_{22}O_{11}$) and water at 20 ^oC [23].

Mass (%)	Viscosity (mPa · s)
1	1.03
10	1.34
20	1.95
40	5.31
50	15.43
60	58.49
70	481.56

2.5 Relevant studies – Smoldering fires and extinguishment with viscous liquids

Some studies relevant to this thesis are presented in this part.

2.5.1 Viscous water and algin gel as fire-control materials

A study was conducted by the Pacific Southwest Forest and Range Experiment Station in California in 1962 to explore how a high-viscosity liquid can be used for coating the surface of fuels to retard and suppress wildfires. Viscous water and algin gel had been tested in laboratory and field tests on more than 200 forest and wildland fires over a 2-year period [26].

Viscous water is normal water thickened with a powder that resembles cornmeal, sodium-carboxymethyl-cellulose (CMC). The water is thickened to a viscosity of light motor oil (100-200 mPa · s) where it still is easy to pump and handle but adheres well to vegetation [26].

Algin water is water with high viscosity made by adding calcium chloride solution to water mixed with algin. This mixture holds water tenaciously and dries slowly. The mixture can stay moist for days in humid areas [26].

Laboratory studies indicated that viscous water was several times more effective than plain water in extinguishing fires. Suppression time was 4 times lower, and rate of reignition was lowered [26].

Some main points of the study were [26]:

- Viscous water is more effective than plain water for most forest fuels. Both liquids work best on hot fires and are probably not useful for low-intensity fires.
- The fires do not rekindle as rapidly as for normal water when mopped up with viscous water.
- Viscous water does not penetrate deeply into litter and duff, and most be mixed or stirred in.

2.5.2 Extinguishing smoldering fires in wood pellets by cooling

A study conducted at Western Norway University of Applied Sciences has investigated experimentally how the influence of a closed water-cooling loop inside the fuel bed can have an impact on extinguishing a smoldering fire. Wood pellet sample was contained in an insulated steel tube and a heat source warmed up an aluminum plate that distributed heat evenly to the wood pellets. A Keysight data recorder monitored the results from the thermocouples throughout the experiment. For experimental setup, see Figure 2-3 [27].

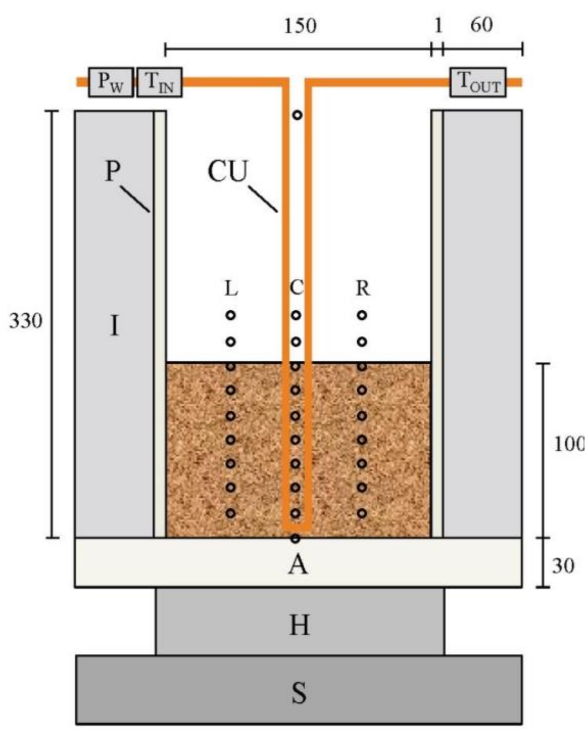

Figure 2-3 - Experimental setup with scale (S), heating unit (H), aluminum plate (A), insulation (I), steel pipe (P), cooling unit (CU), water pressure (P_W) and water temperature measurement points (T_{in}, T_{out}). Thermocouples were distributed evenly in the fuel. Dimesions are in mm [27].

The study showed that increased cooling decreased intense combustion at an early stage, and eventually full extinguishment in half of the self-sustained smoldering fires. This extinguishing method can possibly be extrapolated to larger storage units [27].

2.5.3 Extinguishing methods with little water

SP Fire Research AS wrote a report in 2017 on behalf of The Norwegian Directorate for Civil Protection (DSB). The goal of the study was to get an overview of how different extinguishing equipment was used in fire departments in Norway [28].

Experiments conducted in laboratories have shown that fire gel is better than water for preventing ignition and fire spread. The powder used to form the gel is usually different polymers or clay particles. Several of these have no negative impact on the environment, and it has been shown that only a minimal amount of water is needed to prevent ignition over time. As the gel is exposed to heat, the water will evaporate from the gel, but with short-term water shocks against the protected surface, the gel will be amplified [28].

It is believed that gel will also have a good effect in terms of preventing the spread of fire in areas with densely built wooden settlements. More research is still needed to confirm this, and one should also compare the effect of gel with the effect of different types of foams [28].

The report states that the fire service has viscous water, in form of water with polymers/gel available for forest fires and densely built wooden settlements. No other areas of use are mentioned [28].

2.5.4 Extinguishing smouldering fires in silos

A study in 1998 conducted by the Technical Research Centre of Finland, funded by Brandforsk, researched the extinguishment of smouldering fires in silos. Self-heating in porous, combustible materials in silos may lead to self-ignition, resulting in smouldering fires that are difficult to extinguish [21].

Water is the most widely used extinguishing agent but may cause issues when applied in silos. The material in the silo will get wet and swollen, making it difficult to remove and provide such high weight load that the structures may break down. The water can also whirl up powder, which in several cases have resulted in a dust explosion [21].

The water may also evaporate while approaching the smouldering fire, thus never reaching the target. Application of more water tends to create channels since water follows the path with least flow resistance. These channels often lead to the bottom of the silo without reaching the target, causing water filling in the bottom of the silo with structural problems and a smoldering fire burning freely at another part of the silo [3].

Some small-scale and intermediate scale tests were conducted and materials that are prone to self-igniton were used. The materials were wood chips, peat, grain and coal. Wood chips was chosen because samples was easy to prepare at different moisture contents and particle sizes, and the experiments were sufficiently repeatable. This was not the case for peat and coal. The self-ignition temperature increased with increasing moisture content and decreasing density. Moisture content of 8 % and 15 % were not observed to affect the burning, but the grain size had a considerable effect. Smaller grain size led to faster burning [21].

Table 2-4 - Self-ignition data for wood chips of grain size <1.89 mm and moisture content 15 % [21].

Sample volume (l)	**Radius (m)**	**T_{ign} @ midpoint (°C)**	**T_{ign} @ half radius (°C)**
0.1	0.025	220	215
0.7	0.05	190	190
4.9	0.1	179	179

It was observed after the test that the plain water had not wetted the top layer of the material, but rather channelled through it, only wetting the lower region. Extinguishment occurred only after the water level had reached the combustion front. The next experiment was conducted with the same set-up, but the water was treated with an additive that decreases surface tension. This agent was shown to be a potential candidate in fighting smouldering fires in open storage piles. This was not investigated further as it was not within the scope of the project [21].

3 Experimental setup and procedure

The purpose of this master thesis was to conduct experiments for exploring the extinguishing effect of viscous liquids. Experiments was chosen as the best approach to study the effects of liquids with variating viscosity as an extinguisher, since there is limited research on the topic.

3.1 Preliminary experiments

Preliminary experiments were conducted to determine the experimental setup and procedure.

In the first experiments a steel tube with 15 cm diameter and 40 cm height was filled with wood pellets. The tube was placed on a heater for 120 min to achieve a self-sustaining smoldering fire. This did not occur, probably due to low ambient temperatures and large heat loss to the surroundings.

The next experiments used 400 g wood pellets, which was ignited using a butane torch from above until all the pellets were flaming. This burning material was poured into the small steel tube with 1.5 kg pellets in the bottom. Thereafter, 700 g pellets were poured on top of the flaming pellets to limit the amount of oxygen to the fire. This was to simulate a smoldering fire in the middle of the pile. The temperature was kept at approximately 300 $^{\circ}$C and 1 l water was poured over the pellets after 150 min to extinguish the fire. The wood pellets expanded when water was added, thereby quenching the fire. However, the cleanup of each experiment took several hours due to expanded and hardened pellets. Therefore, wood waste was chosen as new fuel.

Initially, 15 thermocouples and steel structures as shown in Figure 3-1 were used. In later experiments, this number had to be reduced due to practical problems with starting the experiment and cleaning up. The thermocouples broke easily and were changed to thicker ones. The steel tube was changed to a larger one (20 cm x 50 cm) to obtain a self-sustained smoldering fire more easily.

Figure 3-1 – Left: Overview of experimental setup in the preliminary experiments. Right: The expansion of the pellets.

3.2 Experimental setup

The experimental setup is illustrated in Figure 3-2 and consisted of a steel tube, wood waste material and thermocouples. The experimental setup, fuel and extinguishing agent used are described in the following sections.

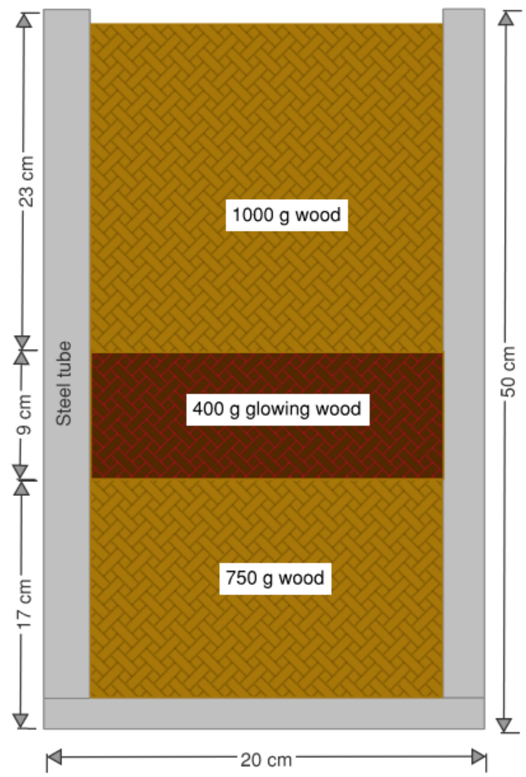

Figure 3-2 - Experimental setup. The location of the wood is only an illustration as the actual location will vary for each experiment.

3.2.1 Fuel

The fuel used in the experiments was wood waste, with material properties as described in Table 3-1. Wood waste represent one of the fire hazards at waste facilities and is a typical combustible material in waste. Smoldering fires can also occur in for example other biofuels and batteries. Wood waste was used as fuel because self-ignition in biological material is common at waste facilities [11].

There has to be a self-sustained smoldering fire for the experiments to be relevant, and wood is a material with known behavior when exposed to high temperatures. Therefore, wood waste is suitable for experiments with smoldering fires. Relatively small-sized wood waste as described in Table 3-1 was used for the experiments. The waste does not come from residual waste, but from recycled wood that is used to produce chipboards etc. Therefore, the material also contained wood dust. Wood waste from was the waste facility was sorted to a length and diameter suitable for smoldering fires with sufficient amount of air entrainment into the steel tube. This was tested in preliminary experiments.

Table 3-1 - Properties of wood waste used as fuel in experiments.

Property	**Value**
Sample size per experiment	2.15 kg
Length	5–15 cm
Diameter	2-5 cm

The amount of the fuel was the same for all experiments, as shown in Figure 3-2. But the wood waste probably had small variations in size and density from experiment to experiment that may have affected the results.

Figure 3-3 - Sample of wood waste used as fuel

3.2.2 Test tube

The steel tube with closed bottom was built in stainless steel and uninsulated. Isolation was not applied at side walls, since it was assumed that variations in heat loss would not have a significant impact on the extinguishing effect of the agent.

The steel tube has 20 cm diameter, 50 cm height and 2 mm thick walls. The volume of the cylinder was 15.7 l. Hence, 1 l of liquid could fill up 6.4 % of an empty cylinder, which equals a height of 3.2 cm. When the steel tube is filled with wood waste, 1 l of liquid will reach higher in the steel tube. However, the level of the liquid will not reach the smoldering fire in the experiments and will only contribute to the extinguishment as it flows through the sample. Based on visual observations, the liquid may stay three times higher than for an empty tube when the void volume and porosity of the material is considered.

Figure 3-4 - Steel tube used in experiments. The metal-band construction is used to keep the thermoelements in place.

3.2.3 Placement of thermocouples

Thermocouples used in the experiments were of type K – 1.5 mm. These thermocouples can measure temperatures from -40 to 1100 $^{\circ}$C [29].

A steel construction was used to keep the thermocouples at the intended location, even if the fuel moved due to the combustion. The construction consisted of crossing steel wiring where thermocouples were attached as shown in Figure 3-5.

Figure 3-5 - Steel construction used to keep thermocouples at the same location.

The thermocouples were positioned as shown in Figure 3-6. Seven thermocouples were used to locate the spread of the fire. Two thermocouples were placed 15 cm from the bottom, two at 19.5 cm, one at 24 cm and two at 28.5 cm from the bottom. The vertical distance between the thermocouples was 4.5 cm.

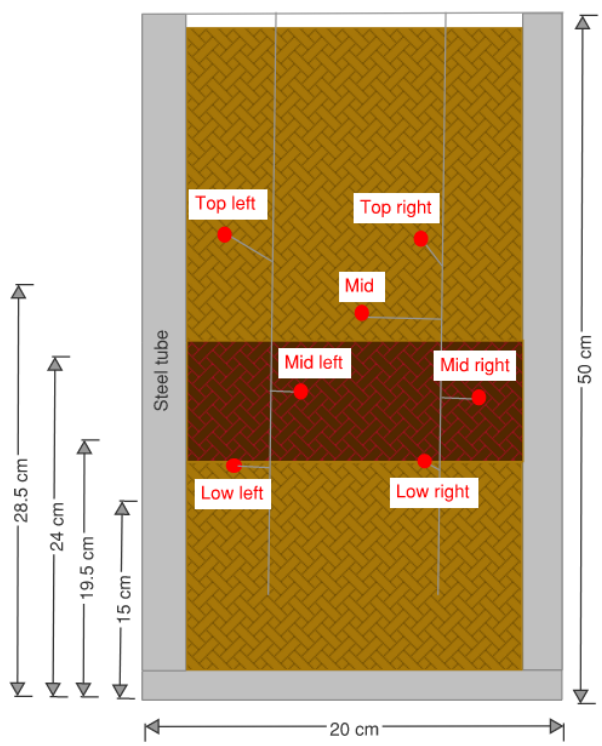

Figure 3-6 - Placement of thermocouples in experiments. Distribution of wood is illustrated in Figure 3-2.

3.2.4 Extinguishing agent

The experiments were conducted with six variations of extinguishing agent. Water mixed with sugar was chosen as the extinguishing agent because of the well-documented range of viscosity.

1 l of liquid was used as extinguishing agent. This amount was chosen as it could extinguish the fire, but it was not enough to fill the liquid level up to the fire source. It is assumed that the waster will fill up 10 cm of the tube when filled with fuel, while the fire source is estimated to be located 17 cm from the bottom of the tube.

The main issue with using sugar as an additive to increase the viscosity is that sugar may contribute to the fire. This was tested in the preliminary experiments, and the tests indicated that the temperature was too low for sugar to contribute to the fire, as the estimates of minimum ignition temperature for sugar dust vary from 330-480 $^{\circ}$C [30].

Water and sugar were mixed to vary the viscosity as described in Table 3-2. A description of 10 % sugar by mass, means that the extinguishing agent consist of an aqueous solution of sucrose ($C_{12}H_{22}O_{11}$) and water, with 10 mass percentage of sucrose.

Table 3-2 – Mass % of sugar in the fluid used as extinguishing agent with viscosity at 20 ℃[23].

Mass (%) sugar	Viscosity (mPa · s)
0	1.00
10	1.34
20	1.95
40	5.31
60	58.49

3.3 Procedure

The following procedure was followed for the experiments.

The fuel was weighed and prepared for the experiments. Wood waste was poured into the steel tube with the glowing wood in the middle of the tube. The wood waste used to start the smoldering fire was heated by a butane torch until all the wood was glowing.

Ambient conditions were measured by turning on the data recorder 2 minutes before the experiments started. When the 2 minutes was passed, the glowing wood was poured into the steel tube. Immediately after, more wood waste was poured onto the glowing wood to limit the oxygen access. The temperature was high enough to sustain a smoldering fire, but not high enough to start a flaming fire within the time interval of the experiment. This method was based on preliminary experiments.

The smoldering fire was left undisturbed for 60 minutes before application of extinguishing agent.
60 min was the time it took for the smoldering fire to establish at a temperature of 300-400 $^{\circ}$C in accordance with the preliminary experiments.

Application of the extinguishing agent was carried out by pouring the liquid of 1 l over the center of the tube at a constant rate for 10 seconds. The pouring distance was 5 cm over the tube.

The experiments were considered finished after 180 minutes or when the temperature inside the tube was below 40 $^{\circ}$C and still decreasing towards ambient temperature. The experimental setup was then cleaned to be ready for new experiments.

4 Results

The aim of this thesis was to conduct experiments to investigate the efficiency of viscous liquids for extinguishing smoldering fires. The results from the experiments are presented in this section.

4.1 Representative experiment

Two representative experiments using plain water and an aqueous solution of sugar and water with 60 mass percentage of sugar are chosen to illustrate the differences in extinguishment effect. Temperatures are shown in Figure 4-1.

Figure 4-1 show that there was a large difference in temperature during the first 60 minutes of the experiment with water as extinguishing agent. The first two minutes of every experiment recorded the ambient temperature, and the glowing wood was poured into the steel tube after two minutes. The highest temperatures were observed at the low left side, and this is where the fire region was located. The heat from the fire spread to nearby material and the smoldering propagated towards the right side, as seen on the temperature in the mid right thermocouple. The temperatures were between 250 – 450 °C when extinguishing liquid was introduced at 60 min. After pouring in 1 l of water, the temperatures decreased to 80 – 120 °C within 2 minutes. Temperatures stabilized for 20 min after which, the temperature at the low right thermocouple started to increase. The temperature at low right increased for 20 min together with the mid right and mid thermocouple until it started deceasing after 100 min. At this point, the other thermocouples in the experiment registered a temperature increase that lasted until the experiment finished. The highest registered temperature was 552 °C after 154 min at the low left thermocouple. It was concluded that the smoldering fire in this experiment did not extinguish due to the use of water.

The bottom plot in Figure 4-1 illustrates an experiment conducted with an aqueous solution of sugar and water with 60 mass percentage of sugar. This is the liquid with the highest viscosity that was tested in the experiments. The temperature increased up until 45 min where the temperature for all seven thermocouples was stabilized between 180 – 300 °C. The temperatures were fluctuating between these temperatures up until the application of extinguishing agent at 60 min. The temperature immediately decreased to 60 – 70 °C for all thermocouples except for the low left one, which decreased to 160 °C. At the low left thermocouple, the temperature stabilized for 5 min until a rapid increase occurred for the next 20 min, achieving the highest recorded temperature in the sample of 700 °C. This occurred after 92 min. This resulted in a transition to flaming fire in this fire region in the steel tube, which affected the temperature at the other thermocouples. The temperature at the six other thermocouples followed with a rapid increase and the temperature fluctuated between 180 – 580 ˚C after this. After 140 min, the temperature slowly decreased at all thermocouples, and this is an indication that the fire was fuel controlled. The experiment was terminated after 180 minutes.

The average temperature after 60 min was 326 ˚C for experiment 1-3, where water was used as extinguisher. 60 minutes later, the temperature had fallen 119 ˚C to 207 ˚C. This is a percentage decrease of 20 %, calculated in Kelvin. For experiment 5-3 with 60 % sugar, the temperature increased from 381 ˚C at 60 min to 466 ˚C at 120 min. That is an 13 % increase in temperature.

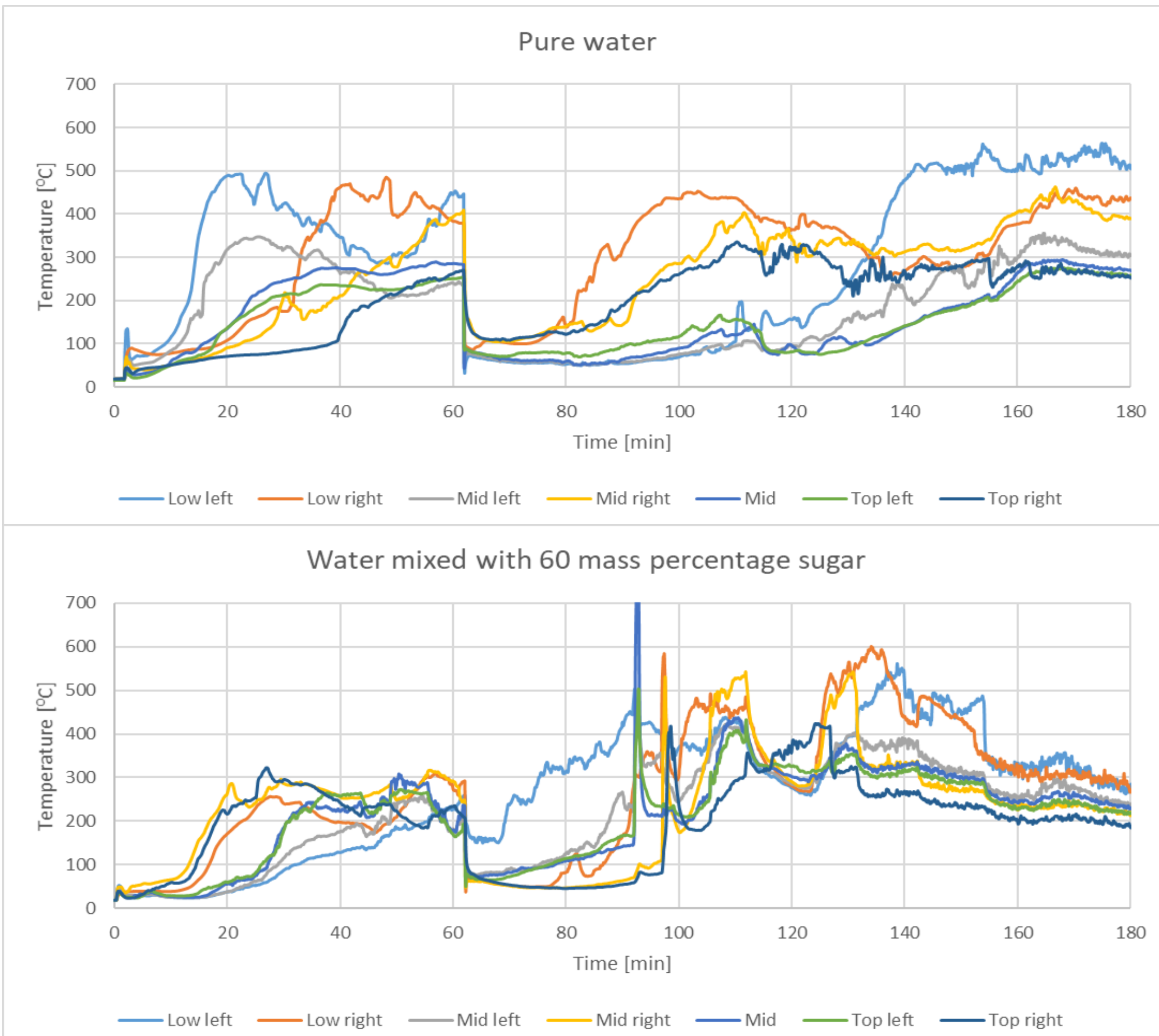

Figure 4-1 - Top graph: Temperature of experiment 1-3, where water is used as an extinguisher.
Bottom graph: Temperature of experiment 5-3, where 60 % sugar by mass solution is applied.

4.2 Summary of experiments

The average temperature of the seven thermocouples in all fourteen experiments is plotted in Figure 4-2. This summary shows that eight of the fires in the experiments flared up again after the extinguishing agent was applied, while six of the fires extinguished. Application of extinguishing agent occurred 60 min after the fire was started.

The average temperature of the thermocouples is used in this illustration as a representation of the fire development inside the steel tube for each experiment. It can be seen in Figure 4-2 that the temperature is rising quickly after extinguishing agent was applied for most of the high-viscose liquids (40 and 60 mass % sugar), there is a moderate temperature increase for the water experiments, while the experiments with a low viscosity (10 and 20 mass % sugar) have a slower fire developments after application of extinguishing agent.

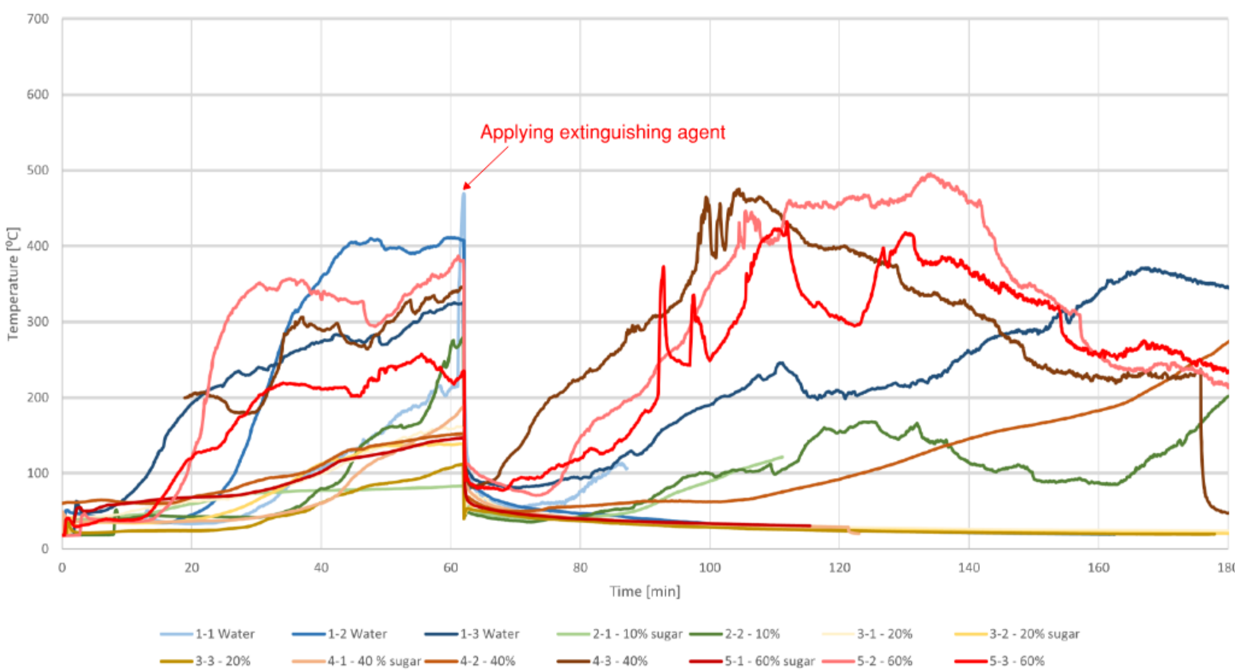

Figure 4-2 - Result from all experiments showing average temperature of the thermocouples. The fires are burning freely up until 60 min after ignition when extinguishing agent is applied. Some of the experiments were extinguished early and temperature logging was therefore stopped earlier for these experiments.

Experiments 4-3 and 5-3 had different preconditions than the other experiments in terms of moisture content. The wood sample did not dry as much for these as for the other experiments due to shorter time to dry and to the different seasons in which the experiments were conducted, resulting in higher moisture content. Therefore, the fuel in these two experiments required preheating to be able to get a self-sustaining smoldering fire. These two experiments had the most rapid fire development after extinguishing agent was applied.

4.3 Temperature

4.3.1 Water

Three experiments were conducted with 1 l water as extinguishing agent. In only one of those experiments (1-2) did the water put out the fire. Results are illustrated in Figure 4-3. It is worth noting that the temperatures 60 min into the experiments were the highest for this configuration where water was used as extinguishing agent. The viscosity of the extinguishing agent was 1 mPa · s.

Experiment 1-1 had a rapid fire development the first 60 min. The temperature increased so rapidly that the application of extinguishing agent was decided to be conducted 17 minutes earlier to avoid a flaming fire. The temperatures remained low for 10 minutes after the application before another rapid increase started. The experiments were finished 27 min after extinguishing agent was applied when the fire transitioned to a flaming fire.

Experiment 1-2 started at 2 min and had a slow development the first 30 min. Then the temperature increased rapidly before it stabilized at approximately 50 min. After 60 min the extinguishing agent was applied and there was no new temperature increase after this. The experiment was terminated at 165 min when the temperature was back to ambient temperatures.

Experiment 1-3 quickly achieved high temperatures that stabilized between 200 – 450 ℃ after 40 minutes. The temperatures decreased to approx. 50 - 100 ℃ after extinguishing agent was applied, but 20 minutes later the temperature began to increase again. The experiment finished after 180 min. The temperatures were still high (250 – 500 ℃) at this time.

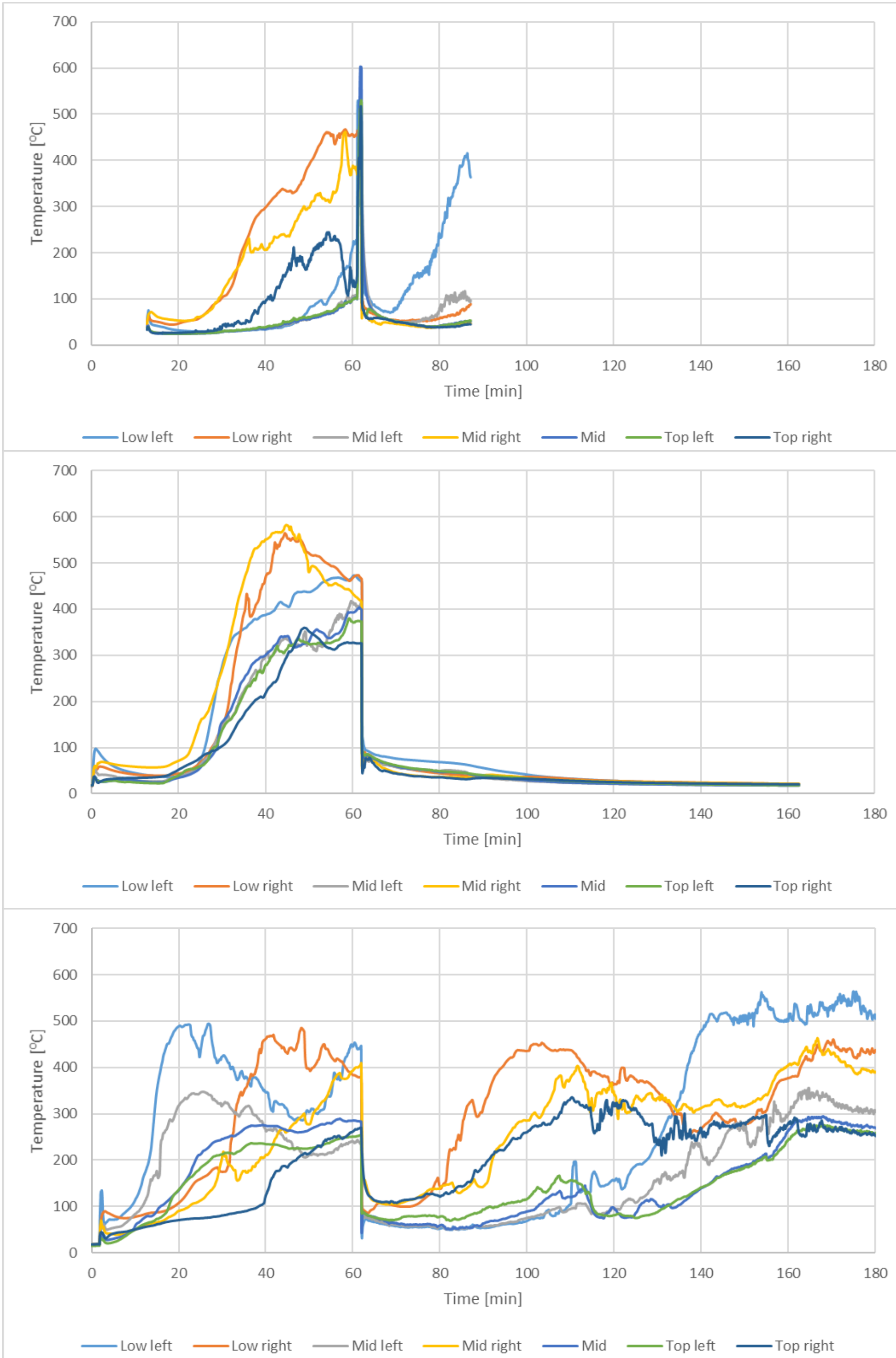

Figure 4-3 - Temperature as function of time for three experiments with water as extinguishing agent.
1-1) The smoldering fire transitioned into a flaming fire quickly after applying the extinguisher.
1-2) The water extinguished the fire.
1-3) The fire rekindled 20 minutes after extinguishing agent was applied.

4.3.2 10 % sugar by mass

Two experiments were conducted with an aqueous solution of water mixed with 10 mass percentage sugar (Figure 4-4). The fires were not extinguished in any of the experiments. Only two experiments with this configuration are recorded because of faulty data in the third experiment. The viscosity of the extinguishing agent was 1.3 mPa · s (30 % higher than for pure water).

In experiment 2-1 the temperature stabilized below 200 ℃ for the two lowest thermocouples to the right in the tube before extinguishing agent was applied, while the rest of the thermocouples in the tube still were little affected by the fire. 30 minutes after application, the temperature rose rapidly for the two lowest thermocouples on the right side of the tube and the experiment ended early because the fire transitioned into a flaming fire. This is not shown in the graph as the fire likely occurred at the right edge of the tube where there were no thermocouples, but it is shown as a rapid temperature increase at the two thermocouples to the right. The top right thermocouple was positioned a little further from the edge and this might explain why there is lower temperatures at this thermocouple.

Experiment 2-2 was started 7 minutes later than the other experiments. It's still considered representative as the fire was smoldering when extinguishing agent was applied 53 minutes after the primary ignition. The temperature decreased to under 50 ℃ in the tube, but after 20 minutes the temperature started rising slowly and steadily and this continued throughout the rest of the experiment.

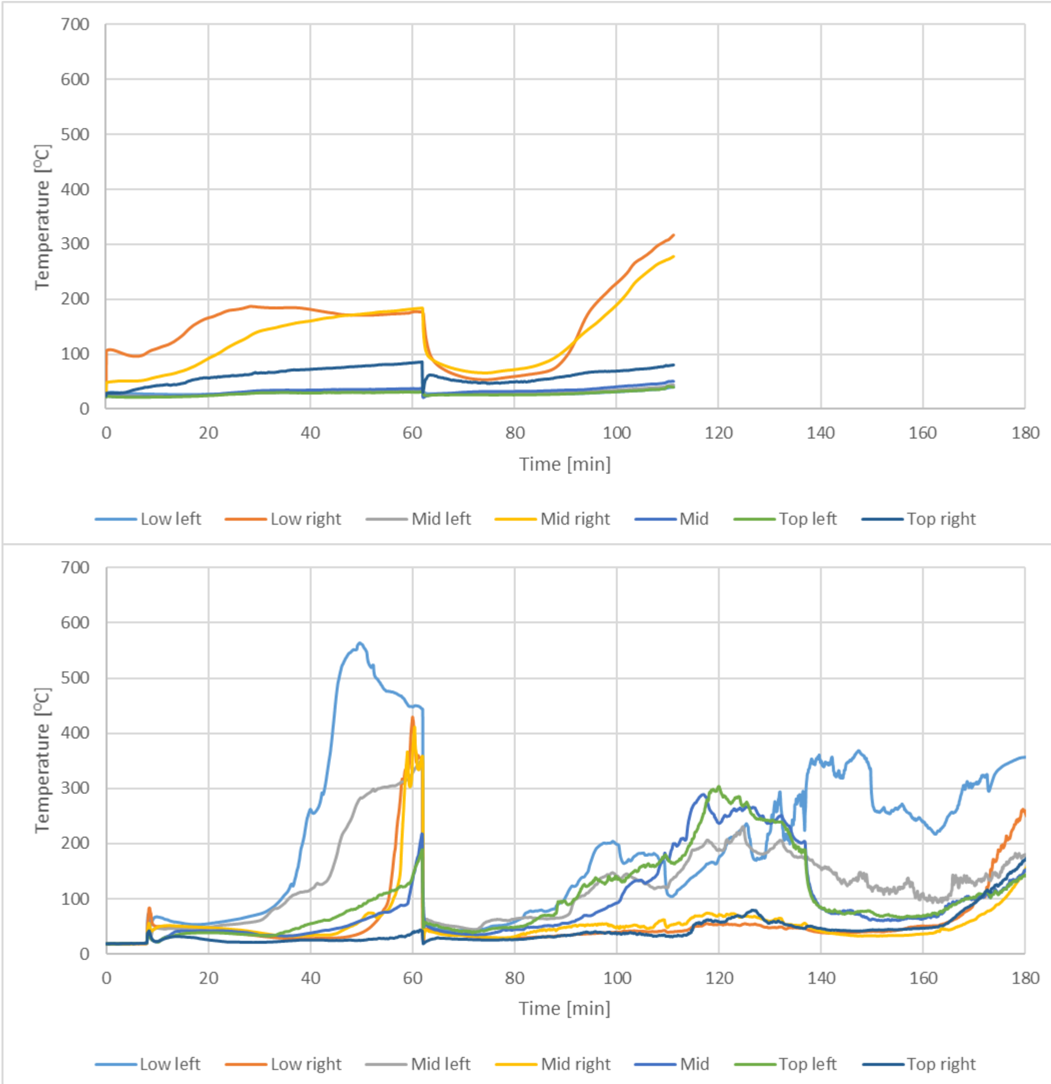

Figure 4-4 - Temperature as function of time for two experiments with 10 % sugar by mass mixed with water as extinguishing agent.
2-1) The fire was not extinguished.
2-2) The smoldering fire transitioned into a flaming fire.

4.3.3 20 % sugar by mass

Three experiments were conducted with an aqueous solution of sugar and water with 20 % sugar by mass. The fire development was similar, and the fire was extinguished in all three experiments. The viscosity of the extinguishing agent was 2 mPa · s (100 % higher than for pure water).

The temperature started increasing after 20 minutes for all three experiments and it steadily rose until the fire reached a temperature of 300 – 400 °C after 60 min at the lowest thermocouples. The temperature decreased to 50 – 100 °C after application of extinguishing agent and slowly decreased for the rest of the experiments (see Figure 4-5).

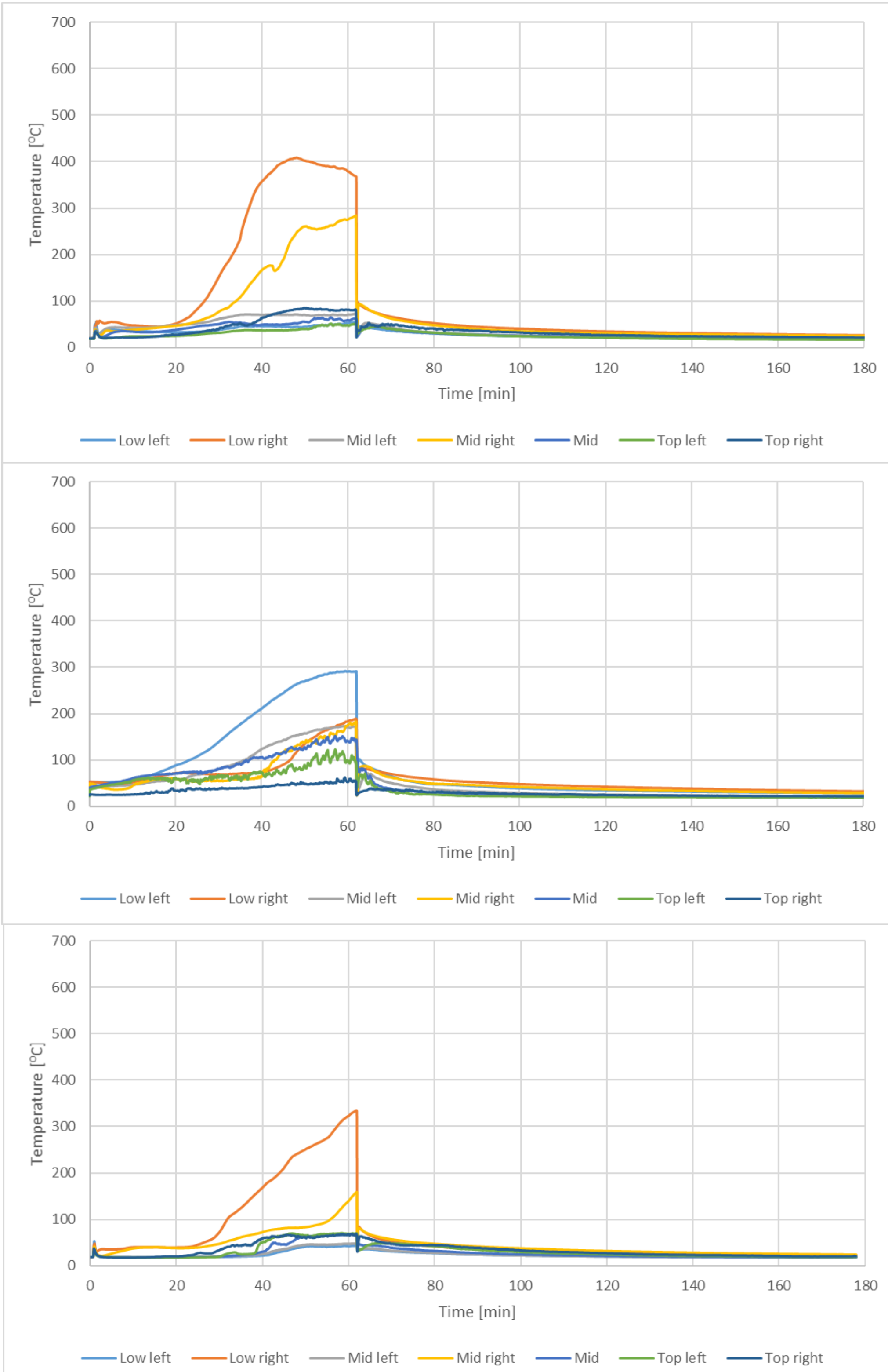

Figure 4-5 – Temperature as function of time for three experiments with 20 % sugar by mass mixed with water as extinguishing agent. The smoldering fire was extinguished in all three experiments.

4.3.4 40 % sugar by mass

Three experiments were conducted with an aqueous solution of sugar and water with 40 mass percentage of sugar. The viscous mixture extinguished the fire in one of the experiments, as illustrated in Figure 4-6. The viscosity of the extinguishing agent was 5.3 mPa · s (430 % higher than for pure water).

Experiment 4-1 had rising temperature after 40 minutes and reached temperatures up to 350 °C after 60 min. The temperature dropped quickly after application of extinguishing agent and was below 40 °C after 120 min. Therefore, the experiment was terminated.

Experiment 4-2 had a slow temperature development and the lower right thermocouple registered 330 °C after 60 min while the rest were relatively low. The temperatures decreased to 50 - 70 °C after application of extinguishing agent, and the fire in the tube kept that temperature for 40 minutes before it started rising again. After 130 min, the temperature in the lower right thermocouples had surpassed the temperature before application of liquid, and it was still rising. When the experiment was terminated after 180 min the temperature was still rising at the thermocouples.

Data logging was not activated for the first 15 minutes of experiment 4-3. The moisture in the wood waste for this experiment was initially higher than for the others, as explained in chapter 4.2. The temperature in the tube had increased to 200 – 450 °C at the thermocouples when application of extinguishing agent initiated. The temperature did not decrease significantly for this experiment as for the others and the temperature at the low left thermocouple was still at 200 °C. The temperatures increased rapidly after extinguishing agent was applied and after ten minutes the temperature was higher at three of the thermocouples, than it was before application of the liquid. The temperature peaked at 700 °C at the mid right thermocouple at 100 – 110 min and decreased after this point in the experiment. The fire may have been fuel-controlled at this point and the experiment was terminated after 176 min.

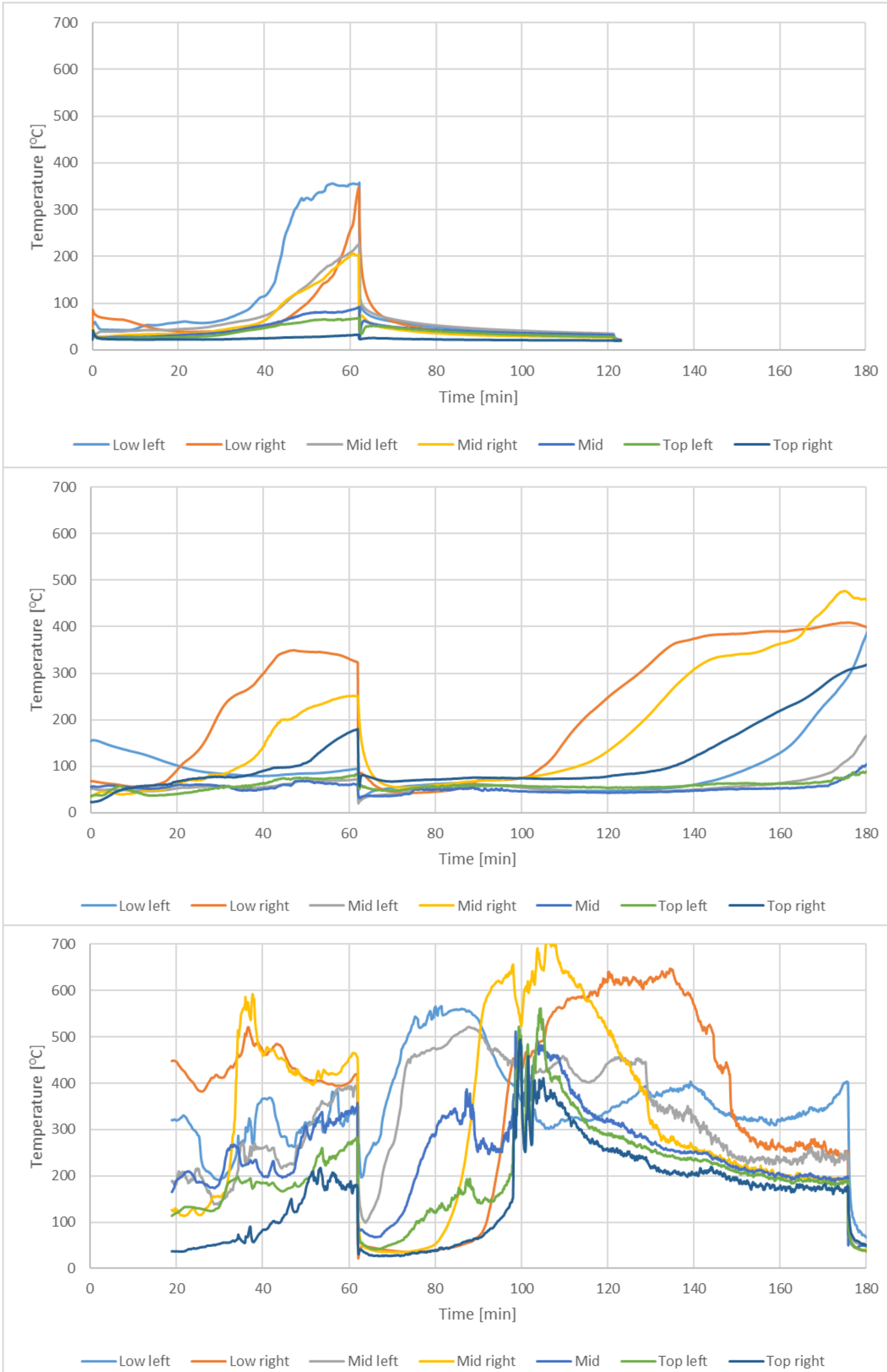

Figure 4-6 - Temperature as function of time for three experiments with 40 % sugar by mass mixed with water as extinguishing agent.
4-1) The fire was extinguished in the experiment.
4-2) The fire was not extinguished.
4-3) The fire was not extinguished.

4.3.5 60 % sugar by mass

Three experiments were conducted with an aqueous solution of sugar and water with 60 mass percentage of sugar, see Figure 4-7 for illustration. The viscous mixture extinguished the fire in one of the experiments. The viscosity of the extinguishing agent was 58.5 mPa · s (5750 % higher than for pure water).

The smoldering fire in experiment 5-1 had temperatures ranging from 50 – 380 °C after 60 min, where the temperature at the low right thermocouple was the highest. Extinguishing agent was applied, and the experiment was considered finished after 115 min, as all the temperatures were below 40 °C and decreasing.

Experiment 5-2 quickly achieved high temperatures and the temperatures stabilized between 300 – 600 °C after 40 minutes for the lowest thermocouples. The highest temperature after 60 min was recorded at the low left thermocouple at 580 °C. The temperatures decreased to approx. 100 °C at all thermocouples after the extinguishing agent was applied, but then slowly increased again. 40 minutes after application of extinguishing agent the temperatures were higher than before. The highest recorded temperature of 808 °C in the experiment was after 132 minutes at the mid right thermocouple, and with such high temperatures it is assumed that the fire had transitioned to a flaming fire. The experiment finished after 180 min when the temperatures still were high (200 – 300 °C) but decreasing together with the available fuel.

The moisture in the wood waste in experiment 5-3 was higher than for the other experiments, as explained in chapter 4.2. The temperature increased steadily up to 300 °C where it stabilized after 30 minutes for most of the thermocouples, except at the low left and the mid left thermocouples that increased slower, but 200 °C was reached after 50 minutes. When extinguishing agent was applied after 60 min, the temperatures ranged from 180 – 300 °C. The high-viscosity liquid made the temperature fall beneath 80 °C for all thermocouples except the low left which only sank from 260 °C to 160 °C. The temperature increased again quickly 30 minutes after extinguishing agent was applied, and a peak of 750 °C was the highest recorded temperature. The decrease in temperature began 70 minutes after application of extinguishing agent and the fire may have been fuel-controlled.

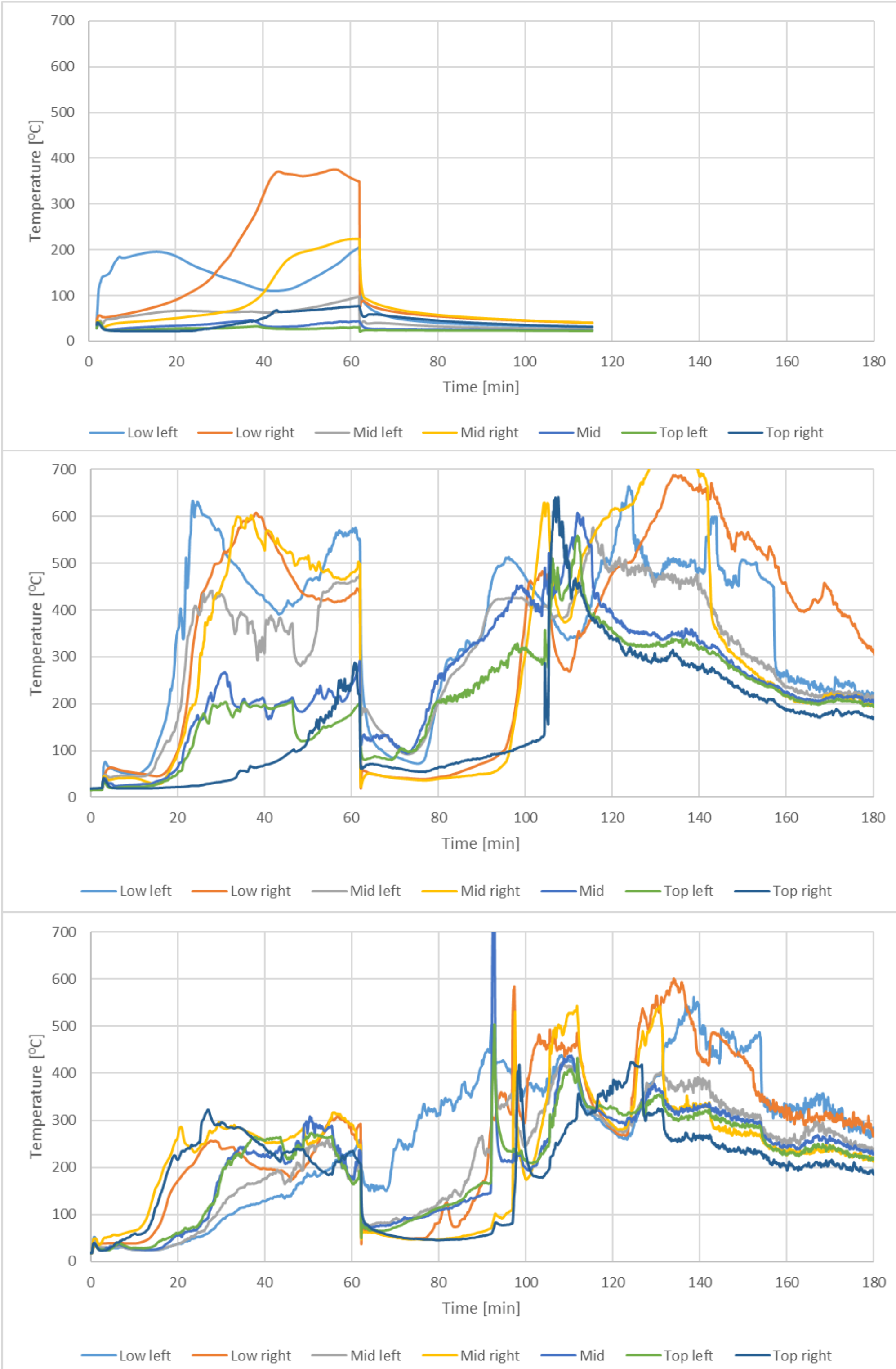

Figure 4-7 - Temperature as function of time for three experiments with 40 % sugar by mass mixed with water as extinguishing agent.
5-1) The smoldering fire was extinguished in the experiment.
5-2) The smoldering fire was not extinguished in the experiment.
5-3) The smoldering fire was not extinguished in the experiment.

5 Discussion

This part of the thesis will discuss different aspects of the experiments, from the results to the setup and compare this with previous research and theory.

5.1 Viscous liquid as extinguishing agent

5.1.1 Results

Wood waste from a waste facility was used as fuel for the experiments. This may have caused variations in the fire development in the different experiments. Hence, making it more difficult to compare the results. But they are more representative of how a smoldering fire develops in early phase at a waste facility than if the fuel was homogeneous. There was uncertainty related to the fire development as no samples of wood waste were the same, but the fire development was as intended for most of the experiments, reaching temperatures around 300 ℃ with a self-sustaining smoldering fire within the first 60 min of the experiments.

The results indicated that the extinguishment effect is better for liquids with higher viscosity than water, but the viscosity should be limited so that the liquid does not evaporate before reaching the hot region. The fire in all the experiments with 20 % sugar by mass as extinguishing agent were extinguished and did not reignite. Several of the experiments with more than 20 % sugar by mass had a rapid fire growth following the initial temperature decrease as suppression agent was applied. This may have been caused by the water evaporating and the sugar that was left contributed to the fire. When cleaning up after the experiments, it was observed that a lot of water was left in the bottom of the tube for the low-viscosity liquids, while less was left as the viscosity increased. It is uncertain if this is because the water evaporated or if the liquid spread more out in the fuel, being absorbed into the wood. The water may have evaporated as the high-viscosity liquids flowed through the fuel, giving it more time to reach high temperatures and evaporate.

Two of the experiments (4-3 and 5-3) were conducted with wood waste that had higher moisture contents due to storage outside during the autumn, while the rest of the wood was dried during the summer. The fuel in these two experiments were preheated in a convection oven before the experiments as the fuel was difficult to ignite. The smoldering fires in these experiments had a more rapid temperature increase after application of extinguishing agent and achieved the highest maximum temperature around 100 minutes into the experiments. This may have been because the fuel in these samples ended up with lower water contents than the other samples after the preheating.

Figure 5-1 illustrates the average temperature of all thermocouples for each experiment when the extinguishment agent was applied and 5 minutes after. The average temperature at the x-axis gives a measure of the heat intensity in the smoldering fire in the sample when extinguishing liquid was applied. Average temperature in the sample 5 min after the liquid was applied is shown at the y-axis. The results should have aligned linearly upwards to the right if the cooling effect was the same for all experiments. However, the results show that high average temperature as the suppression starts for the water and 10 % sugar by mass experiments gives lower temperature and thus a higher cooling effect compared with the cooling effect for the more viscose liquids. This may be caused by water evaporating as the high-viscosity liquids flow slower through the fuel, which means that less water was available for cooling the fire at the early stages of the extinguishing. The high-viscosity liquids may have had advantages later in the extinguishing process, such as adhering to the fuel and spreading more in the sample.

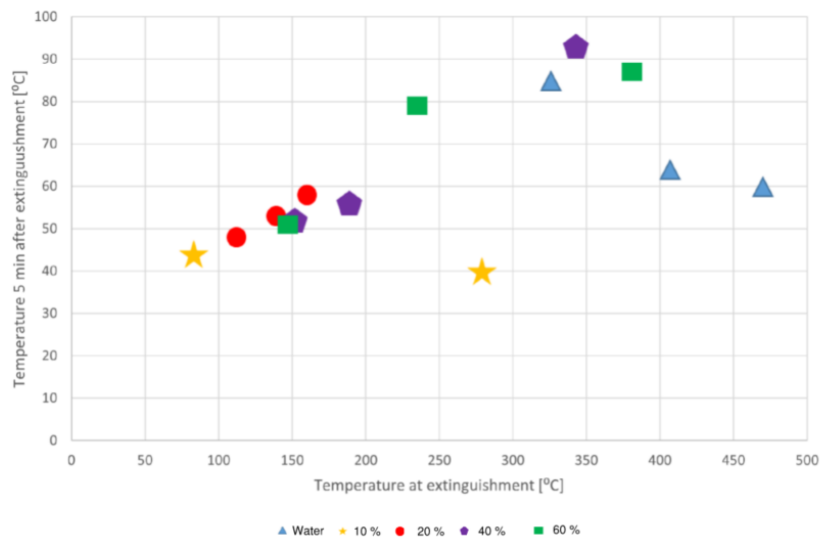

Figure 5-1 - The correlation between temperature at extinguishment and 5 minutes after for each experiment.

The temperature at the start of suppression also seems to determine if the fire flares up again or not. Figure 5-2 illustrates the correlation of the average temperature of all thermocouples for each experiment and extinguishment. The results show, not surprisingly, that a higher temperature in the sample at application of extinguishing agent, increases the chances of the fire to flare up again after applying the agent. Most of the fires that did flare up again had higher temperatures (T > 200 ℃) as suppression started than those who did not and 5 of the 6 fires that did not flare up again had relatively low temperature as suppression began. However, a 10 % sugar solution had the lowest average temperature when application of extinguishing agent occurred, but the fire did still flare up again.

Furthermore, one experiment with an average temperature of over 400 °C was extinguished with plain water.

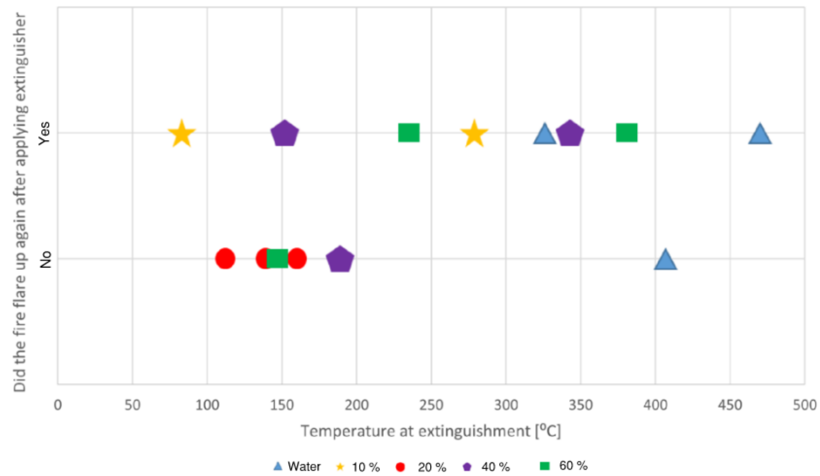

Figure 5-2 - The correlation between average temperature as liquid is added and extinguishment.

5.1.2 Comparison with previous research

The studies conducted by the Pacific Southwest Forest and Range Experiment Station in California in 1962 showed that the fire department had good experience with viscous water. The water was thickened to a viscosity of light motor oil (100 - 200 mPa · s) so that it was still easy to pump and handle but adhered well to vegetation.

The most effective concentration in the experiments conducted had 20 % sugar by mass and 80 % water by mass. This mixture has a viscosity of 2 mPa · s at a temperature of 20 °C and is quite different from the mixture that was tested in 1962. Liquids with higher viscosity than what was tested in the experiments in this thesis could be a viable option if non-combustible additives are used in the water. At higher viscosities, the liquid uses more time to reach the fire, thus the water evaporates faster close to the fire region. For the experiments conducted this may have occurred for the higher concentrations and the sugar may have contributed to the fire, increasing the heat production.

5.2 Experimental setup

5.2.1 Small-scale

These experiments were small-scale, and extinguishing was simpler than for a large-scale fire because the liquid spreads more easily over the fuel. Even though the more viscous liquids were better than water in these small-scale experiments, they might be inefficient on a larger scale due to problems with reaching the hot region of the smoldering fire. The method of applying the extinguishing agent could have an impact on how effective the agent would be [31].

Locating a smoldering fire in a large pile and mapping the propagation can be challenging, an advantage of small-scale experiments is that extinguishing agents can more easily be applied in the area of the smoldering fire.

Heat loss to the environment is not considered as a variable in the experiments. It is limited how much heat loss it is in the steel tube during the experiments, and it is not considered to have a significant impact on the results. The heat loss for a smoldering fire at a waste facility is mainly by heating up nearby fuel and the heat loss to the ambient air through the steel tube in these experiments is not too different from this. Insulation of the steel tube to simulate a larger system would therefore not be as realistic regarding heat loss. The radiation back to the smoldering fire would have been higher and higher temperatures would be achieved, causing a faster transition to flaming fire.

5.2.2 Placement of thermocouples

Several thermocouples were used to information on the fire spread and the impact of the liquid. There could have been used more thermocouples to get an even better understanding of the fire spread, but the configuration did not allow it and more metal in the system could also have an impact on the combustion. The two metal-band constructions used to keep the thermocouples in place may have caused some channeling for the applied extinguishing agent, but this could not be determined by the current setup since observations inside the tube was not possible, see Figure 3-5.

The diameter of the cylindrical steel tube was chosen to be large enough to reduce heat loss as a consequence of large surface to volume ratio. A smaller diameter would have had an unrealistic effect on the fire spread and temperature, with a greater heat loss to the ambient, compared to a smoldering fire at a waste facility.

Differences in temperatures between the experiments were expected since the fire develops differently depending on the properties of the fuel and the location/temperature of the initial fire. The average temperature of all 7 thermocouples in the experiments gives a useful measure on the temperature in the sample which can be used to compare the experiments before and after extinguishing agent is applied. Differences in temperatures between experiments are dependent on the location of the fire. The glowing wood used to start the smoldering fire was poured from the top of the steel tube and developed differently for each experiment. This caused some of the fires to develop close to the thermocouples and some a few centimeters away, this may have affected the results. It is unknown how much impact this had on the results as it was not possible to directly observe the fire spread in the steel tube during the experiments.

5.2.3 Extinguishing agent

The experiments conducted to simulate a smoldering fire are considered representative for a smoldering fire in a waste facility. The extinguishing agent was not. The viscous solution of sugar and water were chosen as the extinguisher because of the well-documented viscosity range of the liquid, the practicality of having a cheap and easily available material and because the preliminary experiments indicated that it was an effective extinguisher for smoldering fire compared to regular water.

There was a concern that the sugar would ignite and contribute to the fire, but this was not the case in the preliminary experiments. The smoldering fire did not reach high enough temperatures to ignite the sugar and the high-viscose solution was more effective than the water solution.

For the high-viscosity solutions (40 % and 60 %) there seems to be a trend of higher temperatures and a more rapid-fire development in the experiments. This could have been because of the sugar's involvement in the fire. The extinguishing seems more effective for liquids at lower viscosity (10 – 20 %). The water may not evaporate that quickly for these lower-viscosity liquids, thus cooling the fuel to temperatures where the sugar does not ignite. This makes a liquid with a viscosity of 2 mPa · s (2x water) more effective than water by engulfing the smoldering fire better than normal water, as seen in the experiments with 20 % sugar solution where all the experiments where extinguished.

The viscosity of a liquid will drop when the temperature gets higher, and it will increase when the temperature gets lower. Therefore, the chosen viscosity needs to be suitable for the expected temperature range. The high temperature from the conducted experiments lowered the viscosity substantially. For water the viscosity drops 69 % from 20 – 90 ℃ and the viscosity most be changed accordingly to be low enough to extinguish the fire, and high enough to not flow straight through.

1 l extinguishing agent was used for each experiment. This amount was purposely chosen as it was shown in the preliminary experiments that the cooling effect of 1 l agent did not extinguish the fire every time, but it was sufficient to extinguish the fire in some cases. It might have been more difficult to see differences in the result if less extinguishing agent was used, and more agent might have extinguished the fire in every experiment, also making it difficult to read the results. A larger amount of agent would

also have an impact on the fire by filling up to the fire region because there was no draining in the steel tube.

The extinguishing agent was applied at the center of the steel tube. This was done to see if the liquids with higher viscosity was spreading in the tube than water. The extinguishing effect might have been better if the extinguishing agent was applied over the whole top area of the steel tube. Then the liquid would spread more, moistening more of the fuel.

5.3 Other applications

Fire extinguishing can be a complicated process where there are many factors to consider. Every fire case needs to be assessed on its own regarding for example type of material ignited, fire size and oxygen supply. Ambient conditions as temperature and wind may also have a great impact on how the fire behave.

The method of extinguishing a fire with a viscous liquid may be applicable for bush fires or to limit fire spread between building. The high temperatures that are obtained in a fire causes evaporation of the water and a humid environment where the fire thrives. This factors are especially critical in bush fires where the water supply and pressure are inadequate. Liquids with higher viscosity may be a more effective extinguisher in these cases.

This could also be applicable for surfaces that are water resistant or non-absorbent. On moist surfaces, the water needs to evaporate before the surface catch fire. The problem is that if you spray water on a building to avoid the spread of fire, the surface will often not soak up the water and so the water will drain away from the surface and to the ground, not reaching its full potential. Fire protection of the surfaces could be optimized to mitigate the consequences of fire spread by using viscous liquid as a preventive measure.

The fire suppressant may be an issue for the environment, and it is not desirable to have toxic extinguishing agents contaminating nearby fire sources.

6 Conclusion

This experimental study was based on small-scale experiments to extinguish smoldering fire in wood waste by using viscose liquids as extinguishing agent. One important finding is presented.

There was experienced promising results for the experiments with viscosity the double of water, while previous research has good experience with viscosity 100 – 200 times higher than water. Additional work within this range of viscosity should be carried out to test the optimal extinguishment effect a high-viscosity extinguishing agent could have on smoldering fires at waste facilities. There are also other areas where these liquids may be an more effective extinguishing agent than water, such as for densely built wooden settlements or bush fires.

7 Further work

The experiments and research conducted in this thesis is limited compared to the broad and undiscovered terrain we call smoldering fires. There is still research to be done on the topic on effective methods to extinguish these fires. Research topics that are considered to be relevant for future work is listed:

- The use of viscous liquids in bushfires and densely built wooden settlements.
- Experiments with more configurations of high-viscosity liquids.
- Up-scaled experiments.
- Find viable viscous liquid that are effective, cheap, easy to handle and environment friendly.

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